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Holocene vegetation succession and forest history in the upper Monts du Forez, Massif Central, France

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ABSTRACT

On the basis of seven palynological records, we reconstruct the forest-limit composition and dynamics during the second part of the Holocene, in the upper montane and subalpine zones of the Monts du Forez in the north-eastern Massif Central, using a 2 km long, elevational transect of sites at 1335–1590 m elevation. All sites are mires today, varying in size from 2 to <0.1 ha. The chronology of the pollen diagrams is based on calibrated radiocarbon dating combined with pollen-stratigraphic correlation among the diagrams using the regional pollen component. *Corylus avellana* forest with *Ulmus* developed in the study region soon after the start of the Holocene. Soon after *Fagus sylvatica* arrived in the study area and expanded after ca. 3500 BC (5450 cal yr BP) to full abundance within a few centuries at the cost of *Corylus*. *Abies alba* expanded slowly within the *Fagus* forest after ca. 3300 BC (5250 cal yr BP), taking two millennia to reach its final abundance. During ca. 800–650 BC (2750–2600 cal yr BP) *Fagus* and *Abies* had reached similar overall abundances and formed forests only minimally affected by prehistoric human impact, which could serve as a natural baseline condition for extant forest management. We hypothesise that during this period dense *Abies–Fagus* krummholz had an upper limit of 1570 m, with scattered *Abies* trees above this and open woodland of *Sorbus*, *Betula* and *Acer* up to the summit (1634 m a.s.l.). A varied cultural landscape was in place in medieval times, with cereal cultivation and grasslands in a predominantly forested landscape. A baseline condition of this kind of cultural landscape could be found in late medieval times. During the last several centuries major deforestations took place and planted *Pinus sylvestris* replaced much of the originally natural *Abies–Fagus* forest. Crop cultivation increased in the cultural landscape. All diagrams have hiatuses (missing peat layers), which in most cases could be attributed to domesticated animals damaging the mire surface. For mire protection we therefore recommend a limited grazing pressure by cattle. The major phases in settlement history from the Neolithic to medieval times can be recognized in the pollen diagrams.

1. Introduction

This paper reports on the Monts-du-Forez extension of the Middle High Mountain project by C.R. Janssen (Janssen and Punt, 1998). This

project aimed to use palaeoecological methods in order to compare the post-glacial vegetation histories of European middle-high mountain ranges with a core of granite and a climate that has marked Atlantic influences. A main question at the onset was whether, how, and why the

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Holocene immigration and dynamics of the main trees in their upper elevational reaches differ among mountain ranges in relation to climatic and human impacts. This question has gained renewed relevance today in the light of the current accelerated changes in land-use and climate.

The project started between 1969 and 1982 in the Vosges Mountains in NE France. This mountain range was selected because it has a clear vegetation zonation and an abrupt forest limit of deciduous trees today at about 1200 m a.s.l., contrasting with the nearby Alps where the much higher forest limit is diffuse and consists mostly of conifers. It emerged from various studies, especially by [de Valk \(1981\)](#), that the abrupt upper forest limit is indeed natural and formed by deciduous trees, mainly *Fagus sylvatica* (beech) today, but also that the immigration of beech (4100–3500 BC (6050–3450 cal yr BP); [Kalis 2014](#)) was preceded by *Corylus avellana* (hazel) woodlands at the forest limit during the first part of the Holocene. The question arose whether or not this situation had parallels in other middle-high mountain ranges. In [Janssen's](#) own words: “During the seventies it became evident that the study of just one mountain range would be too limited for studies on a more continental scale. Three other mountain ranges were selected along a climatological and phytosociological gradient from the Vosges to the western Mediterranean (..): the Monts du Forez on the Massif Central, France, the Sierra Cabrera Baja in western Cantabria, Spain [[Janssen, 1996](#)], and the Serra da Estrela, Portugal [[van der Knaap and van Leeuwen, 1994, 1995, 1997; Connor et al., 2012](#)]. (..) The underlying idea is that the role of climate and competition between plant species could be separated and more meaningfully explained by the combined study of the local and regional vegetation development in the various elevational belts of these mountain ranges” ([Janssen and Punt, 1998](#)). The main palaeoecological research questions for the Monts du Forez, as previously for the Vosges Mountains, were: (1) Have there been fluctuations in the elevation of the upper forest limit? (2) When did beech form the upper forest limit? (3) What was the position of the upper forest limit and what was the vegetation before the arrival of beech? A further question concerns the management and protection of forests and the cultural landscape: can we suggest periods in the past that had natural baseline conditions? We discuss the vegetation development during the entire Holocene. The pollen data will be stored in the EPD (European Pollen Database) and NEOTOMA.

2. Regional and local settings

2.1. Study area

General descriptions of the physiography of the Monts du Forez and adjacent parts of the Massif Central are given in [Cubizolle et al. \(2012, 2013, 2014, 2017, 2022, This Issue\)](#). Modern flora and vegetation of the Monts du Forez, especially of the upper mountain reaches centred around the highest top where our palaeoecological studies were carried out, are described in [Thébaud \(1988\)](#), [Schaminée and Meertens \(1991\)](#), [Schaminée and Hennekens \(1992\)](#), [Schaminée et al. \(1992\)](#), and [Schaminée \(1993\)](#). The montane and subalpine vegetation consists of mixed *Abies-Fagus* forests, meadows, pastures, and *Calluna-* and *Vaccinium*-dominated heathlands that are or have been grazed by domesticated animals. The study sites are located in open terrain, but the existence of closed forest locally up to 1500 m elevation 0.5 km north-east of the transect, scattered trees in the grazed area up to ca. 1520 m, and planted trees within the fenced area on the mountain top above 1620 m suggest that the upper forest limit was much higher in the past, before it was suppressed by grazing by domesticated animals.

The backbone of the Forez-project is an elevational transect of sites on the eastern to southern slope of the highest top of the Monts du Forez (Pierre-sur-Haute Mountain, 1634 m a.s.l.) ([Fig. 1, Table 1](#) Nos. 2–8). Two study sites about 2 ha in size lie close together on a relatively flat plateau, of which Gourds des Aillères is the main site of the project. This plateau carries a mosaic of grasslands, heathlands, a few arable fields, and mires. The slope above these sites runs directly to the top of the

Pierre-sur-Haute Mountain. Especially above 1450 m a.s.l. this slope has an irregular and at places interrupted network of peat mires mostly associated with springs. The tiny mires vary in size typically between a few and a few hundred square metres. The mires alternate with rocks, grassy and heathland patches and small streams. The summit area above 1570 m a.s.l. is flattish and treeless and has rather thin, stony soils and very few, tiny mires. In order to obtain an elevational transect of sites between Gourds des Aillères and the mountain top, we selected four of these tiny mires for detailed study (Nos. 5–8 in [Table 1](#)) after extensive test coring during field work in the early 1980s. The following field observations suggested that peat accumulation in these tiny mires might not be continuous: (1) Surface water on the mires was in all cases derived from tiny springs; (2) The base of all the tested mires consisted of peat without underlying aquatic sediments, showing that they depended on springs for their initiation; and (3) Mire patches differed in surface wetness, many patches being too dry for active peat growth. This suggests a scenario of shifting hydrology in which active mire patches outgrow the local water table, divert the spring-water flows, and dry out. We also observed that tiny mires are especially sensitive to disturbances such as erosional slope processes and trampling by animals. Spring productivity may also have varied in the past due to variations in forest cover, as forest uses more water than open vegetation and thus suppresses spring activity. We selected mires for study that had a relatively large peat depth, active peat formation, and a peat section without thick sand layers or abrupt transitions in the degree of peat decomposition. The mire in Corniche-en-Cœur, studied by [Cubizolle et al. \(2014\)](#), is larger than most (3000 m²), but we selected the much smaller Pierre-sur-Haute mire lying nearby because it lies slightly higher and closer to the mountain top and it had thicker peat deposits. The highest site, Source Captée (French for ‘enclosed spring’), is a small paludified patch just outside the fenced area on the flattish, treeless mountain top. Right at the transition of the plateau with the larger mires to the slope with the tiny mires, we cored Colleigne (No. 5 in [Table 1](#)), lying in a sheltered position.

Earlier publications from our work in the Monts du Forez comprise [Janssen and van Straten \(1982\)](#) with a pollen diagram of Plateau des Egaux, [Etlicher et al. \(1987\)](#) with an incomplete pollen diagram of Gourds des Aillères (centre) focussing on a tephra layer in the Late-Glacial deposits, and [Janssen \(1990\)](#) with further incomplete pollen diagrams of Gourds des Aillères. Other, later publications with pollen diagrams from this part of the Monts du Forez comprise [Argant and Cubizolle \(2005\)](#) for La Morte, [Cubizolle et al. \(2014\)](#) for Corniche-en-Coeur and Gourgon, as well as [Cubizolle et al. \(2017; 2022, This Issue\)](#) for Gourds des Aillères, with Late-Glacial data in great detail.

2.2. Principles of pollen transport in mountains

At the start of the Middle High Mountain project in 1969, literature on the principles of pollen transport in mountains hardly existed. In the Vosges Mountains, therefore, [Janssen](#) established a transect of modern pollen surface samples across the mountain range, from lowland to lowland crossing the highest elevations ([Janssen, 1981a](#)), and pollen traps were installed and studied annually (unpublished). Pollen deposition on the treeless area above the forest limit (the ‘Hautes Chaumes’) was studied separately in more detail ([Tamboer-van den Heuvel and Janssen, 1976](#)). The mechanisms of pollen transport in mountains were found to differ from those in lowland areas, so they were further explored by [Kalis \(1984, 1985a\)](#) for the Vosges Mountains and by [Lutgerink et al. \(1989\)](#) for the Monts du Forez. We provide here an outline of the results, because they form the basis for the presentation and interpretation of our fossil pollen sequences.

Mountain wind systems have a large impact on pollen dispersal ([Kalis, 1984, 1985a; Lutgerink et al., 1989](#)). On sunny days, vertical air currents and mountain winds transport pollen towards higher parts of the mountains where clouds are formed and rain washes the pollen out to the ground. Pollen on mountain tops derives therefore mainly from

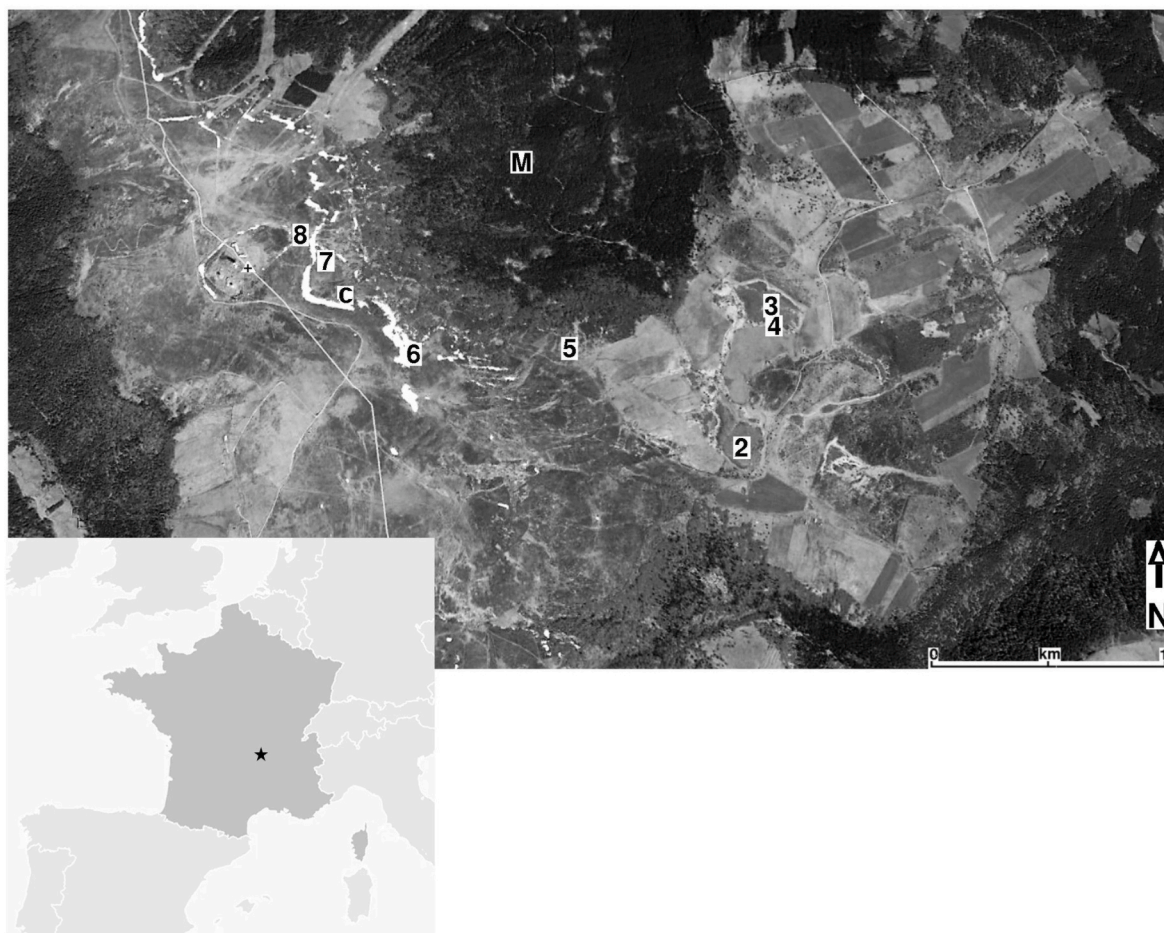


Fig. 1. The research area in the summit area of the Monts du Forez, Massif Central, France (source: GoogleEarth). The star in the map of France (bottom left) indicates the position of the research area. Nos. 2–8 correspond to the pollen diagrams: 2 – Gros Fumé; 3 – Gourds des Aillères (centre); 4 – Gourds-edge; 5 – Colleigne; 6 – Petit Char; 7 – Pierre-sur-Haute mire; 8 – Source Captée. C – Corniche-en-Coeur (Argant and Cubizolle, 2005). M – La Morte (Argant and Cubizolle, 2005). + – highest mountain top (1634 m a.s.l.). Note the snow-covered rocky outcrop ridge W of sites 7 and C, which carries the name Corniche-en-Coeur ('heart-shaped cornice').

lower slopes and lowlands adjacent to the mountains, as Janssen (1981a) argued convincingly for the Vosges Mountains. Tamboer-van den Heuvel and Janssen (1976) found that pollen deposited on the Hautes Chaumes (the treeless area above the forest limit) mainly derives from lowland regions, whereas the Hautes Chaumes themselves hardly produced a regional pollen signal that could be recognized as such. Local and extra-local pollen deposition (sensu Janssen, 1981b) reflected mountain-top vegetation up to tens to at the most a few hundred metres from a pollen collection point. On the basis of this work and that in the Monts du Forez, Lutgerink et al. (1989) distinguished in the Monts du Forez five landscape regions characterized by a uniform regional and extra-regional pollen deposition (regional derived from the same, extra-regional from adjacent landscape regions): plains and foothills east (1) and west (2) of the mountains, broad valleys (3), montane zone (4),

and Hautes Chaumes (5).

These results have two important implications for the interpretation from results of the Monts du Forez. (1) When pollen sites within a landscape region have a uniform (extra-) regional pollen deposition today, they had this also in the past. Pollen diagrams in the same landscape region will therefore show similar trends in their (extra-) regional pollen types. These trends can be used for correlation among the pollen diagrams, thus establishing a relative bio-stratigraphy, which can be turned into a chrono-stratigraphy provided that sufficient radiocarbon dates are available. (2) When the (extra-) regional pollen assemblage is used as the basis for percentage calculation, the remaining pollen types will reflect (extra-) local pollen deposition. These types can be used to reconstruct vegetation close to the sites and thus to reconstruct vegetation patterns within the landscape region. In summary,

Table 1

Palaeoecological research sites in the Monts du Forez (Massif Central, France) with geographical details and coring data.

Fig. No.	Code	Diagram name	Coordinates		Elevation	Coring date	Mire size
2	GrF	Gros Fumé	45.642°N	3.837°E	1350 m	June 1986	2 ha
3	GdA	Gourds des Aillères (centre)	45.6510°N	3.84°E	1335 m	June 1982	2 ha
4	GoE	Gourds-edge	45.6505°N	3.84°E	1340 m	Aug. 1982	
5	CoI	Colleigne	45.643°N	3.822°E	1425 m	Sept. 1982	<0.1 ha
6	PtC	Petit Char	45.643°N	3.819°E	1520 m	Sept. 1982	<0.1 ha
7	PsH	Pierre-sur-Haute mire	45.652°N	3.808°E	1560 m	June 1986	<0.1 ha
8	SoC	Source Captée	45.6523°N	3.806°E	1590 m	Dec. 25, 1984	<0.1 ha

similarities among diagrams can be used for correlation; differences among diagrams can be used to reconstruct vegetation patterns.

The reconstruction of past vegetation follows the concept of the spatial scales as defined by Janssen (1981b; see also 1973, 1986): local, extra-local, regional, and extra-regional. The local scale comprises the vegetation at the very coring location (mostly aquatic or mire vegetation). The extra-local scale concerns the vegetation closely around the coring location (both the mire itself and, for cores taken close to the mire edge, that part of the upland vegetation that lies close to the coring location), which is the scale at which vegetation patterns within the study area are detected. The regional scale concerns the vegetation within the same landscape region as defined by Lutgerink et al. (1989), which in this study comprises the Hautes Chaumes (grazed areas above the forest limit) and can be equated with the study area. The extra-regional scale includes adjacent landscape regions, here the montane zone. Most of our sites are tiny mires or, in one case, a mire edge, and therefore record changes in upland vegetation at the extra-local scale, whereas the core in the centre of Gourds des Aillères records upland vegetation at a more regional scale. We refer to van der Knaap et al. (2020) for a discussion on the distinction between different spatial scales in relation to pollen productivity and dispersal capacity.

3. Material and methods

3.1. Fieldwork

All study sites are mires (Table 1). Coring was performed with an Eijkelkamp gouge of 100 × 8 cm for the upper part and a Dachnowsky coring tube of 40 × 6 cm for the deeper parts of the sediment. Overlapping coring with the Dachnowsky was done in parallel bore holes to obtain an uninterrupted sediment profile.

3.2. Pollen identification and construction of diagrams

The pollen analyses were carried out in the Laboratory for Palaeobotany and Palynology, University of Utrecht, The Netherlands, by various students in the 1980s; the analysts are listed on the individual diagrams (Figs. 2–8). In line with the tradition of the laboratory we made great efforts to achieve a high pollen-taxonomic resolution (Janssen and Punt, 1998), but were nevertheless faced with some difficulties with the identification of a small number of ‘difficult’ pollen types in the early studies. The Ranunculaceae chapter of the Northwest European Pollen Flora (Clarke et al., 1991) was not yet made available at the time of pollen identification, and we now consider some data less reliable due to the fairly similar *Ranunculus acris*-type (grassland plants), *Anemone nemorosa*-type (forest and heathland plants), *Ranunculus acrifolius*-type (wetland plants) and *Ranunculus* Subgen. *Batrachium* (aquatic plants). We adapted the names of these types to suit their contents and placed them outside the pollen sum used for percentage calculation because of the high pollen abundance of wetland and aquatic plants within this group. Another difficulty in the legacy data was that in Gourds des Aillères (centre) reticulate pollen of aquatic plants (*Sparganium*, *Potamogeton*) was in part not recognized by one of the analysts. Also in this diagram, the level of identification of a limited number of pollen types differs somewhat between the two analysts. We therefore provide sum curves for Apiaceae, Asteroideae s.l. (including also Carduoideae but excluding *Artemisia*) and Caryophyllaceae (porate). Furthermore, looking backwards, the identification criteria for Cerealia-type pollen concerning grain size and pore size were not sufficiently strict, so that the type also can include large-size Poaceae grains that do not fulfil today’s criteria. This is notably so in the lower part of Source Captée. In Gros Fumé *Juniperus* pollen was under-counted.

The pollen diagrams were constructed using TILIA software (Grimm, 1990). The pollen sum (100% by definition) includes the groups of Trees, Shrubs, and Regional Upland Herbs shown at the top of the diagrams; percentages of all types of pollen, spores and other palynomorphs

are calculated on this pollen sum. The diagrams show a selection of pollen types; omitted are rare types that are not discussed in the text. In Gourds des Aillères (centre) many additional types are not shown that are mostly restricted to below 290 cm, because they are published by Bos et al. (2022, This Issue).

Macrofossils were studied in the Late-Glacial and early Holocene part of the Gourds des Aillères on the same core; this is reported by Bos et al. (2022, This Issue).

3.3. Constructing the correct pollen sum

All our study sites in the Monts du Forez lie within a small area on a single mountain slope (Fig. 1) in the landscape region ‘Hautes Chaumes’ (the treeless area above the actual forest limit) of Lutgerink et al. (1989), and we follow their results to determine which taxa can be included in the pollen sum (100% by definition) that comprises a uniform pollen deposition in this landscape region. These comprise mainly wind-pollinated taxa, but also a few insect-pollinated taxa that grow outside the landscape region (e.g., *Tilia*, *Vitis*). A few of the included trees grow within the landscape region of study, so their pollen deposition is regional (*Abies*, *Fagus*, *Pinus*), but most woody taxa grow in adjacent landscape regions, so their pollen deposition is extra-regional. Included herbs are wind-pollinated, such as *Ambrosia*, *Artemisia*, *Cerealia*, *Plantago*, *Pteridium aquilinum*, *Rumex*, *Sanguisorba minor*, *Thalictrum* and *Urtica*. Excluded are all wetland taxa but also the wind-pollinated Poaceae (grasses) and *Betula*, which Lutgerink et al. (1989) found to have increased values when the plants are abundant on or near a pollen collection site. Among herbs, we exclude all insect-pollinated genera, among them all Apiaceae, Asteraceae (except the two mentioned above) and Caryophyllaceae, because they may display increased pollen values when the plants grew at or near the collection site. Some of these are in the list of taxa that could be included following Lutgerink et al. (1989) due to the absence of the source plants from near their pollen collection sites in this landscape region, but we exclude them because some of them do grow elsewhere in the region today and others may have grown here in the past. The use of this pollen sum greatly facilitates both the inter-correlation of pollen diagrams and their interpretation in terms of past vegetation.

3.4. Chronology

The chronology of the pollen diagrams is supported by 21 radiocarbon dates of material from the studied cores plus 24 radiocarbon dates transferred from four other, published diagrams from the close surroundings. All radiocarbon dates derive from levels in diagrams where important shifts take place in the (extra-) regional pollen assemblages. Table 2 provides the details. We calibrated all radiocarbon dates with OxCal 4.3 based on the IntCal 20 curve and use the results with 1 Σ (68% probability). We use ‘cal yr BP’ for calibrated radiocarbon ages, BC and AD for (calibrated) calendar ages.

The pollen diagrams were correlated on the basis of trends in (extra-) regional pollen types within the constraints of the calibrated radiocarbon dates. We assumed as a null hypothesis constant rates of peat accumulation within sections of a single type of peat. A shift to a different type of peat, on the other hand, may coincide with a shift in accumulation rate. In several cases the same pollen shift was radiocarbon-dated in different diagrams, which we used to constrain possible ages of the pollen shift to an age range that agrees with all the involved calibrated radiocarbon dates. The resulting chronostratigraphic correlation among diagrams revealed a number of possible hiatuses in our peat sections (missing time periods in the record). The correlation also yielded a number of additional dated levels in some diagrams, namely levels that were radiocarbon dated in other diagrams. It yielded also eight out of the total of 38 synchronous levels among diagrams that were not radiocarbon dated in any diagram. The age of these undated levels was estimated by averaging the ages of this

GdA = Gourds des Aillères (centre) 1335 m a.s.l.

Monts du Forez
 Analysis: Jacqueline van Leeuwen &
 J.A.A. Bos

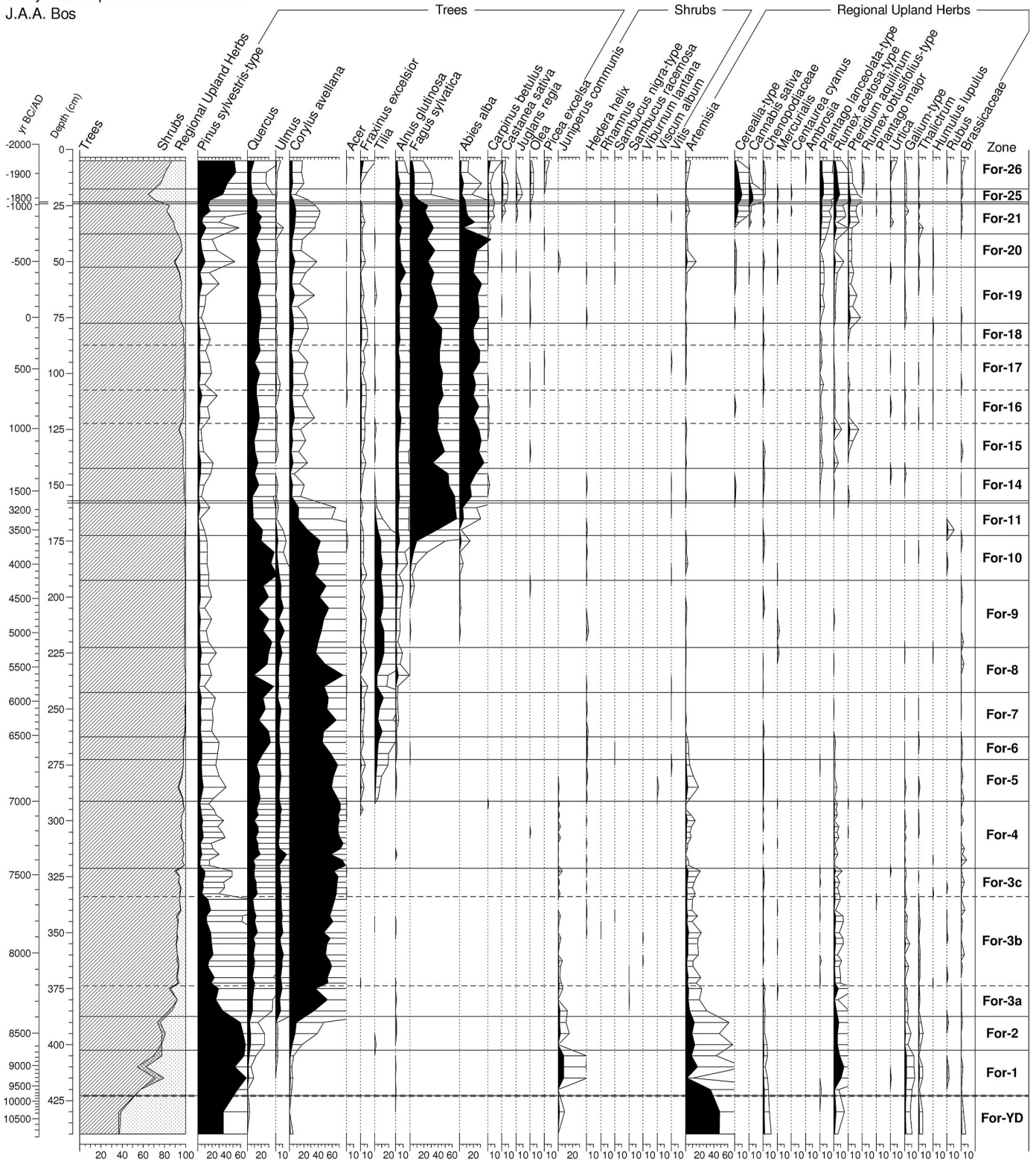


Fig. 3. Pollen diagram of the Gourds des Aillères (centre) mire (GdA) in the Monts du Forez (Massif Central, France). Percentages are in black, five times exaggeration values are shown with depth bars. All percentages of pollen, spores and other palynomorphs are calculated on a pollen sum (100%) that includes the groups of Trees, Shrubs, and Regional Upland Herbs; other groups are Local Upland Trees and Shrubs, Poaceae, Local Upland Herbs, and wetland plants (Moist).

GdA = Gourds des Aillères (centre) *continued*

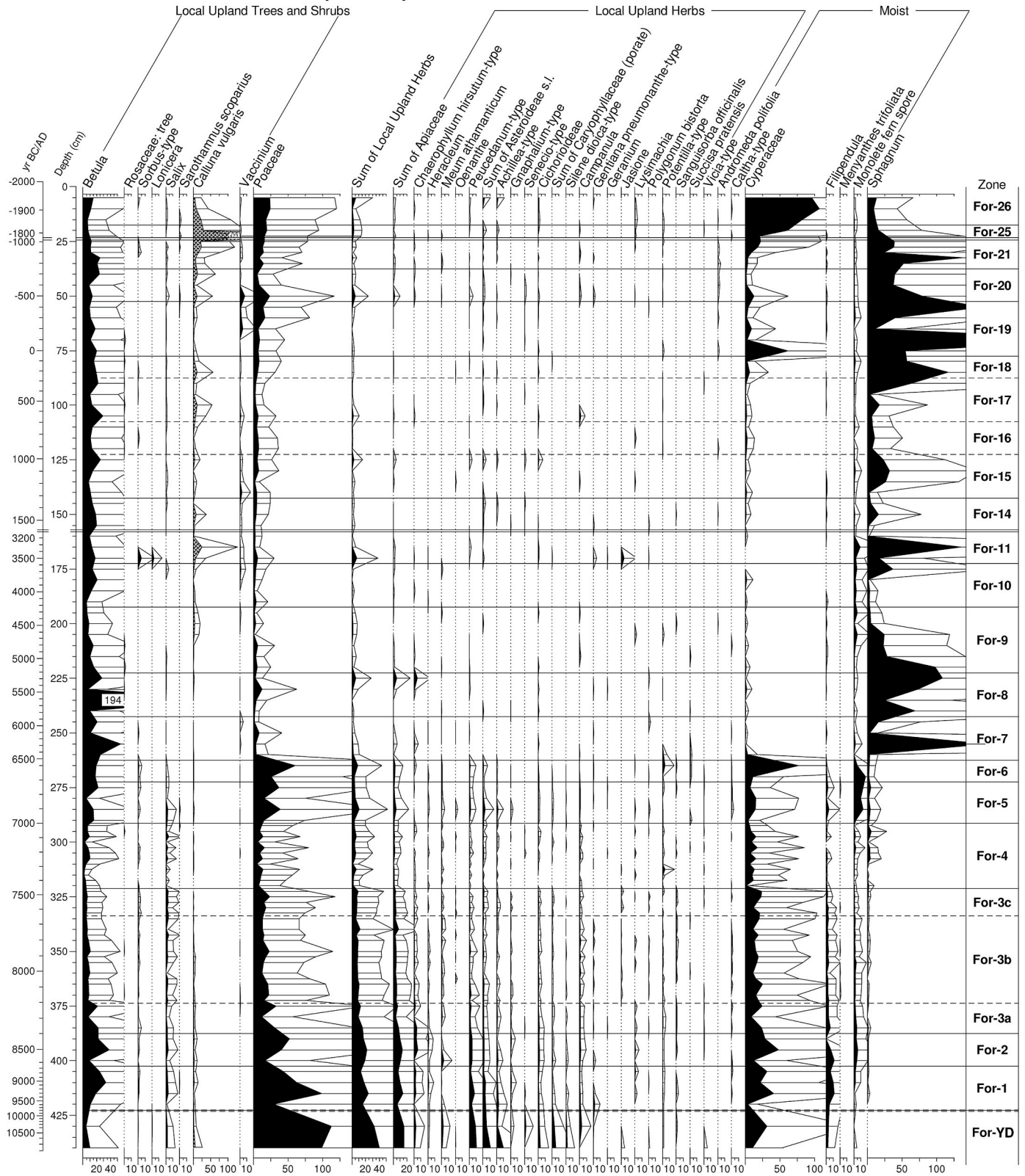


Fig. 3. (continued).

PtC = Petit Char
1520 m a.s.l.
 Monts du Forez
 Analysis: Jeroen Camping &
 Jacqueline van Leeuwen

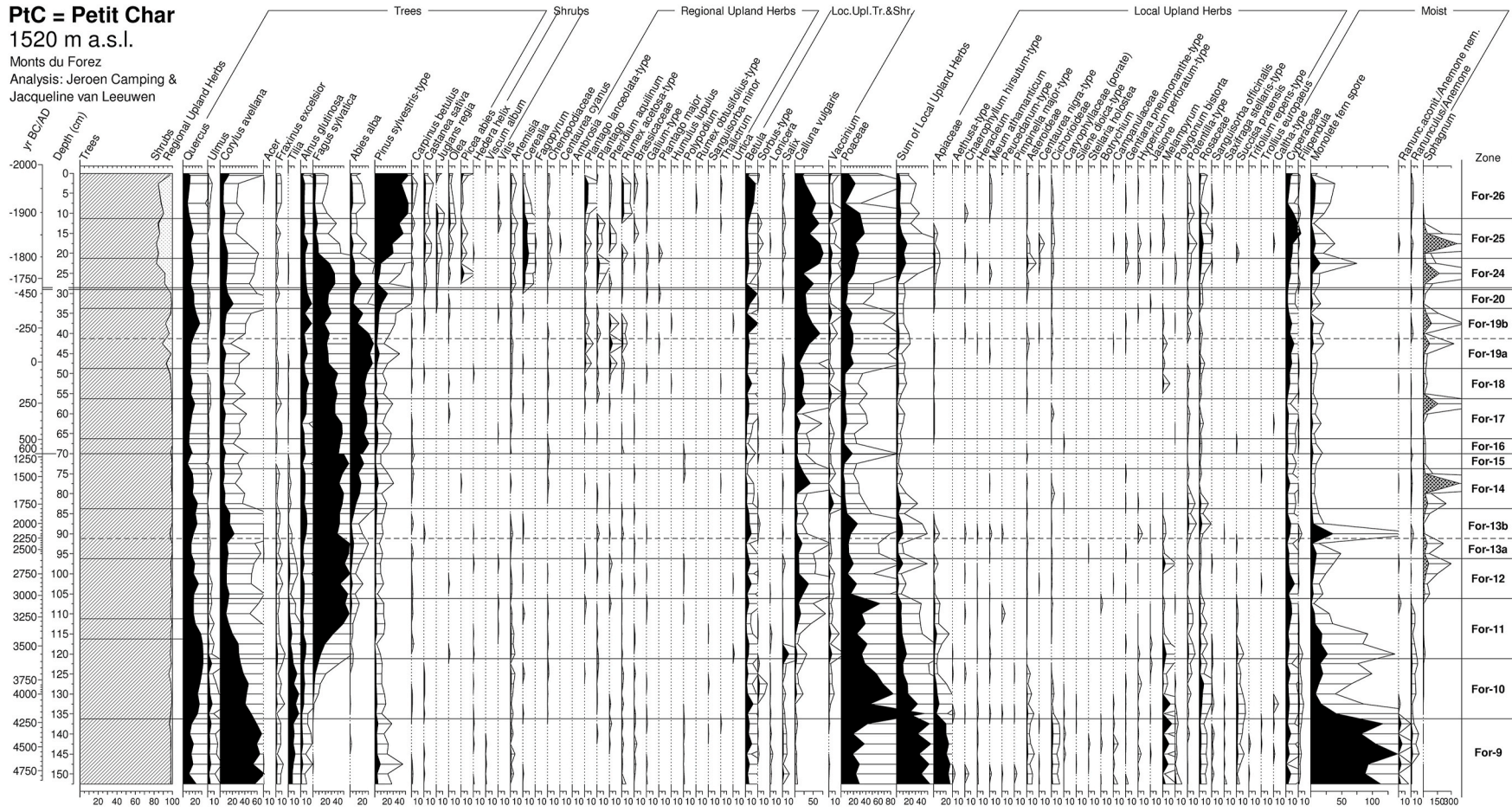


Fig. 6. Pollen diagram of the Petit Char (PtC) mire in the Monts du Forez (Massif Central, France) following [Camping \(1984\)](#). Percentages are in black, five times exaggeration values are shown with depth bars. The pollen sum (100%) includes the groups of Trees, Shrubs, and Regional Upland Herbs. See caption of [Fig. 3](#) for the definition of the pollen sum and pollen groups.

Pierre-sur-Haute 1560 m a.s.l.

Monts du Forez
Analysis: Charlotte Swertz &
Jacqueline van Leeuwen

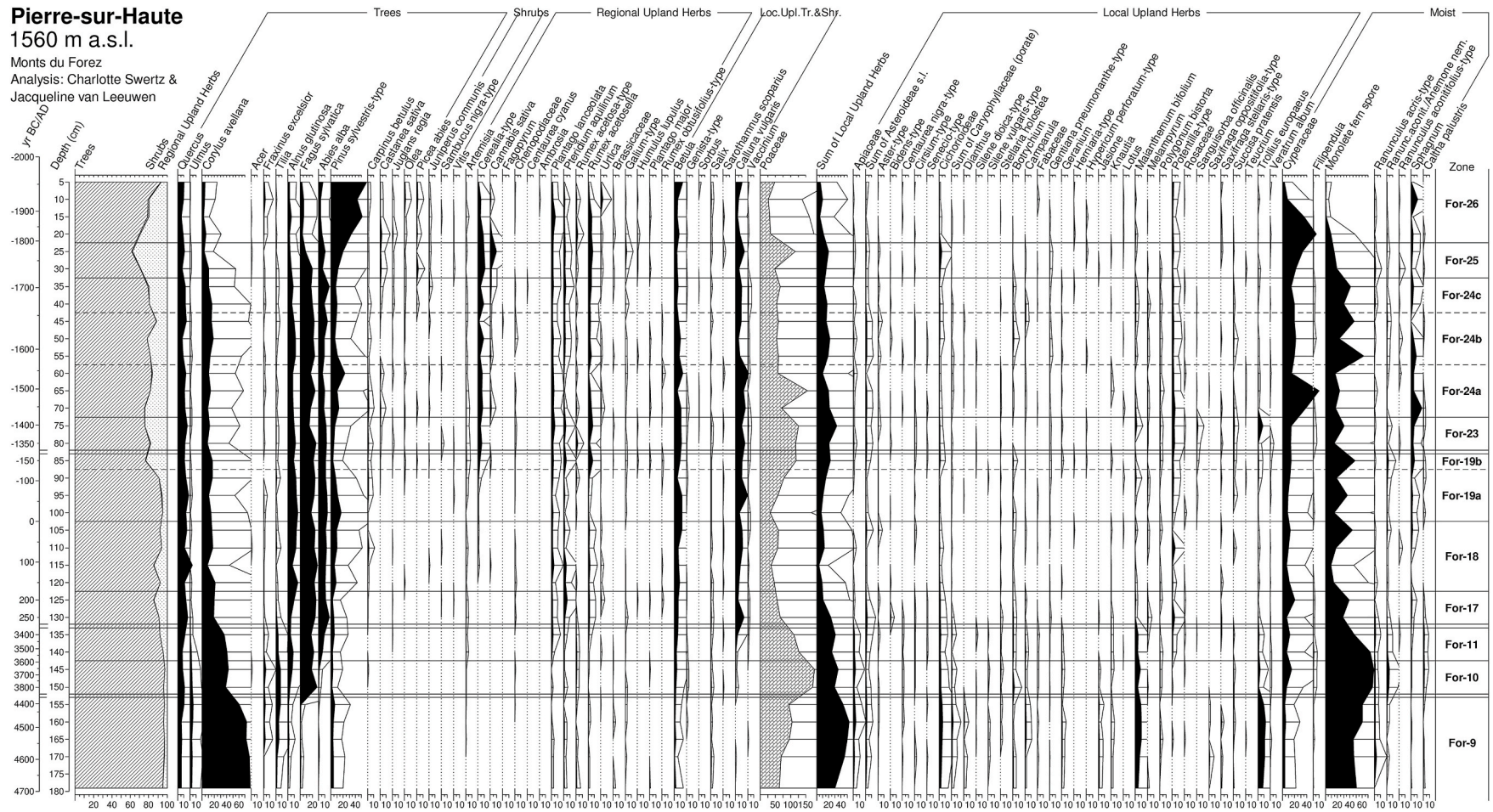


Fig. 7. Pollen diagram of the Pierre-sur-Haute (Psh) mire in the Monts du Forez (Massif Central, France) following Swertz (1989). Percentages are in black, five times exaggeration values are shown with depth bars. The pollen sum (100%) includes the groups of Trees, Shrubs, and Regional Upland Herbs. See caption of Fig. 3 for the definition of the pollen sum and pollen groups.

Table 2

Radiocarbon dates used in the establishment of the chronologies of our pollen diagrams from the Monts du Forez (Massif Central, France). Diagrams are coded as follows: A = Gourdes des Aillères (Cubizolle et al., 2017, 2022, This Issue); C = Corniche-en-Coeur (Cubizolle et al., 2014); Col = Colleigne (this paper); G = Roche Gourgon (Cubizolle et al., 2014); GdA = Gourdes des Aillères (centre) (this paper); GoE = Gourdes-edge (this paper); M = La Morte (Argant and Cubizolle, 2005); PdE = Plateau des Egaux (Janssen and van Straten, 1982); PsH = Pierre-sur-Haute mire (this paper), PtC = Petit Char (this paper); SoC = Source Captée (this paper). Dated material is bulk sediment except in Nos. 14, 25, 27 and 30 (*Sphagnum* peat moss), and No. 48 (sandy peat).

Nr.	Radiocarbon age	Laboratory No.	Diagram and depths	Sample duration	Range (68%) of calibrated age	Best fit by linear interpolation	
						BC/AD	Cal yr BP
1	220 ± 80 BP	GrN-15796	Col 31-35 cm	25 yr	AD 1525–1560; 1630-1700; 1725-1815	AD 1725–1750	–225–200
2	420 ± 90 BP	GrN-15797	Col 65-69 cm	25 yr	AD 1420–1520; 1570-1630	AD 1460–1490	490–460
3	460 ± 80 BP	GrN-15798	Col 48-52 cm	25 yr	AD 1400–1520; 1595-1620	AD 1595–1610	355–340
4	1390 ± 140 BP	GrN-15791	GoE 48-56 cm	110 yr	AD 430–490; 530-780	AD 530–600	1420–1350
5	1520 ± 45 BP	LY-1814 (GrA)	M 157-161 cm	(AMS)	AD 430–490; 530-600	AD 430–490	1520–1460
6	1550 ± 120 BP	GrN-15792	GoE 51-59 cm	110 yr	AD 390–620	AD 450–550	1500–1400
7	1610 ± 55 BP	GrN-9908	PdE 20-22 cm	50 yr	AD 400–540	AD 400–450	1550–1500
8	1640 ± 130 BP	GrN-9909	PdE 30-35 cm	60 yr	AD 250–550	AD 300–400	1650–1550
9	1885 ± 45 BP	GrN-16756	PsH 95-100 cm	70 yr	AD 70–170; 190-210	AD 70–100	1880–1850
10	1905 ± 65 BP	GrN-9910	PdE 40-45 cm	60 yr	AD 20–170; 190-210	AD 190–210	1760–1740
11	1930 ± 80 BP	LY-10761	M 228-231 cm		40 BC – AD 140	40 BC – AD 40	1990–1910
12	1960 ± 30 BP	LY-8233 (SacA)	C 24 cm	(AMS)	AD 0–80	AD 0–80	1950–1870
13	2040 ± 120 BP	GrN-15799	Col 107-112 cm	250 yr	200 BC – AD 80	AD 0–80	1950–1870
14	2180 ± 50 BP	GrN-16757	PsH 125-130 cm	70 yr	360–170 BC	250–170 BC	2200–2120
15	2260 ± 90 BP	GrN-15793	GoE 103-111 cm	110 yr	400–200 BC	300–200 BC	2250–2150
16	2360 ± 110 BP	GrN-9911	PdE 129-134 cm	60 yr	750-640; 590-360; 280-260 BC	700–640 BC	2650–2590
17	2425 ± 75 BP	LY-10762	M 319-322 cm		750-640; 560-400 BC	750–640 BC	2700–2590
18	2955 ± 30 BP	LY-8236 (SacA)	C 63 cm	(AMS)	1220–1120 BC	1220–1170 BC	3170–3120
19	3025 ± 50 BP	GrN-12641	GdA 140-150 cm	200 yr	1390–1210 BC	1390–1350 BC	3340–3300
20	3160 ± 80 BP	GrN-15800	Col 134-138 cm	200 yr	1520–1300 BC	1450–1350 BC	3400–3300
21	3175 ± 35 BP	LY-8237 (SacA)	C 70 cm	(AMS)	1500–1420 BC	1500–1420 BC	3450–3370
22	3320 ± 35 BP	LY-8352 (GrA)	G 23 cm	(AMS)	1660–1530 BC		
23	3375 ± 70 BP	LY-10763	M 380-383 cm	100 yr	1750–1550 BC	1600–1550 BC	3550–3500
24	3420 ± 35 BP	LY-3905 (GrA)	G 34.5 cm	(AMS)	1760–1660 BC	1760–1710 BC	3710–3660
25	3460 ± 90 BP	GrN-15794	GoE 238-246 cm	200 yr	1890–1660 BC	1890–1800 BC	3840–3750
26	3490 ± 40 BP	LY-8238 (SacA)	C 78 cm	(AMS)	1880–1760 BC	1880–1760 BC	3830–3710
27	3810 ± 40 BP	LY-3904 (GrA)	G 67.5 cm	(AMS)	2340-2320; 2300-2200; 2170-2150 BC	2340–2320 BC	4290-4270
28	3850 ± 35 BP	LY-8239 (SacA)	C 96 cm	(AMS)	2440-2380; 2350-2210 BC	2440–2380 BC	4390-4330
29	3885 ± 100 BP	LY-10760	M 393-395 cm	100 yr	2480–2200 BC	2300–2200 BC	4250–4150
30	4010 ± 60 BP	GrN-12639	PtC 92.5–95 cm	100 yr	2620–2460 BC	2560–2460 BC	4510–4410
31	4135 ± 35 BP	LY-8240 (SacA)	C 106 cm	(AMS)	2860-2810; 2760-2630 BC	2860–2810 BC	4810–4760
32	4175 ± 35 BP	LY-8531 (GrA)	G 91 v		2880-2850; 2810-2700 BC	2800–2700 BC	4750–4650
33	4470 ± 80 BP	GrN-15795	GoE 300-308 cm	110 yr	3340–3030 BC	3150–3250 BC	5100–5200
34	4540 ± 40 BP	LY-8241 (SacA)	C 116 cm	(AMS)	3360-3320; 3230-3120	3360–3320 BC	5310-5270
35	4620 ± 110 BP	GrN-15801	Col 169–172.5 cm	175 yr	3630-3600; 3530-3320; 3230-3120 BC	3400–3320 BC	5350–5270
36	4675 ± 60 BP	GrN-9912	PdE 250-255 cm	100 yr	3520–3370 BC		
37	4810 ± 60 BP	GrN-12638	PtC 120–122.5 cm	100 yr	3660–3520 BC	3660–3620 BC	5610–5570
38	5075 ± 40 BP	LY-3903 (GrA)	G 130 cm	(AMS)	3950-3910; 3880-3800 BC	3900–3800 BC	5850–5750
39	5245 ± 45 BP	LY-8242 (SacA)	C 127 cm	(AMS)	4220-4210; 4160-4130; 4070-3980 BC	4070–4000 BC	6020-5950
40	6425 ± 45 BP	LY-8243 (SacA)	C 150 cm	(AMS)	5470–5370 BC	5470–5400 BC	7420–7350
41	7050 ± 35 BP	LY-8350 (GrA)	G 180.5 cm	(AMS)	5990–5900 BC	5950–5900 BC	7900–7850
42	7935 ± 45 BP	LY-3902 (GrA)	G 211.5 cm	(AMS)	7020-6970; 6910-6880; 6840-6700 BC	7020–6970 BC	8970–8920
43	9150 ± 60 BP	LY-3901 (GrA)	G 229.5 cm	(AMS)	8440–8290 BC	8440–8400 BC	10,390–10,350
44	9270 ± 50 BP	LY-13527 (GrA)	A 306 cm	(AMS)	8610–8440 BC	8610–8560 BC	10,560–10,510
45	9830 ± 50 BP	LY-3900 (GrA)	G 275.5 cm	(AMS)	9310–9250 BC	9310–9290 BC	11,260–11,240

level in different diagrams obtained by linear interpolation between adjacent dated points. Finally, we calculated the ages of all analyzed levels in our diagrams by linear interpolation between dated points. Table 3 lists all dated points and gives information on how they were derived.

4. Results

The palynological results are shown as stratigraphical pollen diagrams in Figs. 2–8. A common scheme of synchronous zones was established that is valid for all our diagrams, named For-1 to For-26. We use the short codes for the diagrams given in Table 1. We provide calibrated ages for the beginning of each pollen zone. Zone lines delimit clear changes in the pollen derived from upland vegetation in at least one diagram. Zone lines are shown as dashed lines in a diagram when it does not clearly delimit an upland vegetation shift. The following interpretations in terms of past vegetation take account of the principles of pollen dispersal as set out above.

For-YD (Younger Dryas): GrF and GdA (10,800 BC; 12,750 cal yr BP)

(Extra-) local: Bos et al. (2022, This Issue) discuss in detail the Late-Glacial vegetation development at GdA. The Younger Dryas in GrF differs from GdA mainly in its high values of *Betula*, *Salix*, Cyperaceae and *Sphagnum*, which are all plants that grew on or very close to the collection site. This indicates that GrF was a sedge fen with *Sphagnum* and possibly with dwarf-willows and *Betula nana*, whereas GdA was a lake.

For-1 (start of the Holocene; Preboreal): GrF and GdA (ca. 9800 BC; 11,750 cal yr BP)

(Extra-) local and regional: GrF was still a sedge fen, now with *Potentilla* cf. *palustris*, and GdA was a lake. The scarcity of *Juniperus* pollen at GrF is probably an artefact of the bad preservation of the pollen. There was open pioneer vegetation with a temporary maximum of *Juniperus*, *Galium*-type and *Rumex acetosa*-type, increase of *Salix*, large ferns (Monolete spores) and several herbs, including the persistence of

Table 3

Palyno-chronological markers. Used ^{14}C dates are numbered according to Table 2, in which 0 = year of field coring, ? = palynological feature not expressed in pollen diagram because of low temporal resolution. Pollen diagrams are abbreviated as in Table 2. Ref. = literature for the age of the Holocene (Litt et al., 2003).

Approximate date	Brief palynological characterisation	Settlement & vegetation history	Used ^{14}C dates	Markers in the pollen diagrams in cm below surface								
				GrF	GdA	GoE	PdE	Col	PtC	PsH	SoC	
AD 1982–1986	Field sampling		0		0	0		0	0	0		
AD 1890 estimated	<i>Pinus</i> > 50%; <i>Picea</i> closed >1%; upland herbs minimum		0, 1		17			12	11	15	13	
AD 1780	<i>Pinus</i> > 25%; strong <i>Abies Alnus Corylus Fagus</i> decline	Forestry reforms	1			11		27	23	23	24	
AD 1650	Rising <i>Cannabis Cerealia Plantago lanceolata</i> ; <i>Corylus</i> decline		1, 3			18		45		43	34	
AD 1590	Slight <i>Pinus</i> decline; <i>Corylus</i> rise to top		3					54		55	38	
AD 1400 estimated	<i>Pinus</i> > 10%; slight <i>Abies Fagus</i> decline; <i>Fagopyrum Cannabis</i> rise		2, 3			24		78		73		
AD 950–1300	hiatus in all profiles, no record											
AD 900 estimated	<i>Quercus</i> top followed by <i>Pinus</i> rise >10%; stop in peat growth	Husbandry in summit region				30	29					
AD 800 estimated	strong NAP rise starting around AD 700; after last <i>Abies</i> high	Early Medieval expansion	4, 6			38	36					
AD 450	First <i>Pinus</i> top after high <i>Corylus Alnus</i> at AD 400; NAP minimum	Woodland regeneration	4, 5, 6, 7			50	59	20		30		
AD 300	<i>Quercus</i> maximum; before <i>Alnus Corylus</i> rise AD 350; NAP decline	Maximum Roman land use	7, 8			60	72	30		37		55
AD 200 BC/AD	<i>Corylus</i> decline; strong NAP rise Minimum <i>Alnus Corylus Quercus</i> ; <i>Abies</i> maximum >40%	Roman land reorganisation	8, 10 9, 11, 12				80	38		?	85	70
150 BC	<i>Alnus</i> top; NAP rise	Late Latène	13, 14, 15			83	107	?	?	53	120	95
250 BC estimated	<i>Abies</i> top; <i>Quercus</i> rise; first NAP rise	Latène land use				90	112	90	112	?	130	105
400 BC	Lowest <i>Alnus</i> minimum; <i>Quercus</i> minimum; NAP Poaceae rise					93	117	?	±120	64		120
550 BC estimated	<i>Quercus</i> maximum					100	122	120	?	?		
650 BC	Last high <i>Fagus</i> maximum >40%; short <i>Quercus</i> minimum; closed NAP	Subboreal/Subatlanticum; Late Hallstatt land use	16, 17			105		130	119	69		
1200 BC	First <i>Abies</i> maximum >15%		18			140	216	190	?	71		
1400 BC	Strong <i>Abies</i> rise >20%; <i>Corylus</i> below 6–8%		19, 20, 21, 22			147	220	205	133	73		
1800 BC	<i>Corylus</i> decline after 2400–1900 BC top; begin <i>Abies</i> rise; <i>Tilia</i> < 1%		23, 24, 25, 26				239		140	84		
2150 BC	<i>Corylus</i> top; <i>Quercus Alnus</i> minimum		29				252		149	90		
2600 BC	<i>Corylus</i> minimum; <i>Abies</i> rise >5%; <i>Quercus Alnus</i> minimum		27, 28, 30				277		155	95		
2750 BC	First <i>Fagus</i> top >35% following <i>Quercus</i> top; <i>Abies</i> rising >3%		31, 32				287		158	100		
3400 BC	<i>Fagus</i> rise equals <i>Corylus</i> decline of ca. 30%; <i>Abies</i> > 1%		33, 34, 35, 36			167	307		170	114	135	
3600 BC	<i>Corylus</i> decline <30%; <i>Fagus</i> rise >10%; final <i>Ulmus Tilia</i> decline	Atlanticum/Subboreal	37			173			173	122	143	
3800 BC	Last <i>Tilia</i> top >10%; <i>Quercus</i> minimum within last top >30%; first <i>Abies</i>		38			?				128	150	
4000 BC	<i>Tilia</i> top; <i>Fagus</i> rise		38, 39				185			130		
4200 BC	<i>Corylus</i> decline; <i>Quercus</i> rise >25%; <i>Alnus</i> > 1%; <i>Fagus</i> curve closed						193	320		136		
4700 BC estimated	<i>Quercus Tilia</i> minimum; <i>Alnus</i> > 1%; first <i>Fagus</i>						207	343		148	180	
5500 BC	<i>Corylus</i> decline; <i>Tilia Ulmus</i> rise from minimum; <i>Alnus</i> curve closed		40				232					
5950 BC	<i>Tilia</i> top; <i>Ulmus</i> minimum; <i>Fraxinus</i> curve closed		41			500	245					
6600 BC estimated	First <i>Quercus</i> top (>30%); <i>Tilia</i> > 5%					523	265					
7000 BC	First <i>Tilia</i> rise; <i>Fraxinus Alnus</i> start; <i>Ulmus</i> decline; <i>Corylus</i> top	Boreal/Atlanticum	42			538	292					
7650 BC estimated	<i>Pinus</i> decline <10%; <i>Corylus</i> rise to maximum (>50%)						334					
8350 BC	% <i>Pinus</i> (decline) equals <i>Corylus</i> (rise)	Preboreal/Boreal	43			554	387					
8600 BC	<i>Pinus</i> maximum (>50%); start of <i>Corylus Quercus</i> rise	Preboreal <i>Pinus</i> maximum	44			558	402					
9800 BC	Start decline Poaceae and other herbs; <i>Pinus Betula</i> start of rise	Beginning of Holocene (Preboreal)	45, Ref.			572	421					

many herbs of the Late-Glacial period (e.g. *Artemisia*). Following Bos et al. (2022, This Issue), open boreal woodlands with *Betula* and some *Pinus* established on the plateau. *Extra-regional*: Most *Betula* and *Pinus* pollen reflects woodland development at lower elevations. Also *Quercus* started to increase, but was still sub-ordinate.

For-2: GrF and GdA (ca. 8600 BC; 10,550 cal yr BP)

(Extra-) local: GrF was still a fen, again with *Sphagnum*, and GdA was still a lake. *Regional*: The decline of *Juniperus* indicates that nearby vegetation became denser, but there were still habitats for the steppe plant *Artemisia*. Varied herbal vegetation occurred near the site, and large ferns had a maximum, indicating sufficient moisture and light and very low grazing pressure. *Pinus* increased in the *Betula*–*Pinus* woodland on the plateau. *Extra-regional*: *Corylus* and *Quercus* expanded rapidly, but their low pollen values indicate that the trees were far away.

For-3 (start of the Boreal chronozone): GrF and GdA (ca. 8350 BC; 10,300 cal yr BP)

Local: GrF has a hiatus for a large part of this period. The local vegetation shifted from rheotrophic fen rich in herbs in zone For-2 to possibly an ombrotrophic mire poor in herbs in zone For-4. This indicates a drop in the water table, which may have caused the hiatus. The strong expansion of *Corylus* may have caused the hydrological shift. *(Extra-) local*: Forest of mainly *Corylus* and some *Ulmus* established in the study area and began replacing *Betula*. From For-3b (ca. 8200 BC; 12,150 cal yr BP) onwards the forest around the site became gradually denser, suppressing light-demanding plants such as *Artemisia*, *Pinus* and *Betula*. Several herbs disappeared that had continued to be present since the Late-Glacial; see Bos et al. (2022, This Issue). The high abundance and high diversity of local herbs and grasses indicates, however, presence of open patches close to the site. In For-3c (ca. 7600 BC; 9550 cal yr BP) a somewhat stronger push in forest closure occurred and *Pinus* virtually disappeared, which suggests a climatic amelioration. Also in For-3c the first *Acer* pollen appears; but this taxon is such a low pollen producer that it may have been present earlier, but unrecorded. *Extra-regional*: Assuming that the thermophilous *Quercus* never reached the elevations of the study area, the data show that dominant *Betula* and *Pinus* at lower elevation were replaced by *Quercus*, *Corylus*, and *Ulmus*. *Ulmus* also rapidly invaded the north-facing and otherwise shady slopes up onto the plateau and reached already in For-3b its greatest extension during the Holocene.

For-4: GrF and GdA (ca. 7400 BC; 9350 cal yr BP)

(Extra-) local: *Corylus* formed the forest limit. *Betula* pollen is much more common in GrF than in GdA, suggesting abundant *Betula* on the GrF mire close to the sampling location. The low values of *Pinus* in GrF compared to GdA suggest that *Betula* formed a belt around GrF that acted as a filter for pollen of pine trees growing just outside the belt. The decline of regional upland herbs indicates that forests became denser, but the still considerable (though declined) abundance and diversity of local upland herbs in GdA, but not in GrF, indicates open vegetation close to the GdA mire. *Extra-regional*: In analogy to the situation in the Vosges Mountains, presumably also the montane vegetation belt north of the Forez study region, with its steep north-facing and shadowy slopes, was covered by closed *Corylus* woodland with *Ulmus* (Kalis, 1985b, 2014). The *Quercus* pollen originated from lower elevations.

For-5 (start of the Atlantic chronozone): GrF and GdA (ca. 7000 BC; 8950 cal yr BP)

Local: The vegetation changed at the coring location of GdA. Poaceae and Monolete fern spores suggest a reed belt, with *Phragmites* and ferns (possibly *Thelypteris palustris*), forming a transitional stage from lake to

fen. *Extra-regional*: *Tilia* and *Fraxinus* appeared and expanded. Lower *Tilia*, *Fraxinus* and *Ulmus* values in GrF are explained by the filtering effect by the *Betula* belt around the mire. *Regional*: *Corylus* declined but still remained dominant.

For-6: GrF and GdA (ca. 6700 BC; 8650 cal yr BP)

Extra-local: At GrF the *Betula* belt disappeared, resulting in a pollen maximum of the nearby growing *Ulmus*. *Extra-regional*: *Tilia* was expanding in the forests at lower elevations. *Quercus* increased in the forests and started outshading *Corylus*. *Fraxinus* and *Alnus* were establishing in the riverine woodlands.

For-7: GrF and GdA (ca. 6500 BC; 8450 cal yr BP)

Local: The vegetation at the coring location of GdA changed drastically, from lush wetland to *Sphagnum* dominated mire. Many herb taxa declined as a result. *Extra-local*: *Artemisia* and other upland herbs declined to their minimum, indicating further forest closure. *Extra-regional*: *Tilia* played an important role in the forests. Its high pollen percentages (>10%) indicate that the trees grew nearby, probably *Tilia platyphyllos* growing up to the edge of the steep slope just N of the study area.

For-8: GdA (ca. 5800 BC; 7750 cal yr BP)

(Extra-) local: The four samples of For-8 (in GdA) all have their own features, which together indicate a major local disturbance of such a short duration that the pollen signal catches only glimpses. Short-lived very dense growth of *Corylus* (240 cm) followed by *Betula* and *Alnus* (235 cm) intercepted part of the *Quercus*, *Tilia* and *Fraxinus* pollen. The local vegetation instability ended with a short-lived collapse of *Corylus* and *Betula* and a peak of Poaceae (230 cm) and *Chaerophyllum hirsutum* (225 cm). High *Sphagnum* values indicate that the local mire was not particularly nutrient-rich. There are no positive indications that animals were involved in these events, but we cannot exclude it. *Extra-regional*: The local pollen filter formed by *Corylus*, *Betula* and *Alnus* vegetation masks possible events outside the region. If the *Tilia*, *Quercus* and *Ulmus* minimum also reflects events far away, it may possibly indicate pre-historic human impact on forests at lower elevation.

For-9: GdA, GoE, PtC and PsH (ca. 5200 BC; 7150 cal yr BP)

Extra-local and regional: *Corylus* pollen is dominant, meaning that dense *Corylus* thickets bordered all sites. The values were lower in the treeless mire centre (GdA) because of the larger distance to the thickets. Other woody species were admixed, like *Acer*, *Lonicera*, *Salix*, and *Sorbus*. Local upland herbs were diverse and increased in both abundance and diversity with increasing elevation, and Poaceae and ferns (Monolete spores) were abundant except at GdA. This shows patches of treeless vegetation near all sites except GdA, i.e. on the slope towards the summit. *Extra-regional*: *Quercus*, *Tilia* and *Ulmus* reached abundance, *Alnus* and *Fraxinus* were established. *Abies* and *Fagus* pollen was so scarce that we assume that the trees were not yet growing in the study region. A possible scenario for the forest vegetation pattern in the Monts du Forez at that time (Late Atlantic chronozone), in analogy to the Vosges Mountains (Kalis, 1985b, 2014), was that *Tilia cordata* forest existed on deep soils at low and middle elevations, mixed with *Ulmus glabra* and *Quercus* forest on the slopes of the montane vegetation belt, *Corylus* thickets in the upper montane and lower subalpine vegetation belts, and riverine forests of *Alnus glutinosa*, *Fraxinus excelsior*, *Ulmus* (div. spec.) and *Quercus* along water courses.

For-10: GdA, GoE, Col, PtC and PsH (ca. 4200 BC; 6150 cal yr BP)

Ulmus declined, to different degrees near the different sites, and also

Corylus declined. *Regional and extra-regional*: *Abies* and *Fagus* started to expand, *Quercus* expanded and *Corylus* started to decline. The inferred small hiatus at the transition to zone For-11 in two sites higher on the slope (GoE and PsH) is possibly due to the impact of domesticated animals.

For-11 (start of the Subboreal chronozone): GdA, GoE, Col, PtC and PsH (ca. 3600 BC; 5550 cal yr BP)

(*Extra-local*): There are several palynological indications that the 'large' GdA mire was heavily grazed by animals. At 170 cm depth, high peaks of the otherwise rare *Sorbus*-type, *Lonicera*, *Rubus* and *Jasione* indicate an animal dropping on the peat surface at that time (compare a similar case of an animal dropping recognized by pollen in the Praz Rodet mire in the Swiss Jura Mountains, Mitchell et al. 2001). Short-lived peaks of *Calluna* and *Sphagnum* in the overlying spectrum indicate a drier peat surface, and this is followed at the top of the zone by a standstill in peat accumulation (hiatus). *Extra-local*: Also the tiny mire PsH was heavily grazed, which became apparent from the following. The *Abies* increase agrees with the other diagrams, but other features do not agree (approximately constant *Corylus* and *Fagus*; more pollen of the lowland plant *Plantago lanceolata*). These features did hamper the chronological delimitation of especially the base of the zone. A likely explanation is that the peat layers have been mixed through trampling by animals. The zone ends in a hiatus (missing peat layers; ca. 3300–300 BC (5250–2250 cal yr BP)). The long duration of the hiatus, however, makes it highly uncertain when the trampling phase could have been – directly at the beginning of the hiatus or much later, or both. *Regional and extra-regional*: A radical change in forest composition took place within a short time: *Fagus* expanded to become the dominant tree at the cost of *Corylus*; *Tilia* and *Ulmus* collapsed nearly completely, *Quercus* declined strongly, and *Abies* continued to expand.

For-12: GoE, Col and PtC (ca. 3000 BC; 4950 cal yr BP)

Extra-local: *Fagus* became dominant over *Corylus*. Col had distinctly more *Fagus* and less *Corylus* than GoE. This may be due to the more sheltered position of Col (favourable for *Fagus*) compared to the more open GoE (favourable for *Corylus*). PtC, lying on the slope above, had even less *Corylus* and more *Fagus*. The three sites have low abundance and a comparable diversity of both regional and local upland herb pollen, indicating that they all lay within closed forest.

For-13: GoE, Col and PtC (ca. 2550 BC; 4500 cal yr BP)

Regional and extra-local: Col and PtC have distinctly more *Fagus* pollen and less *Corylus* pollen than GoE. In For-13b, *Corylus* had a maximum between ca. 2300 and 1900 BC (4250–3850 cal yr BP). This is most pronounced at the highest elevation (PtC) and least at the lowest (GoE). In **For-14** (GdA, GoE, Col and PtC, ca. 1900 BC; 3850 cal yr BP), *Corylus* declined and *Abies* expanded further inside the *Fagus* forest.

For-15: GdA, GoE, Col and PtC (ca. 1400 BC; 3350 cal yr BP)

Most of this zone and the next correspond to a hiatus in PtC, at 70 cm between two samples taken at the same depth but from different cores from adjacent boreholes. *Extra-local and local*: GdA 125 cm (ca. 1000 BC; 2950 cal yr BP) has an array of taxa that are less abundant in adjacent samples: *Pteridium*, *Rumex acetosa*-type, *Peucedanum*-type, *Asteroidae* and *Cichorioideae*. This is reminiscent of the sample at 170 cm in zone For-11 though with different pollen types, so we tentatively interpret also this as an animal dropping on the peat surface of that time. *Extra-local*: The higher representation of *Corylus* in the sites close to mire edges (GdA and Col) than in the mire centre (GdA) shows that *Corylus* was mainly growing at forest edges. *Corylus* generally declined, but much stronger in GoE than in Col. *Regional*: *Abies* increased slowly to its

postglacial maximum (lateral and vertical) expansion probably even up to the upper limit of *Fagus*. This strongly suggests that woodland herding was not practised any longer in the Monts du Forez. *Extra-regional*: *Tilia* and *Ulmus*, already rare, declined still further.

For-16: GdA, GoE, Col and PtC (ca. 950 BC; 2900 cal yr BP)

Extra-local: *Corylus* declined to its lowest postglacial levels, meaning that *Fagus* had finally reached the upper forest line. *Abies* remained at its maximum. Upland herb pollen reaches very low values and low diversity and is mainly derived from wetland plants growing on the sites. We can, therefore, not detect any treeless vegetation near the sites. The records on the slope are, however, rather fragmentary (Col and PtC; each one spectrum only) and more detailed on the plateau (GdA, GoE), from which we cannot see whether the highest mountain summit was densely forested or rich in herb species. *Regional*: This period represents probably the last phase of montane and sub-alpine *Abies-Fagus* forest development without major forest destruction. *Extra-regional*: *Humulus* pollen became more frequent, which was in this time still derived from wild growing plants. *Quercus* pollen has a maximum in the lower half of this zone.

For-17 (start of the Subatlantic chronozone): GdA, GoE, Col, PtC, PsH and SoC (ca. 650 BC; 2600 cal yr BP)

Extra-local: *Fagus* declined somewhat both on the plateau and on the slope above it, whereas *Corylus* expanded near GoE, filling gaps near the edge on the mire. *Abies* was little affected. High on the slope the interrupted peat formation in PsH had started again, and in the summit region peat formation was initiated (SoC). The proportion of local to regional upland herb pollen increased strongly with elevation, which indicates increased vegetation openness (fewer woody plants, more herbs). It also implies that very little or no pollen of local upland herbs growing in the summit region can be detected on the plateau. This strengthens the point made for zone For-16 that local upland pollen in sites on the plateau (GdA, GoE) is not informative on the openness of the summit region at just over 1.5 km distance. Especially the high abundance and diversity of local upland plants and abundant Poaceae in the summit region (SoC) indicates the presence of various grasslands. The Cerealia in SoC are considered to be a counting artefact; see above. The initiation of peat formation in SoC may have been triggered by the removal of taller, woody vegetation by farmers. *Extra-regional*: There is a moderate increase of anthropogenic grassland indicators (*Plantago lanceolata*, *Pteridium aquilinum*), probably reflecting increasing agriculture at lower elevations.

For-18: GdA, GoE, Col, PtC, PsH and SoC (ca. 200 BC; 2150 cal yr BP)

Extra-local: Grazing activity continued as before, and only declined somewhat high on the slope near PsH (less Poaceae and local upland herbs). *Extra-regional*: Indications of human activities at lower elevations are manifold. Anthropogenic grassland indicators began to increase (*Plantago lanceolata*, *Pteridium*, *Rumex acetosa*-type) and around 150 BC (2100 cal yr BP) *Quercus* had a short maximum and *Abies* a minimum.

For-19a: GdA, GoE, Col, PtC, PsH and SoC (ca. 50 BC; 2000 cal yr BP)

Extra-local: Increasing local upland herbs on higher slopes (PsH) and in the summit area (SoC) indicates increased grazing. This was harmful for *Fagus* in the upper mountain reaches of the forest. *Abies*, on the other hand, had in part of the diagrams even a temporary maximum, which indicates that it was mostly growing in less accessible, not grazed parts of the forest. *Regional and extra-regional*: Cerealia and grassland indicators (*Plantago lanceolata*, *Rumex acetosa*-type, *Pteridium*, Poaceae) indicate a period of human activity.

For-19b: (GdA), GoE, PtC, PsH and SoC (ca. AD 200; 1750 cal yr BP)

Extra-local: SoC 55 cm has the highest *Centaurea nigra*-type, *Senecio* and *Sphagnum* of the entire diagram and remarkably high values of *Plantago lanceolata*. The latter does not grow at such high elevation, and a tentative explanation is that the sample contains material brought up to the site by humans or their animals. This would also explain the single *Vitis* pollen grain. Human activity on both this tiny mire and the nearby PsH may also be the cause of the hiatus at the top of the zone (Sjögren et al., 2007). **Regional and extra-regional:** Grassland indicators became stronger, *Abies* and *Corylus* declined and *Quercus* had a maximum.

For-20: GdA, GoE and PtC (ca. AD 450; 1500 cal yr BP)

Regional and extra-regional: There is a strong decline of agricultural indicators and Poaceae and increase of arboreal pollen. Early successional trees like *Alnus*, *Betula*, *Corylus* and especially *Pinus* invaded the lands, part of which is clearly visible in our diagrams. *Abies* regenerated to a degree in the montane and lower subalpine vegetation belts. The now closed dark silver fir–beech forests may have offered the habitat for *Carpinus betulus* to expand.

For-21: GdA, GoE (ca. AD 750; 1200 cal yr BP)

Extra-regional: Increasing Cerealia, anthropogenic indicators and other upland herbs and a decrease in tree pollen indicate a recovery of land-use. The crop trees *Castanea* and *Juglans*, earlier imported and planted by the Romans, were increasing. The period represented by zone **For-22** (ca. AD 950–1250; 1000–700 cal yr BP) is missing in all diagrams.

For-23: Col and PsH (ca. AD 1250; 700 cal yr BP)

Extra-local: Grassland use was more intensive high on the treeless slope (PsH) than at the forested foot of the slope (Col). The latter site (Col) was surrounded by *Betula*, and the adjacent forest included *Abies* and *Fagus* in about equal proportions, all of which were absent or scarce near PsH. **(Extra-) regional:** The pollen diagrams show a fully developed agriculture. Cerealia (including *Secale*) were cultivated more than ever before. New is *Cannabis sativa* as an important textile plant. *Castanea* and especially *Juglans* became important.

For-24: Col, PtC, PsH and SoC (ca. AD 1400; 550 cal yr BP)

In **For-24a** (Col, PsH and SoC; **extra-local**), grassland pasture was a general feature of the area. *Betula* was persisting in the sheltered position near Col. **Extra-regional:** Large-scale *Pinus sylvestris* plantations were initiated and *Castanea* and *Juglans* increased in importance. In **For-24b** (Col, PsH and SoC, ca. AD 1540; 410 cal yr BP), increasing *Corylus* and *Abies* may indicate a slight woodland regeneration, whereas *Pinus* pollen decreased somewhat. In **For-24c** (Col, PtC, PsH and SoC, ca. AD 1650; 300 cal yr BP), *Corylus* declined, whereas cultivated plants (Cerealia, *Cannabis*, *Castanea*, *Juglans*) and grassland indicators (e.g. *Plantago lanceolata*) increased strongly. This indicates an increased level of agricultural activities, the highest level seen in our pollen diagrams and probably also in the landscape.

For-25: GdA, GoE, Col, PtC, PsH and SoC (ca. AD 1780; 170 cal yr BP)

Extra-local: Peat accumulation resumed in the ‘large’ mire on the plateau (GdA and GoE), being the latest of the study sites. The local vegetation on the mire started with a *Calluna* maximum and major increase of Cyperaceae, presumably *Eriophorum vaginatum*. These two species dominate the mire vegetation still today. The other diagrams show a continuation of grassland pasture. *Calluna* became generally more important also in other diagrams, which indicates a change to

more oligotrophic soil conditions, probably caused by overexploitation of the grasslands in the summit region. **Regional and extra-regional:** All diagrams show further, strong declines of *Abies*, *Fagus*, *Quercus* and *Corylus*, a strong increase in *Pinus*, and a strong continuation of grassland expansion and crop cultivation. This was the most drastic change in vegetation since the immigration of *Fagus* and *Abies*. The previously ‘endless’ *Abies*-*Fagus* forests of the Monts du Forez were finally transformed on an immense scale into plantations of *Pinus sylvestris* and (to a lesser extent) *Picea abies* during the 19th century.

For-26: GdA, GoE, PtC, PsH and SoC (ca. AD 1890–the 1980s; 60 to –30 cal yr BP)

Regional and extra-regional: *Pinus* became stronger, whereas the other trees remained at a low level. There was a general decline, though not disappearance, of grasslands and crop cultivation.

5. Discussion

5.1. Phases in settlement history of the Monts du Forez in a wider, W European context

Above we reconstructed the past vegetation from our palynological studies in the Monts du Forez in the different time periods of the Holocene on a range of spatial scales (Fig. 9); here we focus on the relation

Time periods in the palynological diagrams

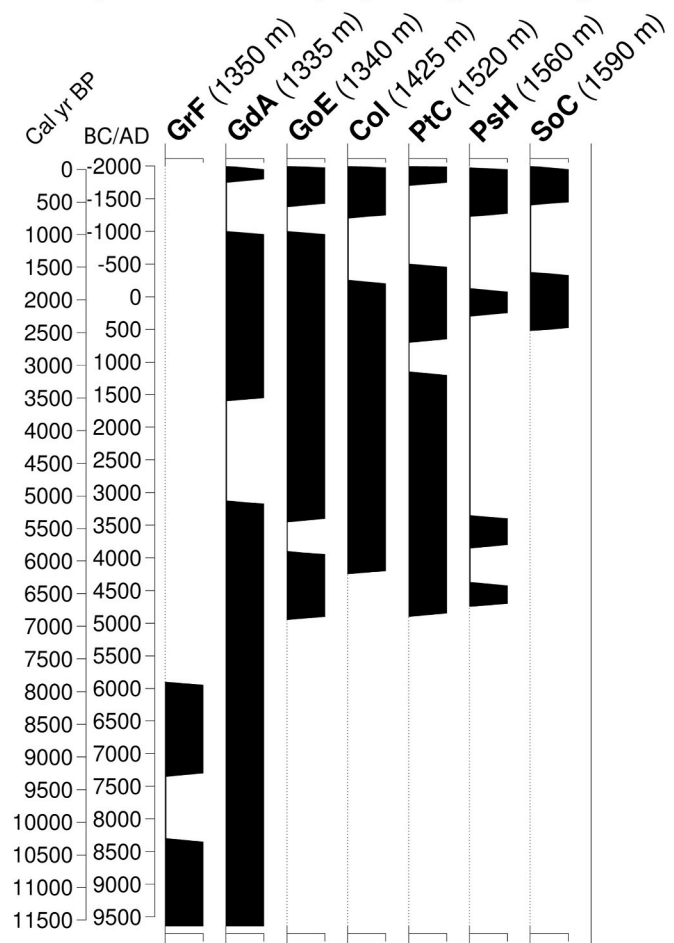


Fig. 9. Time periods covered in the studied pollen diagrams from the Monts du Forez (Massif Central, France). For site codes see Table 1; elevations are given in brackets.

between changes in reconstructed vegetation and the phases in settlement history in a W European context.

The inferred increased forest openness in its upper elevational areas after ca. 5200 BC (7150 cal yr BP) could well have been created by humans with use of domesticated animals. This period is contemporaneous with the Early and Middle Neolithic I. Indications of summer transhumance date back to these periods in many regions of Europe (Kalis et al., 2003) and this is plausible for the Monts du Forez, too. Neolithic people were farmers and practised husbandry, and mountainous regions were the most attractive because of their high biomass production.

In agreement with the findings by Argant and Cubizolle (2005), the first pollen indicators for cereal cultivation (Cerealia, Chenopodiaceae as weeds, *Plantago lanceolata* expanding on the treeless land created to lay out the fields) are present in our diagrams from ca. 4900 BC (6850 cal yr BP), during the Middle Neolithic, reflecting the first agriculture in the lowlands. In addition, we detected the expansion of treeless vegetation in the hazel (*Corylus avellana*) woodland around the study sites on the slope towards the summit, indicating anthropogenic disturbances most probably caused by browsing and grazing of domestic animals. Early farmers of the Middle Neolithic I (4900–4200 BC; 6850–6150 cal yr BP) therefore not only practised arable farming in the lowland, but also animal husbandry with woodland pasture in the mountains up to the summit area. These signs of early land use are the oldest known for the Monts du Forez. Anthropogenic pollen indicators of similar age are known from other regions of the Massif Central (Cantal, Limagne clermontoise and Limousin; Cubizolle et al., 2014).

During the Middle Neolithic II (4200–3500 BC; 6150–5450 cal yr BP), grazing on the woodland vegetation increased and was common practice, because of the lack of natural treeless grassland (Kalis, 2010). Around 4200 BC (6150 cal yr BP) a remarkable change began in the Paris Basin (northern France) in agricultural practices with an increased importance of animal husbandry. The required extra space for herding was found in the mountain ranges, where woodland grazing expanded in the open, light, mountainous mixed oak forests. These offered with their abundant understory and many good forage trees like maple (*Acer*), ash (*Fraxinus excelsior*), linden (*Tilia*) and above all elm (*Ulmus*) (Hejmanová et al., 2014) the best grazing areas. Because elm was the most abundant tree and its highly nutritional leaves favoured by the animals (Hejmanová et al., 2014), it suffered the most and gradually disappeared, so that oak (*Quercus*) with its unpleasant taste and low nutritional value could expand. An elm-decline during this period is a common phenomenon in W Europe (literature in Kalis et al., 2003); among several causes under discussion the most plausible is the herding of domestic animals. This phenomenon is visible in most mountain ranges within and adjacent to the area of the Michelsberg Culture (Kalis, 2010), as it is in the Monts du Forez (our data). Also, silver fir (*Abies alba*) and beech (*Fagus sylvatica*) started to expand in the Monts du Forez, but so slowly that they could not (yet) outcompete hazel (*Corylus avellana*) so we assume that the expansion of oak caused hazel to decline.

At the start of the Subboreal chronozone ca. 3600 BC (5550 cal yr BP), woodland pasture seems to have increased in the mountains, with drastic effects on the floristic composition of the forest vegetation both in the Monts du Forez and elsewhere, the most important outcome being the spread of beech (*Fagus sylvatica*) forests all over the mountain range at the cost of other deciduous trees. The ecological preferences of beech are so similar to those of small-leaved linden (*Tilia cordata*) that from a phytosociological point of view many plant communities of small-leaved linden can only be separated from those of beech by the composition of the tree layer (Ellenberg, 1978). Like elm (*Ulmus*) also linden (*Tilia*) has nutritious and palatable leaves for herbivores, but also the bark is a favourite fodder. Linden, however, is very vulnerable to bark biting and suffers heavy from woodland pasture. Beech on the other hand is much more resistant and herbivores normally avoid eating its bark and leaves. Woodland herding in linden forest leads therefore automatically to a conversion into beech forest. This happened during the Subboreal in the

greater part of W Europe (Kalis and Meurers-Balke, 1993). Quoting Bottema (1988), “It seems that expanding farming cultures had the beech in their wake as an oversized weed, passively or maybe even actively. It can be postulated that the immigration of beech in large parts of Europe was not a natural process but a process instigated by human activity.” After taking over the montane linden woods, beech spread into the elm–oak (*Quercus*) woodland on the slopes. Because beech brings much more shadow than elm and oak, regeneration of the latter two was hampered. Also the highly light demanding hazel (*Corylus avellana*) could not regenerate below beech and disappeared. The beech forest had become too dark to harbour sufficient undergrowth and domesticated animals avoid eating beech, so woodland herding was no longer attractive (Kalis, 2010, 2014). Also in the Monts du Forez the consequences of this forest conversion for the farmers were probably severe. This is apparent in our data from the diminishing pollen indicators of herding near the sites. The extra-regional pollen component on the other hand, shows a continuation of agriculture in the lowlands, not only by the indicators for arable farming, but also by the strong decrease of linden and elm. Small-leaved linden and elm species used to grow just on the fertile soils that were predestined to become fields and they had to give way. An increased number of archaeological finds from the Late Neolithic (3500–2500 BC; 5450–4450 cal yr BP) in the Forez Basin corroborate the expanding settling and land use in the lower mountain range (Cubizolle et al., 2014).

Hazel (*Corylus avellana*) pollen had in our data a maximum during the Early Bronze Age (2300–1700 BC; 4250–3650 cal yr BP). A hazel maximum of this age is widespread in Europe and was recognized as the ‘Co IV-top’ already by early palynologists (literature in Firbas, 1949). In contrast to the original explanation of climate change (Subboreal = back to the Boreal), the preferred explanation today is intentional vegetation change, probably by burning during the Late-Neolithic/Early Bronze Age (Eckmeier et al., 2008). The opening-up of the tree layer of forests is usually followed by the spread of so-called early-successional tree species to close the gap. In our data, we see this as a birch (*Betula*) and hazel maximum around 2200 BC (4150 cal yr BP), an alder (*Alnus glutinosa*) maximum around 2000 BC (3950 cal yr BP), and finally an oak (*Quercus*) maximum at about 1800 BC (3750 cal yr BP). This shows a severe intervention in the lowland forests, which was a new type of land use. Extensive herding in a landscape prepared by burning is a possible explanation.

During the Middle and Late Bronze Age (1700–800 BC; 3650–2750 cal yr BP), human impact on the mountain landscape is initially hardly detectable in our data, whereas the continued decline of linden and elm after ca. 1400 BC (3350 cal yr BP) indicates an expansion of agriculture in the distant lowlands.

During the Early Iron Age or Hallstatt period (800–450 BC; 2750–2400 cal yr BP), the indicators of agriculture at lower elevations augment in the Monts du Forez. Rare pollen grains of olive (*Olea europaea*) could mean that olive trees were grown already by the Hallstatt time farmers in the south. An increase in oak (*Quercus*) pollen points to forestry management. Oak at lower elevations on less fertile soils was subordinate to beech because its regeneration was hampered by the lack of sunlight. Beech, however, had no economic use apart from fuel, whereas oak yielded excellent construction wood and produced acorns used as mast for pigs and later during the Bronze Age also consumed by humans (cf. Karg and Haas, 1996). Early humans therefore favoured oak by suppressing beech. Our data show this by a maximum of oak pollen during the Early Iron Age. For the Early Hallstatt period (800 BC; 2750 cal yr BP) we have no indications in our data that our research area and the adjacent montane forests were used for herding or otherwise visited by humans. That changed drastically during the Late Hallstatt/Early La Tène period, from ca. 650 BC (2600 cal yr BP) on. Our data indicate that the upper mountain reaches were cleared of forest, treeless grassland expanded again and the area became used as pasture and meadows. At the same time, we find increasing open-land indicators for arable farming in the lowlands.

During the Late La Tène period, from ca. 200 BC (2150 cal yr BP) onwards, strongly rising grassland indicators in our data show a drastic expansion of pasture and meadows in the lower mountain reaches and in the lowlands. Increasing oak pollen and decreasing silver fir (*Abies alba*) pollen indicate major forestry activities to obtain high quality wood of both taxa for construction purposes. This seeming contradiction is explained by the observation that exploitation of oak woodland favours the growth of oak, whereas exploitation of silver fir woodland suppresses its natural regeneration.

The Roman occupation began around 50 BC (2000 cal yr BP). Early Roman land use is, from a palynological point of view, a continuation of that of the Late Iron Age (zone For-19a). The extra-regional pollen component shows basically a continuation of the Iron Age agriculture in the lowlands, with three new arrivals: rare pollen grains of chestnut (*Castanea sativa*), walnut (*Juglans regia*) and rye (*Secale cereale*). Other cultivated plants such as olive and wine grapes (*Vitis*) show a slight increase. Silver fir forests initially started to regenerate. Around ca. AD 200 (1750 cal yr BP) this picture changed drastic: the pollen curve of grass and of all indicators of arable farming and animal husbandry rose strongly and reached the highest level up till then. The two most important suppliers of high-quality wood, oak and silver fir, reached their highest, respectively lowest pollen values up till then, suggesting heavy exploitation. The effects of Roman land use are one of the most striking features in pollen diagrams from NW Europe; those from the Monts du Forez are no exception. In this context, Küster (1994) in his overview on the economic use of silver fir (*Abies*) within the Roman Empire, states that “it can be concluded that the *Abies* decline is a very good time-marker for dating sections of pollen diagrams to the Roman period”.

During the early-fifth century AD, strongly decreasing values of grass pollen and almost all agricultural indicators and rise of early-successional tree species like alder, birch, hazel, pine and oak in the Monts du Forez show the severe economic consequences of the disintegration of the Roman Empire and its internal power, the Pax Romana. The following Dark Ages (AD 450–750; 1500–1200 cal yr BP) are characterized by very low anthropogenic pollen indicators and high values of tree pollen. The greater part of W Europe was sparsely populated and densely forested; agriculture was abandoned and the fields were invaded by pioneer trees. This is clearly visible in the pollen diagrams everywhere within the boundaries of the former Roman Empire. The strongest feature in the Mont du Forez pollen diagrams is the successful regeneration of the silver fir forests in the montane and lower subalpine vegetation belts.

The Early Middle Ages repopulation and economic recovery of the Monts du Forez from ca. AD 750 (1200 cal yr BP) is clearly marked in our data by the strong increase of all agricultural indicators (zone For-21). But unfortunately, we know nothing about the vegetation history between ca. AD 900 and 1250 (1050–700 cal yr BP), because of the lack of peat deposits from that time.

From AD 1250 (700 cal yr BP) onwards, during the High Middle Ages, the pollen diagrams show a fully developed agricultural landscape in and around the Monts du Forez. Cereal growing was important and hemp (*Cannabis sativa*) was cultivated as a textile plant with increasing importance. Chestnut, walnut, olive and grapes were grown as economic important woody species. These pollen types are part of the extra-regional component, from plants not necessarily growing within the mountain range, but rather in lowlands nearby with a suitable climate.

The diagram from Colleigne shows the vegetation history of the last millennium in great detail (zones For-24, -25 and -26). Unfortunately, we are not familiar with the regional history of the eastern Massif Central, so we refrain from further interpretation of the human impact detectable in this diagram.

5.2. Hiatuses in the sequences

Fig. 9 shows that all our pollen diagrams have hiatuses (missing time

periods). When comparing with our results, one may wonder why Argant and Cubizolle (2005) and Cubizolle et al. (2014) did not identify any hiatuses in their pollen sequences from the same region. The simple explanation is that their method of age–depth modelling, namely linear interpolation among accepted calibrated radiocarbon dates, excludes the possibility of hiatuses. Also, we cannot judge from their published diagrams whether or not hiatuses might be present, because a detailed visual comparison of their diagrams with our pollen stratigraphies is hampered by their different choice of inclusion or exclusion of pollen types in the pollen sum (100%), which was apparently not designed to trace hiatuses. One possible cause of a hiatus is a coring artefact, when the mire does contain the required deposits at the coring location but they are not collected in the field or not sampled in the laboratory. 1150–700 BC (3100–2650 cal yr BP) missing in PtC is a clear case of coring artefact: overlapping cores retrieved from closely adjacent boreholes were sub-sampled in such a way that the complete sequence was not covered. A very regrettable error.

Another possibility is that the peat layers were actually missing at the coring location due to the former activities of domesticated animals. We may assume this when the inferred hiatus is associated with pollen-stratigraphic indications that the mire had been frequented just before and/or just after the inferred hiatus. Palynological evidence of animal droppings on the GdA mire was found twice, dated ca. 3600 BC (5550 cal yr BP) and ca. 1000 BC (2950 cal yr BP). The typical peat- and pollen-stratigraphical pattern of new peat formation after an erosion phase caused by cattle trampling the mire is named a “kultureller Trockenhorizont” (cultural dry horizon), discussed for Europe and described in detail for the Alps by Sjögren et al. (2007). Cattle on the mire does not only cause a stagnation of peat formation, it can also lead to erosion of superficial peat layers and thus extend the hiatus into earlier periods before the cattle arrived (Sjögren et al., 2007). This may help explain the long duration of some of the hiatuses in several mires. It would also explain the frequent absence of pollen indications for cattle presence in the peat just below an inferred hiatus. Sjögren et al. (2007) commented that the “kultureller Trockenhorizont” is ‘at least a Europe-wide phenomenon that has so far escaped adequate attention’, and found that in the Alps, the presence of a cattle-related hiatus is the rule rather than exception. In the Forez mountains, we found indications for it in GdA where the time period of 3150–1500 BC (5100–3450 cal yr BP) seems to be missing, and in PsH where sediment is missing between 4400–3750 BC (6350–5700 cal yr BP). GoE, situated at the mire’s edge, misses the time span of 3900–3450 BC (5850–5400 cal yr BP), whereas the same period in the centre of the same mire (GdA) provides strong indications that cattle used the mire, thus suggesting that the hiatus at the mire’s edge is cattle-related. The beginning of the long hiatus in PsH (3300–300 BC; 5250–2250 cal yr BP) also falls in this period with strong indications of cattle presence in the study area, which makes it a realistic hypothesis that mire disturbance played a role also in this PsH hiatus. The period ca. AD 950–1200 (1000–750 cal yr BP) is lacking in all diagrams, and this general hiatus in all mires forms part of a longer hiatus. A common cause may explain such coincidence. The palynological pattern after the end of the hiatus in the large mire (both GdA and GoE), ca. AD 1780 (170 cal yr BP), is characteristic of a “kultureller Trockenhorizont” (see above). This, combined with the reasonable assumption that the study area was grazed during the time of the general hiatus (medieval period), makes it likely that presence of domestic animals or related anthropogenic activities were the cause of the hiatus. For example, humans may have shifted water courses for the improvement of fodder production, resulting in temporarily drying out of parts of mires (Cubizolle et al., 2012). Climate change seems unlikely as a cause of the general hiatus in this period because of the widespread high anthropogenic pressure on the landscape during medieval times overruling other effects.

A third possible cause of a hiatus is natural events that are not human-induced, such as climate change or shifts in water availability. The only remaining candidate for this cause is the hiatus at 551 cm in GrF (8350–7400 BC; 10,300–9350 cal yr BP), where the vegetation

development supports this hypothesis.

A related question is, why we could not trace any peat formation earlier than ca. 5000 BC (6950 cal yr BP), except in the centre of the ‘large’ Gourds des Aillères mire (GdA). The answer may reside in the pollen zone For-8 in GdA just before this date, where we found clear signs that the vegetation of the study area became more open at the arrival of domestic animals. This partial deforestation probably led to increased spring activity, providing the water that initiated peat formation on multiple places (PtC, PsH, and possibly Col) and allowed lateral expansion of the Gourds des Aillères mire (GoE). In summary, domesticated animals can have two different effects on peat formation: initiation of mire development; or stagnation of peat formation and erosion of peat layers. Active growth of peat mires is, however, an important concern of mire conservation. The history of the mires in our study area shows that low animal densities may not harm, but that over-grazing should be avoided.

Peat formation on the highest site on the flattish mountain summit (SoC; 1590 m a.s.l.) started after the marked decline of *Fagus* ca. 500 BC (2450 cal yr BP). We infer from our other pollen diagrams that shortly before this time, domesticated animals opened up the tree or shrub vegetation in the summit region, and this led to increased surface wetness sufficient to enable peat formation.

5.3. Timing and speed of the expansion of *Fagus* and *Abies*

Cubizolle et al. (2014) wrote that “we can accurately date around 5000 years cal. BP [= 3050 BC] the start of *Fagus* distribution, quickly followed by *Abies* and their development over the course of the Sub-Boreal period”. In the light of their own findings, however, this is rather inexact wording. Their pollen diagrams suggest an older date of the major beech (*Fagus sylvatica*) expansion, namely 3307 ± 200 BC (5257 cal yr BP) in Etui, 3232 ± 134 BC (5182 cal yr BP) in Corniche-en-Coeur, and 3883 ± 92 BC (5833 cal yr BP) in Gourgon. Also, our data suggest an older age. Though notoriously difficult to pinpoint the beginnings of a tree expansion exactly on the basis of pollen (see Magri et al., 2006 for beech), we found that *Fagus* started to expand its populations rapidly around 3500 BC (5450 cal yr BP). The silver fir (*Abies alba*) pollen increase was initially very slow, which makes it even more difficult to pinpoint its first expansion date, but this is roughly 3300 BC (5250 cal yr BP). Silver fir expanded indeed slowly, taking about two millennia up to ca. 1300 BC (3250 cal yr BP) to reach approximately constant values, whereas beech had fully established within a few centuries, by ca. 3200 BC (5250 cal yr BP). The initial expansion of beech was at the cost of hazel, linden and elm (*Corylus*, *Tilia*, *Ulmus*), all of which declined along with the beech increase, whereas silver fir expanded within the beech forest.

5.4. Natural baseline conditions of the forest and the cultural landscape

It may be of interest for the management of the extant forests in the upper reaches of the Monts du Forez to have an idea of the natural state of the forests before the tree composition was modified through direct or indirect human action. Our results provide the following insights. In the pre-Neolithic period before ca. 5500 BC (7450 cal yr BP), the forests of the Monts du Forez were mainly composed of deciduous trees, among which mainly *Corylus*, *Betula*, *Alnus* and *Sorbus* reached the higher elevations of our study area, but also *Ulmus*, *Fraxinus*, *Quercus* and *Tilia* may have had much higher upper limits than today. *Fagus* and *Abies* arrived during the Neolithic and rapidly replaced most of the former forests, especially at higher elevation. During approximately 800 to 650 BC (2750–2600 cal yr BP) the two trees were in equilibrium and formed stable *Abies–Fagus* forests up to their highest limit and with relatively little human impact. This period can therefore be accepted as a baseline for near-natural tree abundance. The two trees had roughly equal shares, but this varied from place to place according to local conditions.

Not just the forest, but the entire cultural landscape of the Monts du

Forez may be of interest for management purposes. Part of the forest was cleared for creating fields and pastures after about 650 BC (2600 cal yr BP), and initially mainly *Fagus* was affected. Various phases of landscape transformations followed, but much of the *Abies–Fagus* forest remained in place up into late medieval times. In the last several centuries major deforestations took place, while *Pinus sylvestris* was strongly favoured by planting. The late medieval period could thus serve as the baseline condition for a cultural landscape in which the composition of the remaining forest was reminiscent of the preceding two millennia.

5.5. Can we reconstruct former forest limits?

We defined the period ca. 800 to 650 BC (2750–2600 cal yr BP) as the last period with more or less stable, little disturbed *Abies–Fagus* forests, so this is the target period for which we might estimate the natural upper (closed) forest limit and (open) tree limit. The target period is represented in the sites on the plateau below the present-day forest limit (GdA, GoE en Col), but it is missing in the sites on the slope (PtC and PsH) and in the flattish summit region (SoC) where peat formation started ca. 500 BC (2450 cal yr BP), not long after the target period (Fig. 9). The period 650–200 BC (2600–2150 cal yr BP) is on the plateau marked by the anthropogenic *Fagus* decline and *Corylus* expansion related to Iron Age woodland foraging, and in the summit region diverse treeless grasslands were found that most likely also were also used by the Iron Age farmers. We can reconstruct former forest limits during periods for which we have pollen data at the relevant elevations, but our reconstruction must remain speculative for the target period.

The palynological tools for our tree-line reconstruction include the pollen of local upland herbs and grasses (Poaceae) used to estimate vegetation openness and pollen of the main trees in the study area used to estimate extra-local tree composition (*Corylus*, *Fagus*, *Abies*).

We first reconstruct the elevational gradient in the degree of forest closure during the ‘post-target’ period 650–200 BC (2600–2150 cal yr BP). On the plateau near the ‘large’ mire (GdA, GoE), local upland herb pollen is scarce and not diverse, indicating that no large forest openings had been created there. The site at the foot of the slope (Col) differs in having slightly higher abundance and diversity of local upland herbs and abundant grasses, indicating forest opening and patches of grassland near the site. Low on the slope (PtC), the rather scarce and not so diverse local upland herbs, the low proportion of grasses and low *Corylus* values indicate that the nearby-surrounding forest was dense. Higher up on mid-slope (PsH), local upland herbs were abundant and diverse and grasses were abundant, but also the main trees *Abies* and *Fagus* were growing nearby. So this represents a treeline ecotone (gradual transition from forest to open vegetation) intermediate between forest and grassland, which is an elevational zone rather than a sharp limit. The site in the summit region (SoC) had very abundant local upland herbs of high diversity, abundant grasses and no trees that could be detected by pollen, so this was above the forest limit of that time – and possibly also above the tree limit. Iron Age farmers most probably used the grasslands and open woodland for herding.

On the basis of the forest-limit reconstruction above during the post-target period, we now speculate on the natural position of the forest limit during the target period itself when human impact on the forests in the study area was negligible (ca. 800–650 BC, 2750–2600 cal yr BP). As argued before, pollen in the sites on the plateau (GdA, GoE) gives no clue whether or not the summit was forested during the target period. If, however, we adopt the working hypothesis that the summit region was free of forest and there was an upper tree limit, we have good grounds to speculate where this was positioned. First, it is plausible that the later (post-target-period), human-made treeline ecotone zone at mid-slope (PsH) had its origin in closed *Abies–Fagus* forests during the target period; this forest type is naturally dark and dense unless opened by humans and their domesticated animals. Natural *Fagus–Abies* forest in other middle-high mountain ranges today is fully closed and has an abrupt natural upper limit in the form of krummholz (e.g. in the Black

Forest in Germany and in the Vosges Mountains; de Valk, 1981). If this was also the case in the Monts du Forez mountains during the target period, the closed *Fagus–Abies* krummholz may have had an upper limit at the transition from the slope to the flattish summit area. This transition area has the form of a rocky outcrop ridge just above the PsH site (the ‘Corniche-en-Coeur’ visible as snow-covered arcs in Fig. 1), above which (ca. 1570 m a.s.l.) the flattish summit area begins. The soils in the summit area may be less suitable for closed forest because they are rather thin and stony (personal observation), which strongly contrasts with the thick organic soils in the Vosges Mountains (de Valk, 1981) and the Black Forest. In analogy to the Black Forest (personal observation) but in contrast to the Vosges Mountains (de Valk, 1981), scattered *Abies* trees may have grown above a closed *Fagus–Abies* krummholz. Even if the forest limit was below the mountain summits during the target period, open tree growth in the summit region of the Monts du Forez is very likely because its removal after the target period forms a plausible cause for the initiation of peat formation at SoC early in the post-target period. In analogy to both the Vosges Mountains and the Black Forest, such open tree growth would have included *Sorbus*, *Betula* and *Acer*.

6. Conclusions

In this paper an overview is given of the palaeoecological work that was carried out at the Laboratory of Palaeobotany and Palynology at the University of Utrecht, The Netherlands, between 1982 and 1988. Seven pollen diagrams from the upper montane and subalpine zones of the Monts du Forez in the north-eastern Massif Central (France) are presented in an elevational transect of 1335–1590 m. The transect lies on a single slope, within a surface of 2.1 by 0.7 km. This allowed us to reconstruct the past vegetation in this area of France in detail from the start of the Holocene onwards into the present-day.

During the Holocene, the timing and speed of the expansion of the various trees in the study area (ca. 1300–1635 m a.s.l.) (especially *Fagus* and *Abies*) could be followed and tree-lines could be reconstructed. *Corylus* forest with *Ulmus* covered most of the study area from ca. 8200 to ca. 3500 BC (10,150–5450 cal yr BP). *Fagus* expanded its populations within the *Corylus* forest to high abundance within a few centuries beginning ca. 3500 BC (5450 cal yr BP), whereas *Abies* started expanding some centuries later when *Fagus* was already abundant, and it took *Abies* until about 1300 BC (3250 cal yr BP) to reach equilibrium with *Fagus*. The last period of near-natural *Abies–Fagus* forests, 800–650 BC (2750–2600 cal yr BP) when the two trees had approximately similar abundance, is a suitable baseline of the natural forest composition in the higher mountain belts. During that time, the highest mountain top, peaking at 1634 m elevation, may have emerged above the upper limit of closed forest. If that was the case, we estimate that *Fagus* and *Abies* formed a dense but low krummholz up to a forest limit at ca. 1570 m elevation, whereas *Abies* may have had a higher upper limit with scattered trees above the closed krummholz and open woodland of *Sorbus*, *Betula* and *Acer* up to the summit region. A cultural landscape was well established during medieval times during which part of the *Abies–Fagus* forest remained intact, until major deforestations took place during the last few centuries and open areas and *Pinus sylvestris* plantations replaced part of the remaining *Abies–Fagus* forest.

Concerning the protection of the mires in the upper montane and subalpine zones of the Monts du Forez, we found that over-grazing by cattle resulted in stagnation of peat formation and even erosion, so we suggest a moderate, but not too strong grazing regime in order to keep this highly varied and valuable landscape intact.

Although our study is primarily concerned with reconstructing past vegetation from pollen assemblages, several lessons can be learnt from our results. This intensive study of seven pollen sequences on a single slope over an elevational range of 1335–1590 m, and the separation of the pollen assemblages into local, extra-local, regional and extra-regional components show how complex the vegetation dynamics has been at a range of spatial scales during much of the Holocene. Moreover,

it illustrates the strong impact that human activity and domesticated animals have had on vegetation history and emphasises the problems of identifying unambiguous climatic factors as drivers of the vegetational changes in a study area such as ours (cf. Marquer et al., 2017). It also underlines the problems of reconstructing past forest and tree limits on the basis of pollen data alone. Plant macrofossils may often aid such reconstructions (Birks and Birks, 2000). Finally, it highlights the problems of defining robust and realistic natural baseline conditions relevant to conservation and management today and in the future with changing climate and land-use (Birks, 2019).

Author contributions

CRJ devised the research project and carried out the initial part; WOK and AJK made the chronologies and wrote the text; JFNL, JAAB and WZH provided data and contributed to the interpretation; and JRC, MM, EAS and CAS provided data.

Data availability

All used data have been contributed to the EPD (European Pollen Database) and Neotoma.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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