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From the Neolithic to the present day: The impact of human presence on floristic diversity in the sandstone Northern Vosges (France)

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Abstract – The Northern Vosges and the Pays de Bitche (north-eastern France) are well-known regions for their rich recent industrial heritage. On the other hand, the ancient history of these regions is less well known and the relationships between human populations and their environments during ancient times is still largely unexplored. We carried out a multidisciplinary paleoenvironmental study on the site of the bog pond located below the ruins of the medieval castle of Waldeck in order to reconstruct the history of the vegetation in the region since 6600 cal. BP. Throughout the Holocene, the succession of forest vegetation (pine and hazelnut forests, reduced oak forest, beech forest, oak-beech forest) was largely dominated by pine. Human presence was tenuous during the Neolithic period, then well marked from the Bronze Age onwards with the introduction of crops and livestock crops in the catchment area. From the Middle Ages onwards, anthropic pressure increased dramatically with the building of Waldeck Castle in the thirteenth century, which led to a major opening of the area. The Modern period is characterized by a gradual return of the forest, with decreasing anthropogenic pressure. Over time, occupation phases were interspersed with abandonment phases during which human activities regressed or disappeared. Finally, the rarefaction analysis carried out on pollen data shows that human presence led to a gradual increase in plant diversity, which peaked in the Middle Ages, whereas the forest lost some of its resilience to human disturbance over time.

Keywords: Palynology / coprophilous fungi / XRF geochemical analysis / past floristic diversity / human occupation / Vosges

Résumé – Du Néolithique à nos jours : impacts de la présence humaine sur la diversité végétale dans les basses Vosges Gréseuses (France). Les Vosges du Nord et le Pays de Bitche (nord-est de la France) sont des régions riches en patrimoine industriel récent, à l'histoire bien connue. En revanche l'histoire ancienne de ces régions est méconnue et les relations entre les populations humaines et leur environnement restent, jusqu'alors, inexplorées pour les périodes anciennes. L'étude paléoenvironnementale pluridisciplinaire que nous avons menée sur le site de l'étang-tourbière, situé en contrebas des ruines du château médiéval de Waldeck, a permis de reconstituer l'histoire de la végétation depuis 6600 cal. BP. Durant tout l'Holocène, la succession de végétation forestière (forêts de pin et noisetier, chênaie réduite, hêtraie, chênaie-hêtraie) est largement dominée par le pin. La présence humaine, ténue au Néolithique, est bien marquée à partir de l'Age du Bronze avec la mise en place de cultures de céréales et d'élevage dans le bassin versant. À partir du Moyen-Age, la pression anthropique augmente très fortement avec la construction, au XIII^e siècle, du château de Waldeck qui engendre une importante ouverture du milieu. L'époque moderne voit le retour progressif de la forêt, alors que la pression anthropique diminue. Au cours du temps, les phases d'occupation ont été entrecoupées de phases d'abandon au cours desquelles les activités

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humaines régressent ou disparaissent. Enfin, l'analyse de raréfaction réalisée sur les données polliniques montre que la présence humaine a engendré une augmentation progressive de la diversité floristique, qui a culminé au Moyen-Age, alors qu'au cours du temps, la forêt a, en revanche, perdu un peu de sa résilience face aux perturbations humaines.

Mots clés : Palynologie / champignons coprophiles / analyses géochimiques XRF / diversité floristique passée / occupation humaine / Vosges

1 Introduction

The important and well-known industrial heritage of the Northern Vosges, extending from Saverne town (in the south) to the German border (in the north) (Fig. 1A), developed from the seventeenth century onwards and consists primarily of glass factories (Meisenthal, Saint-Louis crystal factory, Fig. 1A, 8-9) and metallurgy establishments (De Dietrich, Fig. 1A, 4-7, 10-11). Thus, from the seventeenth century onwards – a period of demographic, economic and industrial growth –, the history of this region is well known and abundantly documented (Jacops *et al.*, 1990; Husson, 1995; Jehin, 2005, 2006, 2010; Kraft, 2012).

On the other hand, except for the twelfth-fourteenth centuries, when abbeys and numerous castles were built in the heart of the Northern Vosges, historical and archaeological knowledge for earlier periods is much less abundant, particularly in the Pays de Bitche (in the Moselle region of the Northern Vosges) (Fig. 1A) (Schmit *et al.*, 2017). The plural identity of the Northern Vosges or the Pays de Bitche complicates tracing the history of these regions. These regions are first and foremost geological and geographical entities; the former straddles Alsace and Lorraine, and the latter lies between the Northern Vosges and Lorraine Plateau. Over time, they have repeatedly acted as border areas. Between the city of the Mediomatrici in Belgium Gaul and the city of the Triboci in Germany, between the Kingdom of France and the German Holy Roman Empire, between France and Germany, between Alsace and Lorraine, these “in between countries” (“pays d’entre-deux”) (Jacops *et al.*, 1990) have inherited a complex history. In addition, the oldest archives were often lost during the many conflicts that marked the history of the Northern Vosges, and more particularly the Bitche region, depriving us of records of the past (Oeckinghaus, 1917). In addition, very few archaeological excavations have been conducted in these regions. The rare excavated Gallo-Roman sites are mainly located on the margins of the Northern Vosges or in the south of the Pays de Bitche. In the latter region, discoveries consist mainly of isolated remains discovered by field prospecting organised by local history and archaeology societies. Indeed, the relief and dense forest cover of the Northern Vosges render archaeological research extremely difficult. Thus, archaeological data are fragmentary, scattered and very poorly documented (Schmit *et al.*, 2017) and very few discoveries have been confidently attributed to a specific time period. Nonetheless, these discoveries indicate early human occupation since Palaeolithic times (Schmit *et al.*, 2017).

Consequently, our knowledge of the relationships between societies and their environments, and the identification of the impact of human activities on the vegetal cover in this region have never been explored, except for recent periods (from the sixteenth century), through historical geography or archive studies (Jehin, 2005; Rochel, 2017).

In order to overcome difficulties encountered by archaeological research and historical studies in reconstructing the history of this territory, it is essential to conduct paleoenvironmental studies. Palynological analyses, for example, enable us to trace the evolution of natural vegetation in remote times and to identify anthropogenic changes in a given environment (Behre and Jacomet, 1991). They can thus fill the gap in historical knowledge and enhance our understanding of human-environment interactions over time.

Nevertheless, palynological data are very rare in the Northern Vosges (De Klerk, 2014). To date, only five pollen analyses have been conducted in this region (Hatt, 1937; Dubois *et al.*, 1938). The analytical resolution of those analyses is very low, with a sample every 25 to 50 cm, and they are limited to the identification and presentation of variations of the main tree species. Therefore, they do not shed light on the reconstruction of the landscape nor the study of its anthropisation. In addition, there are no radiocarbon dates in these studies. In the Pays de Bitche (which is currently the subject of a Man-Environment Observatory), only two recent studies have investigated the impact of societies on the dense forests of these regions, through anthracological and palynological analyses (Gocel-Chalté *et al.*, 2020; Gouriveau *et al.*, 2020).

In this context, the study presented here aims to provide new knowledge on the past plant environment and on society-environment relationships in this region, as well as on the impact of human activities on past floristic diversity. To this end, a multidisciplinary study was conducted on the Waldeck bog pond, located in the Pays de Bitche, combining analyses of microfossils preserved in peat (pollen, coprophilic fungus spores, carbonized particles), rarefaction analysis of pollen results, sediment characterization and geochemical analysis.

2 Study site

2.1 Geomorphology, geology and climate

The Waldeck pond (49°01.287'N 7°31.392'E) is part of the Regional Natural Park of the Northern Vosges (*Parc naturel régional des Vosges du Nord*) and of the Natural Reserve of Rocks and Peatland of Pays de Bitche (*Réserve naturelle des rochers et tourbières du Pays de Bitche*) (Fig. 1A). It is located near Eguelshardt village, at an altitude of 253 m a.s.l., in the Pays de Bitche (north-eastern part of the Moselle department, France, straddling the northern Vosges mountains and the Lorraine plateau) (Jacops *et al.*, 1990). The relief of the Pays de Bitche is characterized by wider valleys with gentler slopes than in the rest of the Regional Natural Park, overhung by rocky bars with an appearance of ruins, which are outliers of the former eroded sandstone plateau. This small pond (about 5 ha) and the surrounding peat bog are located upstream of a small dam on the Falkensteinerbach stream, which flows into a large basin below the ruins of Waldeck Castle (Fig. 1B).

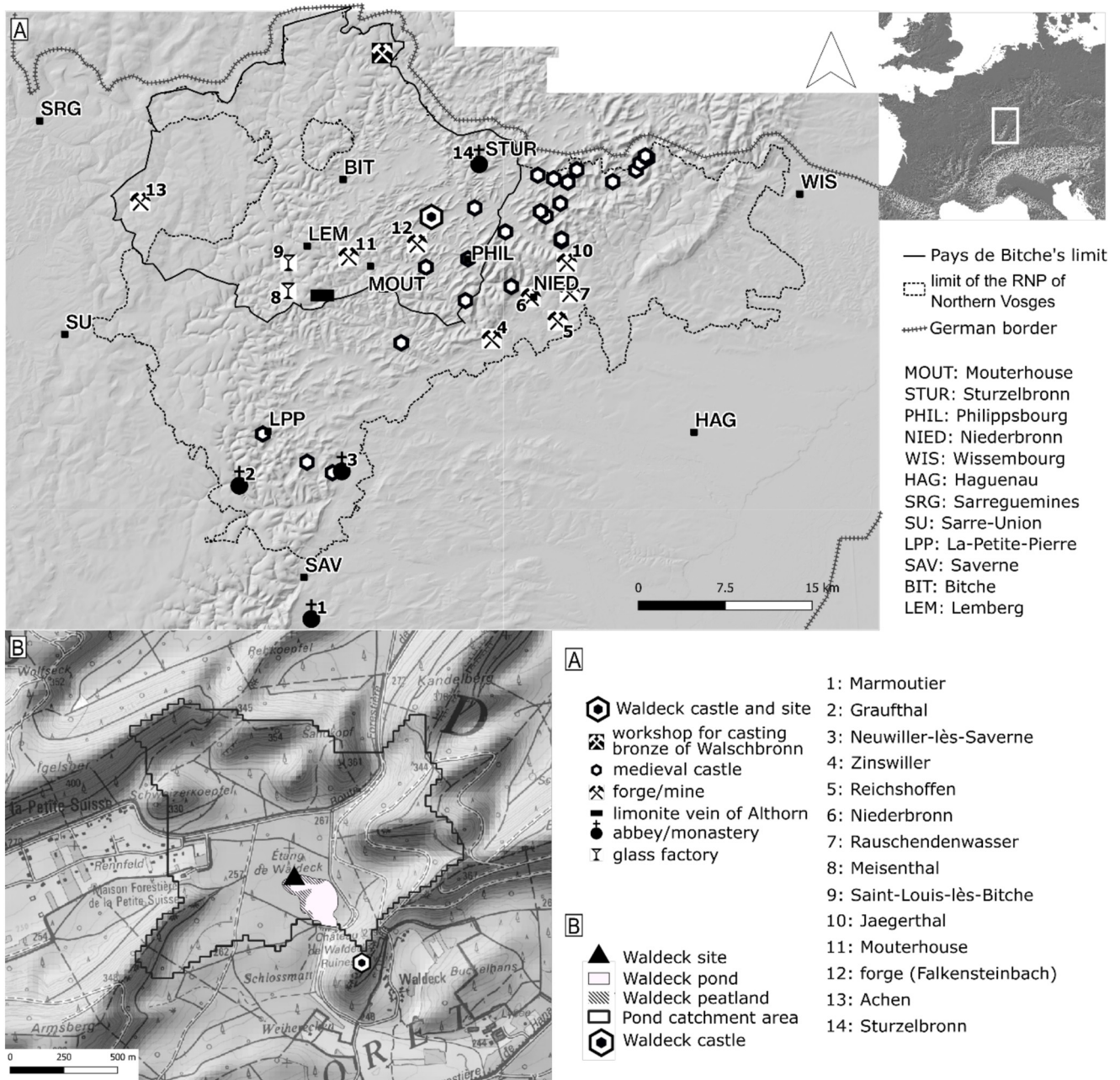


Fig. 1. Geographical location of the studied area: (A) Location of the Northern Vosges Mountains and the Bitcherland and of several historical and industrial sites; (B) Catchment of the Waldeck pond.

The catchment area, formed by red Lower Triassic sandstones (Buntsandstein, t1b), is about 128.4 ha and extends north of the wetland, with a maximal altitude of about 380 m a.s.l. (Fig. 1B).

Weathering of the bedrock produces podzols and podzolic soils, which are very sandy, acidic, and extremely nutrient-poor soils with low water reserves (Blanalt *et al.*, 1967). The sandstones of the Northern Vosges include iron deposits, such as the Althorn limonite vein located near Mouterhouse town (23 km southwest of Waldeck bog pond) (Fig. 1A) (Méloux *et al.*, 1987; Sell *et al.*, 1998).

The climate of the Northern Vosges is sub-Atlantic, whereas in the basins of the Pays de Bitche, it is described as a “microclimate with a sub-continental affinity”, a little colder than in the rest of the Regional Natural Park (Muller, 1986; Bonnel and Tholozan, 2007; Duchamp, 2009).

2.2 Current vegetation

The Northern Vosges present an afforestation rate of around 60%, which reaches up to 80% on sandstones (Muller and Genot, 1991). According to Muller (1986),

Muller and Genot (1991), Duchamp (2011) and Boeuf *et al.* (2014), the main plant communities in the sandy part of the Pays de Bitche are distributed according to an increasing gradient of dryness, temperature and acidity. Acidicline to acidophilic hillside beech (*Fagus*) forests are observed on the coolest slopes exposed to westerly rains (*Luzulo Luzuloidis-Fagetalia*, Scamoni and Passarge, 1959), and particularly *Luzulo luzuloidis-Fagetum sylvaticae*, (Meusel, 1937) and *Leucobryo glauci-Fagetum sylvaticae* on more clement and more acidic soils (Passarge and Hoffmann, 1968; Boeuf *et al.*, 2014). *Quercetalia roboris* type acidophilic oak (*Quercus*) forest (Tuxen in Barner, 1931) with more or less beech trees is the main forest formation, whereas Scots pine (*Pinus sylvestris*) communities dominate (*Vaccinio myrtilli-Pinetum sylvestris*, Juraszek, 1928) on the driest sandstone soils, as well as on top of rocky peaks (*Cladino-Pinetum sylvestris*, Juraszek, 1928).

On wet soils, plant communities associated with alder-birch (*Alnus-Betula*) marshes (*Alnetea glutinosae*, Braun-Blanquet & Tuxen Ex. Westhoff *et al.*, 1946) are the most common, except on hydromorphic or oligotrophic and acidic peat where *Molinia* moors and birch-pine forests develop (*Betulion pubescentis*, Lohmeyer and Tuxen Ex. Oberdorfer, 1957, Boeuf *et al.*, 2014). Some common spruce plantations (*Picea abies*), which are currently suffering from repeated drought in recent years, or other exotic coniferous species (Douglas fir tree (*Pseudotsuga menziesii*), Weymouth pine (*Pinus strobus*)) are also observed.

The Waldeck pond is only supplied by sources with variable flow rates depending on the season and year, and a peat bog extends into the most upstream zone. Currently, vegetation is zoned around the pond, mainly with an amphibious lawn of *Eleocharis multicaulis* (attributed to EUNIS C3. 4131 code) on its banks, interspersed with lawns with *Carex lasiocarpa*, *C. rostrata* and *Sphagnum* (EUNIS D2. 312). Then, towards the periphery, a plant community of peat and wet and acidic sands, with *Rhynchospora alba*, *R. fusca* and *Drosera intermedia* (EUNIS D2. 3H), a wet moorland with *Molinia caerulea* (EUNIS F4. 13), and a peat pine forest with *Pinus sylvestris* (EUNIS G3. E22) follow one another. Upstream, in former partially filled ditches, plant communities similar to rafts of *Sphagnum sp.* and *Eriophorum angustifolium* (EUNIS D2. 38) and, on a bank close to a lateral source, a fragment of swampy alder forest on acidic peat (EUNIS G1. 52), are observed.

2.3 Waldeck Castle

The peat bog is of historical interest on account of its exceptional location at the foot of the ruins of Waldeck Castle (Fig. 1B). This typical castle of the Northern Vosges, namely a troglodyte castle, was built on a rocky outcrop in the thirteenth century, in the middle of the period of castle construction (twelfth-fourteenth centuries) in the border area between Lorraine Duchy and Alsace (Fig. 1A) (Rudrauf, 2008, 2009a, 2009b, 2009c, Mengus, 2009). The castles of the Northern Vosges are characteristic of this landscape, however, many questions surround the choice of their location (Schwien, 2016). The region comprises an impressive number of castles for a very small population and reduced economic appeal at that time. Schwien (2016) rejects the idea of a continuous occupation of these settlement sites, and considers that all the castles were built on “virgin sites”

(p. 46). Palaeoenvironmental analysis of this site may confirm or refute this hypothesis, which appears to be substantiated by the absence of local archaeological and historical data.

3 Material and methods

3.1 Coring

A core was taken down to the substratum, using a Russian GIK-type corer (100 cm long with a diameter of 8 cm). The 1.10 m-long core was extracted from the edge of the peat bog, in the pond edge turf, at the open water limit. Up to a depth of 80 cm, the base of the sequence consists of dark organic sediment, very rich in sand (Fig. 2A). From a depth of 80 to 30 cm, the sand gives way to abundant non-decomposed plant remains in very dark organic matter, particularly between depths of 50 and 30 cm. From 30 to 13 cm below the active peat, the organic sediment contains sand again.

3.2 Dating and chronology

The Poznan Radiocarbon Laboratory and Beta Analytic Laboratory performed AMS radiocarbon dating (acid-alkali-acid pre-treatment) on eight samples (isolated plant remains, leaf, seed, charcoal or total sediment) (Tab. 1). An age-depth model (Fig. 2A) was generated using a “smooth spline” model, with the R software (Blaauw, 2010) “clam” package (2. 3. 1).

3.3 Pollen, coprophilic fungus spores and carbonized particles

Samples were collected every 2 cm and processed for pollen analysis and the study of coprophilic fungal spores and carbonized particles according to the protocol developed by Faegri and Iversen (1989): HCl, screening (200 µm), NaOH, HF and acetolysis. Four *Lycopodium* tablets were added to the samples. At least 500 pollen grains were identified and, in cases where one taxon dominated the assemblage, at least 200 pollen grains of other taxa were counted.

Pollen identification was based on identification keys (Beug, 2004), photography books (Moore *et al.*, 1991, Reille, 1992–1998) and a pollen slide reference collection kept in the “Laboratoire Chrono-environnement” at Besançon (Université de Bourgogne-Franche-Comté). Grass pollen grains with a diameter of 40 µm and an annulus of 10 µm were classified as *Cerealia*-type (Beug, 2004, Joly *et al.*, 2007). Anthropogenic Pollen Indicators (API) include pasture indicators (*Apiaceae*, *Anthemideae*, *Centaurea jacea/nigra*, *Cichorioideae*, *Plantago lanceolata*, *Ranunculaceae* and *Rumex acetosa/acetosella*), arable/ruderal indicators (*Artemisia*, *Centaurea cyanus*, *Chenopodiaceae*, *Fagopyrum*, *Papaver*, *Plantago major/media*, *Polygonum aviculare* and *Urticaceae*) and cultivated plants (*Cerealia*-type and *Secale*-type) (Behre, 1981, 1988).

Relative percentages were calculated using the Tilia software (Grimm, 1991) and are based on the total sum of pollen grains, excluding spores and peatland taxa, namely Cyperaceae, aquatic and mesohygrophilic taxa, as well as *Betula*, *Alnus*, *Salix* and *Frangula*. Pollen diagrams were constructed using Tilia software and local pollen assemblage areas were defined by the CONISS cluster analysis (Grimm, 1987).

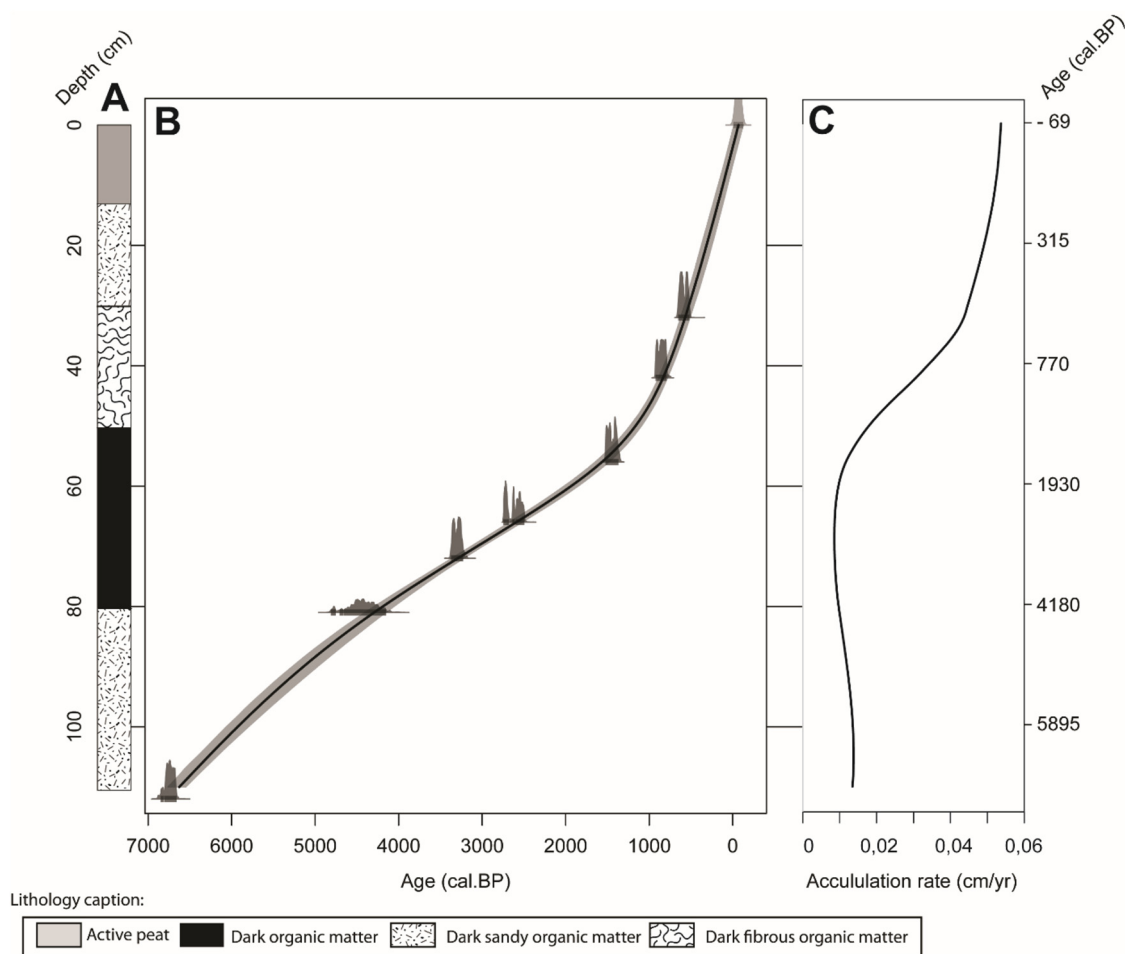


Fig. 2. Lithology of the Waldeck sequence (A), age-depth model (B) and accumulation rate evolution (C).

Table 1. Radiocarbon dates for the Waldeck core.

ID lab	Depth (cm)	Material	Age ^{14}C BP	Age cal. BP (2σ)	Age cal. BC/AD (2σ)
Poz-96853	32	<i>Carex</i> grains	570 ± 50	654 (594) 519	1297 (1356) 1431 AD
Beta-507031	42	Bulk sediment	940 ± 30	925 (853) 791	1025 (1098) 1160 AD
Poz-96854	56	Bulk sediment	1540 ± 30	1525 (1451) 1363	426 (499) 588 AD
Beta-507032	66	Bulk sediment	2530 ± 30	2746 (2618) 2492	797 (669) 543 BC
Beta-507033	72	Bulk sediment	3090 ± 30	3376 (3295) 3226	1427 (1346) 1277 BC
Poz-97970	81	Charcoals/grains	3970 ± 100	4710 (4433) 4149	2761 (2484) 2200 BC
Poz-105878	112	Charcoals	5920 ± 40	6806 (6741) 6658	4857 (4792) 4709 BC

In addition to pollen analysis, coprophilous fungi (*Cercophora*-type, *Sordaria*-type, *Podospora*-type, *Sporormiella*-type) were identified according to the classification devised by Van Geel and Cugny (Van Geel, 2001, Van Geel and Aptroot, 2006, Cugny *et al.*, 2010) and carbonized particles. All black, opaque and angular particles greater than $22\mu\text{m}$ are counted (Clark, 1984, Patterson *et al.*, 1987, Tinner and Hu, 2003, Finsinger and Tinner, 2005). The results of the counts of coprophilic fungus spores and carbonized particles are expressed in concentrations (number per gram of sediment).

The seeds collected in screen rejections after sieving ($200\mu\text{m}$) during pollen preparation were also identified (analysis: C. Schaal). Only the numbers of *Juncus articulatus/acutiflorus* seed remains are presented in the diagrams.

3.4 Physical and chemical characterization of sediments

Measurements were conducted for the main chemical elements at the EDYTEM laboratory (UMR 5204 CNRS, Université Savoie-Mont-Blanc) using the X-ray Fluorescence

(XRF) Avaatech Core Scanner. Measurements at 0.5 cm intervals were carried out at 10 and 30 kV voltage with a 750 mA beam current. In this study, we will only consider silicon (Si), titanium (Ti), lead (Pb) and zinc (Zn) results, as the remaining elements did not show any specific variations. The Si/Ti ratio was calculated to highlight the contribution of biogenic silica (Narancic *et al.*, 2016). The Pb/Ti and Zn/Ti ratios, which normalize lead and zinc inputs to the bog by titanium mainly from erosion, can reveal anthropogenic pollution (De Vleeschouwer *et al.*, 2010, Arnaud, 2014, von Scheffer *et al.*, 2019). The relative values of the different elements are given in counts per second (cps).

Loss on ignition (LOI) was also conducted at the same interval to estimate the organic matter content. Samples were dried overnight at 40 °C. After being crushed in an agate mortar, the samples were placed for four hours at 550 °C to degrade organic matter (Heiri *et al.*, 2001).

The presence of diatoms and quartz grains in sediments was observed and estimated under an optical microscope in the ashes from the LOI analyses but the diatoms were not identified (Figus, 2018).

3.5 Rarefaction analysis

Rarefaction analysis was conducted to estimate pollen-assemblage richness or the expected number of terrestrial pollen taxa (E(Tn)), which corresponds, for each sample, to the number of pollen types identified at a specific counting sum (Birks and Line, 1992). This estimation can be used as an approximation of past floristic richness or a reflection of the structure of the landscape, and allows us to assess their evolution over time (Birks and Line, 1992, Berglund *et al.*, 2008, Miras *et al.*, 2018). The taxa included in the analysis are those from the pollinic sum (*i.e.*, total number of pollen grains without spores and peatland vegetation taxa). The rarefaction analysis used a base pollen sum of 501 for the Waldeck sequence.

4 Results

The age-depth model of the sequence covers the last 6625 years cal. BP, indicating that the sequence concerns periods from Neolithic to modern times. Accumulation rates were calculated for each level using the 'clam' package (Fig. 2B). The bottom of the sequence presents an average accumulation rate of 0.12 mm.yr⁻¹. A slowdown in peat accumulation (0.09 mm.yr⁻¹) occurs at a depth of around 82 cm. Finally, at about 60 cm, the age model shows an increase in peat accumulation with a rate of 0.29 mm.yr⁻¹.

The pollen analysis results, counts of coprophilous fungus spores and carbonized particles, as well as XRF and loss on ignition analyses are presented in Figures 3 and 4. The rarefaction analysis is presented in Figure 5.

CONISS cluster analysis delimited six local pollen assemblage zones (LPAZ, WAL 1 to 6), with two of them subdivided (WAL 4a-4d, WAL 5a-b), according to pollen percentages variations. LPAZ are used to describe all results that are summarized in Table 2.

5 Interpretation and discussion

5.1 Regional and local vegetation history

5.1.1 Middle Holocene (up to 4200 cal. BP) (LPAZ WAL 1-2, Fig. 3)

The Waldeck record begins around 6625 cal. BP, during the mixed oak phase of the Holocene Climate Optimum (Dahl-Jensen *et al.*, 1998, Bradley and Bakke, 2019). In the area under consideration here, pine (*Pinus*) and hazelnut (*Corylus*) forests dominate (reaching 50 and 30% respectively) and this certainly explains why the mixed oak (*Quercus*) forest is reduced around the peat bog (WAL 1-2). The predominance of pine during the mixed oak phase is observed in all the sequences analysed in the Northern Vosges (Hatt, 1937, Gouriveau *et al.*, 2020). The omnipresence of pine, which is not observed in neighbouring regions, such as the Lorraine Plateau, the Central and Southern Vosges and the Black Forest (Janssen *et al.*, 1975, Ruffaldi, 1999, Rösch, 2000, De Klerk, 2014), is due to the competitiveness of this species compared to hardwoods, such as oak (*Quercus*) or beech (*Fagus*), on the very poor and dry Vosges sandstone soils (Guillet *et al.*, 1976, Sudhaus and Friedmann, 2015, Gouriveau *et al.*, 2020). Therefore, the presence of numerous sandstone landforms close to the peat bog (within 400 m) can explain the high percentages of pine (Fig. 1B).

During this period, from 4575 cal. BP onwards, beech gradually develops in the peat bog watershed (WAL 2). The development of beech is attested at the same time (4200–4500 cal. BP) in two other sites in the Pays de Bitche, where it spreads in the mixed oak forest and develops to the detriment of other hardwoods, mainly oak (Gouriveau *et al.*, 2020). Around Waldeck peat bog, beech grows mainly at the expense of pine, competing with it on richer soils and on northern slopes favourable to its development, at the end of the Holocene Climate Optimum and when temperatures decreased during the Neoglaciation (Dahl-Jensen *et al.*, 1998, Bradley and Bakke, 2019, Geirsdóttir *et al.*, 2019). Elm (*Ulmus*) and linden (*Tilia*) also become less frequent, in the same way as the monolete spores that were presumed to colonize the undergrowth of oak forests.

Locally, alder (*Alnus*) and birch (*Betula*) are present on the peat bog, probably constituting alder-birch forests where sphagnum moss and Cyperaceae constitute the herbaceous and mossy strata. Pine also appears to be present on or immediately close to the peat bog, as evidenced by a pine macro-charcoal found in the peat. From 5110 cal. BP onwards (Fig. 3, WAL 2), the mineral fraction in the sediment decreases slightly, concomitant with the increase in the number of jointleaf/sharp-flowered rush (*Juncus articulatus/acutiflorus*) remains. Both species are characteristic of wet, meso-oligotrophic, acidic environments rich in organic matter (Manneville *et al.*, 2006, Lauber *et al.*, 2018). Their development therefore indicates an increase in the water level and/or the creation of acidic conditions at the sampling point, and corroborates the accumulation of organic matter emphasized by LOI. This increase in the water level, contemporaneous with the development of beech, is consistent with the general decline in temperatures after ~5000 cal. BP, which seems to lead to a local increase in humidity (Bradley and Bakke, 2019).

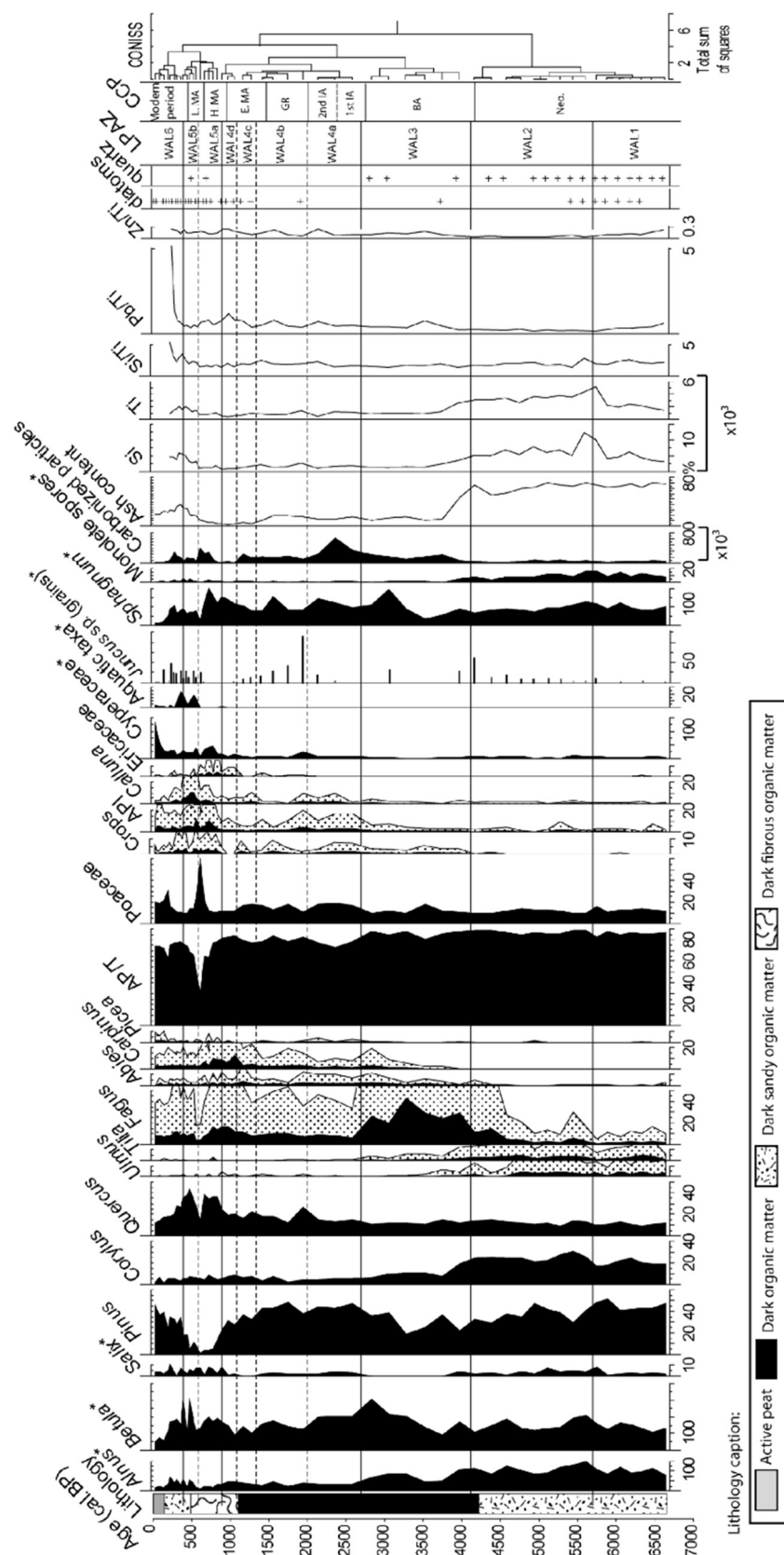


Fig. 3. Pollen diagram of the Waldeck sequence *versus* age (cal. BP). All taxa marked by * are expressed in number of pollen grains or number of remains for *Juncus*. API: anthropogenic pollen indicators; CCP: chrono-cultural periods; Neo.: Neolithic; BA: Bronze Age; 1st IA: first Iron Age (Hallstatt); 2nd IA: second Iron Age (La Tène); GR: Gallo-Roman period; E. MA: Early Middle Ages; H. MA: High Middle Ages; L. MA: Late Middle Ages. LPAZ: local pollen assemblage zones.

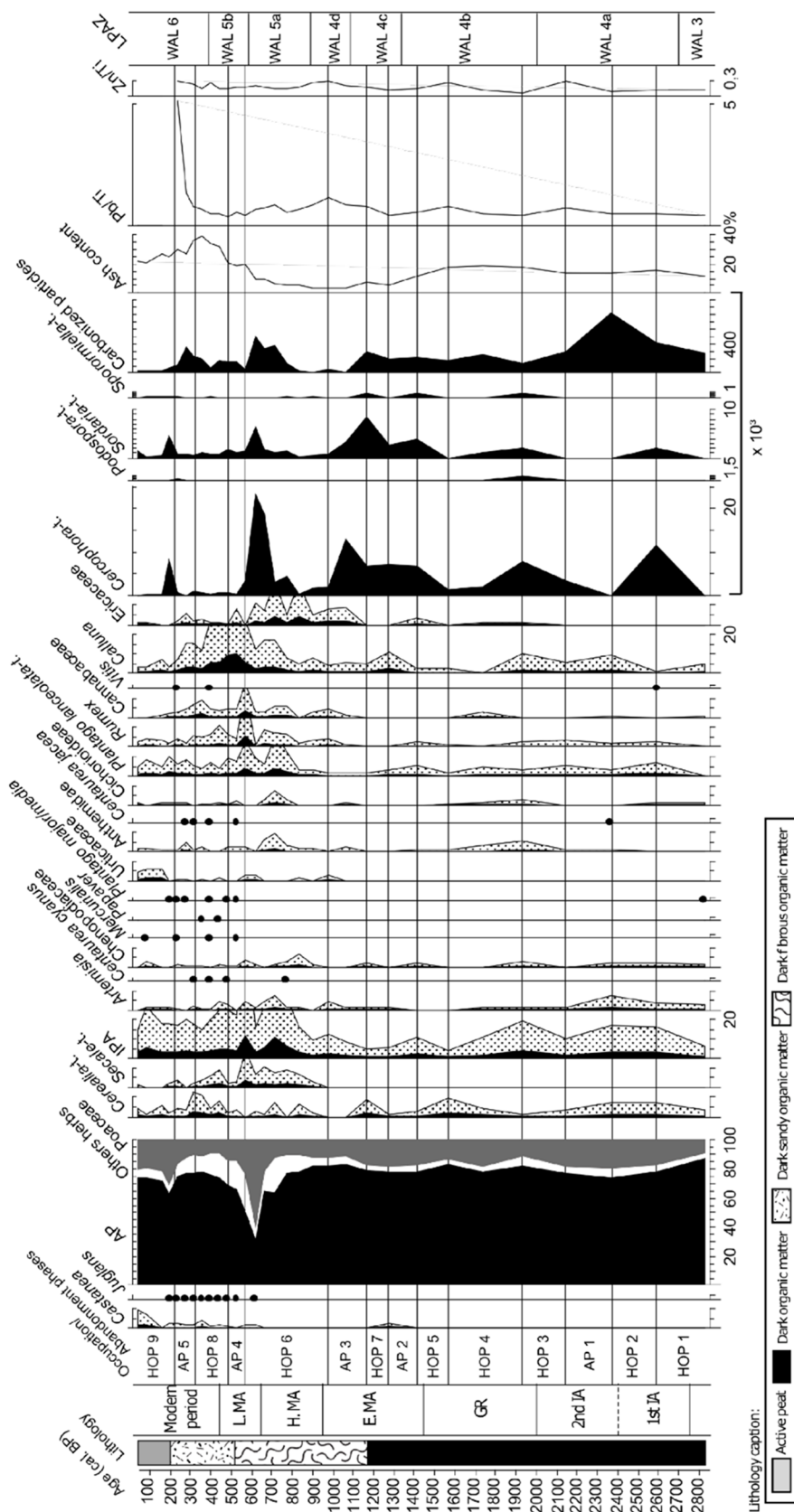


Fig. 4. Simplified pollen diagram of the last 2800 cal. BP. All taxa marked by * are expressed in number of spores per gram of sediment or number of carbonized particles per gram of sediment. 1st IA: first Iron Age (Hallstatt); 2nd IA: second Iron Age (La Tène); GR: Gallo-Roman period; E. MA: Early Middle Ages; H. MA: High Middle Ages; L. MA: Late Middle Ages; HOP: human occupation phase; AP: abandonment phase.

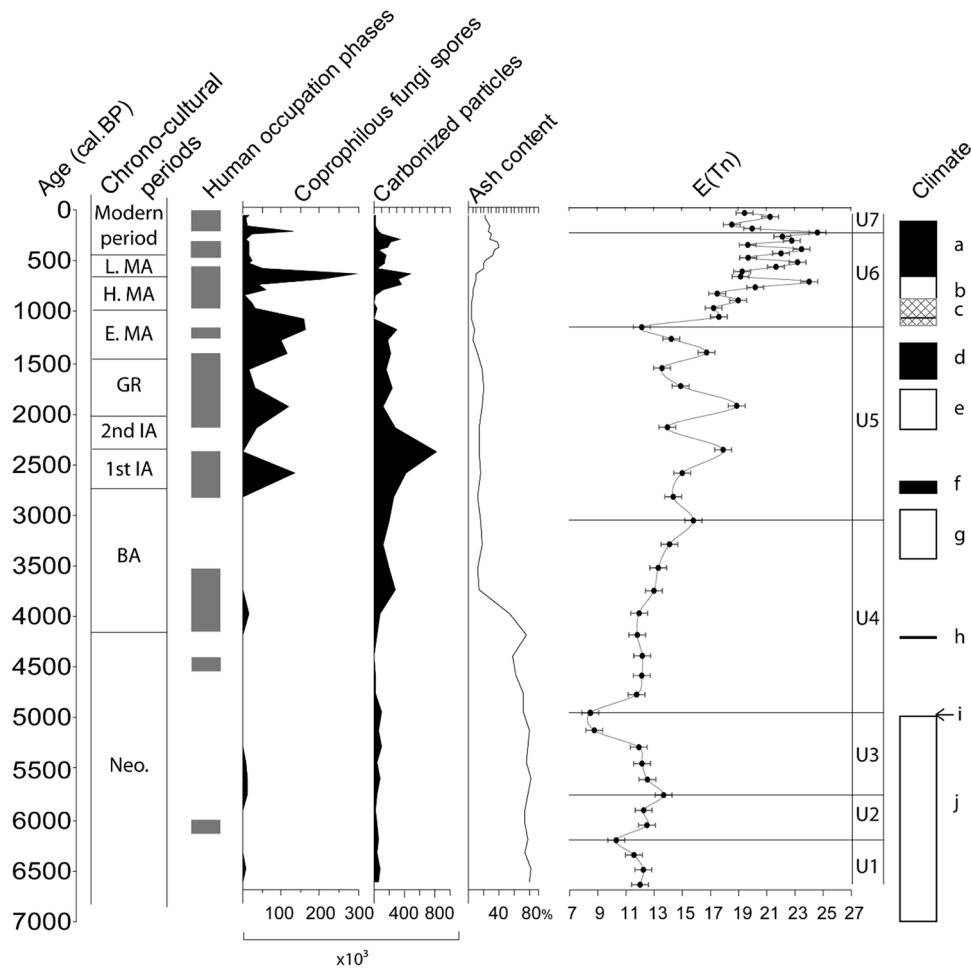


Fig. 5. Age-scaled diagram of chrono-cultural periods, human occupation phases, coprophilous fungus spores, carbonized particles, ash content, E(Tn) and main climatic variations (from [Dahl-Jensen et al., 1998](#); [Mann, 2002a, 2002b](#); [Le Roy Ladurie, 2009](#); [Beck, 2011](#); [Wang et al., 2012](#); [Bradley and Bakke 2019](#)). a: Medieval Little Ice Age, b: Medieval Warm Epoch; c: climate deterioration in Alsace and Lorraine; d: Roman Little Ice Age; e: Roman Warm Period; f: “Hallstatt disaster”; g: climatic optimum of Bronze Age; h: “4.2ka event”; i: onset of Neoglaciation; j: Holocene Climate Optimum.

5.1.2 Recent Holocene (from 4200 cal. BP to today) (LPAZ WAL3-6, [Fig. 3](#))

Beech continues to develop to the detriment of pine, now accompanied by fir (*Abies*) (WAL 3). Fir is very poorly represented due to the low mean altitude of the Northern Vosges (400 m) – at the limit of its natural area ([Rameau et al., 1989](#)) –, the absence of *Picea* west of the region – from where the prevailing wind blows –, and the (extra) local character of the pollen record. Forest vegetation certainly resembles the present-day acidiphilous beech(-oak) forests on the northern slopes of the basins of the Pays de Bitche, where the spontaneous species are beech, pine, oak, fir and birch ([Boeuf et al., 2014](#)). The hornbeam (*Carpinus*) also develops around 3745 cal. BP (WAL 3) and, as in the other sites analysed in the Pays de Bitche, its arrival is contemporaneous with the beginning of human occupations, which become evident from 4100 cal. BP onwards, with the appearance of crops pollen. The opening of dense forests then promotes the spread of the hornbeam ([Huntley et al., 1989](#), [Küster, 1997](#), [Gouriveau et al., 2020](#)).

From 3290 cal. BP onwards (WAL 3), the beech declines while pine percentages increase and reach their middle Holocene proportions, covering large areas once again. From 2590 cal. BP onwards (WAL 4a), oak grows at the expense of pine and beech and becomes more abundant than beech, probably forming acidiphilous oak forests. Today, oak forests are dominant in the basins of the Pays de Bitche ([Muller and Genot, 1991](#), [Boeuf et al., 2014](#)).

Around 4180 cal. BP (WAL 3), there appears to be a change in the functioning of the peat bog or of the watershed. The mineral fraction of the sediment decreases sharply (to 11% around 3520 cal. BP). This increase in organic matter marks the transition from a very sandy organic sediment to a highly decomposed organic sediment. From this event onwards, the vegetation of the peat bog changes with a transition from the Middle Holocene alder-birch forest to a birch forest. The diminution of alder suggests a shift to more acidic and/or oligotrophic conditions ([Bensettiti et al., 2002](#), [Manneville et al., 2006](#)). The origin of this change is not clearly identified but it is contemporaneous with the 4.2 ka cal. BP climate event.

Table 2. Main results of pollen, coprophilous fungus spores (CFS), carbonized particles (CP), ash content and XRF analyses for each local pollen assemblage zones (LPAZ). (AP: arboreal pollens; API: anthropogenic pollen indicators; +, ++, +++: qualitative presence; -: absence).

LPAZ Dates (cal.BP)	Chrono-cultural periods (cal. BP)	Main vegetation	AP	NAP, Spores	Crops	API	CFS	CP	Ash content and XRF
WAL6 400-45	Modern period	<i>Pinus</i> - (<i>Quercus</i> - <i>Fagus</i>)	- <i>Pinus</i> increase - 280 cal. BP : <i>Picea</i> increase	- Second maximum of Poaceae (values %) - 100 cal. BP: increase of Cyperaceae and Juncus, decrease of Sphagnum	++	+++	+	+	- Decrease of ash content after peak at 360 cal. BP - Strong increase of Pb/Ti
WAL5b 600-400	Late Middle Ages (650-450)	<i>Quercus</i>	- Increase of all trees - 480 cal. BP : <i>Quercus</i> maximal values (44%)	- Decrease of Poaceae - Maximum of <i>Calluna</i> and aquatic taxa - Decrease of Ericaceae	+++	+++	-	+	- Increase of ash content - Increase of Si, Ti - Increase of Si/Ti - Increase of Pb/Ti, Zn/Ti
WAL5a 900-600	High Middle Ages (950-650)		- 770 cal. BP : AP decrease - 620 cal. BP : brief fall of all trees - <i>Pinus</i> decrease	- Increase and maximum of Poaceae (values %) - Decrease of <i>Sphagnum</i>	+++	+++	+	++	- Increase of ash content - Increase of Si, Ti
WAL4d 1100-900	Early Middle Ages (1450-950)	<i>Pinus</i> - (<i>Quercus</i> - <i>Fagus</i>)	- Increase of <i>Carpinus</i> - 976 cal. BP : beginning of <i>Quercus</i> increase	- Increase of Ericaceae and Sphagnum	-	++	+	-	- Very low ash content - Small decrease of Si, Ti
WAL4c 1350-1100			- <i>Pinus</i> decrease - Increase of <i>Carpinus</i> and <i>Fagus</i>	- Increase of <i>Calluna</i> and Sphagnum - Decrease of Juncus	+	++	++	++	- Decrease of ash content - Small decrease of Si, Ti
WAL4b 2000-1350	Gallo-Roman period (2000-1450)	<i>Pinus</i> - (<i>Quercus</i> - <i>Fagus</i>)	- 1560 cal. BP : beginning of <i>Pinus</i> decrease - 1935 cal. BP : peak of <i>Quercus</i> (27%)	- Decrease of <i>Calluna</i> - Maximal values of Juncus	++	+++	+	++	- Low ash content - Elements more or less stable
WAL4a 2700-2000	Iron Age (2750-2000)		- Decrease of AP, particularly <i>Fagus</i>	- Increase of Poaceae - Increase of <i>Calluna</i>	++	+++	+	+++	- Low ash content - Elements more or less stable
WAL3 4100-2700	Bronze Age (4150-2750)	<i>Pinus</i> - <i>Fagus</i>	- 3290 cal. BP : peak of <i>Fagus</i> - 3745 cal. BP : decrease of <i>Corylus</i> and beginning of <i>Carpinus</i> - Decrease of <i>Ulmus</i> and <i>Tilia</i>	- Increase of <i>Calluna</i> - 3520 cal. BP : peak of Poaceae (18%)	+	+	-	++	- Decrease of ash content, Si and Ti at the beginning of zone - 3900 cal.BP: increase of Pb/Ti, Si/Ti
WAL2 5700-4100	Neolithic (4150-7450)	<i>Pinus</i> - <i>Corylus</i>	- 4580 cal. BP : increase of <i>Fagus</i> - Occurrences of <i>Abies</i> and <i>Picea</i>	- Rare occurrences of <i>Calluna</i> - Juncus increase - Increase of Monoletes	-	+	-	-	- Decrease of Si, Ti - 4180 cal. BP: peak of ash
WAL1 6620-5700			- Rare occurrences of <i>Picea</i> - Maximal values of <i>Pinus</i> , <i>Corylus</i> , <i>Tilia</i> and <i>Ulmus</i>	- Rare occurrences of <i>Calluna</i> and Juncus - Maximum values of Monoletes	-	+	-	-	- Increase of Si and Ti - 80% of ash content

Table 3. Synthesis of human occupation phases (HOP) and abandonment phases (AP) since the Iron Age; CFS: coprophilic fungus spores; CP: carbonized particles.

Phases	Dates (cal. BP)	Paleoecological evidence
	Chrono-cultural period	Main human activities
HOP9	235-44	Crops, <i>Artemisia</i> , Chenopodiaceae, <i>Plantago major/media</i> , Urticaceae, Anthemideae, Cichorioideae, <i>Plantago lanceolata</i> , <i>Rumex</i> , CFS
	Modern period	Agropastoral activities
AP5	360-235	Decrease in anthropogenic pressure
	Modern period	
HOP8	480-360	Crops, <i>Artemisia</i> , <i>Centaurea cyanus</i> , Chenopodiaceae, <i>Papaver</i> , <i>Plantago major/media</i> , <i>Centaurea jacea</i> , Anthemideae, Cichorioideae, <i>Plantago lanceolata</i> , <i>Rumex</i> , CFS
	Late Middle Ages/Modern period	Agropastoral activities
AP4	570-480	Decrease in anthropogenic pressure
	Late Middle Ages	
HOP7	950-570	Crops, <i>Artemisia</i> , Chenopodiaceae, Urticaceae, <i>Plantago lanceolata</i> , <i>Rumex</i> , <i>Calluna</i> , <i>Centaurea cyanus</i> , Anthemideae, Cichorioideae
	High Middle Ages, Late Middle Ages	Agropastoral activities
PA3	1160-950	Abandonment
	Early Middle Ages	
POH6	1280-1160	Crops, CFS, CP
	Early Middle Ages	Cultures of crops and livestock farming
PA2	1410-1280	Abandonment
	Early Middle Ages	
POH5	1565-1410	<i>Plantago lanceolata</i> , <i>Rumex</i> , CFS
	Gallo-Roman period/Early Middle Ages	Pastoral activities
POH4	1935-1565	Crops, CP
	Gallo-Roman period	Culture of crops
POH3	2150-1935	Anthemideae, Cichorioideae, <i>Rumex</i> , <i>Calluna</i> , CFS
	Iron Age/Gallo-Roman period	Pastoral activities
PA1	2350-2150	Abandonment
	Iron Age	
POH2	2600-2350	Crops, <i>Artemisia</i> , Chenopodiaceae, CP, <i>Calluna</i>
	Iron Age	Culture of crops
POH1	2800-2600	Crops, <i>Artemisia</i> , <i>Plantago lanceolata</i> , <i>Rumex</i> , CFS, CP
	Bronze Age/Iron Age	Agropastoral activities

The latter is part of the Neoglaciation recorded at different points of the Earth and leads to conditions that are either locally drier, or colder and/or wetter (Bradley and Bakke, 2019, Geirsdóttir *et al.*, 2019). Around 3500 cal. BP, sphagnum mosses become more abundant in the environment. However, it is difficult to interpret this development in the absence of a more precise identification of the species.

A new change in local vegetation takes place around 600 cal. BP (WAL 5b): sphagnum moss declines while aquatic plants, such as waterlilies (*Nymphaea*), pondweed (*Potamogeton*) or common bulrush (*Typha latifolia*) develop, indicating an increase in the water level and the formation of a pond. From this time onwards, biogenic silica (Si/Ti) also increases in peat, indicating the development of diatoms. Indeed, diatoms, observed in peat from 1350 cal. BP, become more frequent as the water level increases (Figus, 2018).

As with most ponds in the Northern Vosges, the date of creation of the Waldeck pond is unknown. A small dam was built downstream of the pre-existing peat bog to raise the water level and create a pond for fish farming. As the pond appears on the Naudin's map (1728–1739), but does not appear on previous maps, it is believed that its creation dates back to the eighteenth century. However, it is possible that the pond is older but was dried out at certain times, as was common practice for fish ponds, and therefore is not shown on older maps.

Finally, from 360 cal. BP (WAL 6), the water level seems to decrease and aquatic plants are gradually replaced by Cyperaceae, indicating the establishment of white beak-sedge (*Rhynchospora alba*) communities and the current sedge (*Carex*) and sphagnum lawns.

5.2 Human occupations and their consequences on the landscape

5.2.1 From the Neolithic to the Bronze Age: first traces of human occupation (Fig. 3, WAL 1–2–WAL 3)

The presence of the first Danubian Neolithic settlers is attested in Alsace-Lorraine around 5300–5500 cal. BC (*i.e.*, 7300–7500 cal. BP) (Blouet and Lansival, 1993, Schnitzler, 2006). However, in this area, archaeological evidence of human occupation for this period is extremely rare. Linearbandkeramik Culture populations were concentrated on loess areas in the Alsace Plain and on the Lorraine Plateau, rather than on the very poor soils of the sandstone Vosges (Whittle, 1985, Schmit, 2006). Pollen data confirm this sparse and short-lived human presence which generally did not generate any significant opening of the still very wooded landscape (AP > 85%).

Around the Waldeck site, the first significant paleoecological evidence of human presence dates back to the early Bronze Age (4100 cal. BP, WAL 3) with the first record of crops pollen in the sequence. The increase in carbonized particles and the presence of woody macro-charcoals in peat suggest that these crops are located on land opened by fire close to the peat bog.

From the Bronze Age (3965 cal. BP) onwards, atmospheric inputs of lead (Pb/Ti) and zinc (Zn/Ti) increase in the peat bog. These inputs may be regional pollution generated by the metallurgical activities, as several bronze objects – of unknown

origin – were discovered in the region (Schmit *et al.*, 2017). Although bronze is a copper-tin alloy, lead may be present in the ore as a residual impurity (von Scheffer *et al.*, 2019).

5.2.2 From the Iron Age to the High Middle Ages (Fig. 4, WAL 4a–4d)

5.2.2.1 Diversification of activities

After the transition from the Bronze Age to the Iron Age, between 2800 and 2600 cal. BP (WAL 3–4a), the landscape tends to open up (decrease of more than 10% in AP, increase in heather (*Calluna*), a heliophilic species). However, the forest prevails in the region until the end of the High Middle Ages (approx. 800 cal. BP), although this does not imply that the landscape remains unchanged. Indeed, the comparison of paleoecological data shows successive phases of local human impacts between 2800 and 800 cal. BP (Fig. 4, WAL 4a–4d and Tab. 3), suggesting a fragmented forest. These occupation phases are either dominated by pastoral activities (HOP3, HOP5, increase in coprophilic fungi and prairie species), or dominated by crops (HOP2, HOP4), or marked by both types of activities (HOP1, HOP6). In occupation phases HOP4 and HOP6, the increase in lead inputs in the peat bog can also attest to the development of mining activities, and suggests that ore extraction and/or metallurgy were carried out in the region. The first phase of mining (during HOP4) is consistent with Gallo-Roman archaeological discoveries in the Pays de Bitche (Achen, Walschbronn, Fig. 1A) and on the eastern slopes of the Northern Vosges massif (Reishchoffen, Fig. 1A) (Flotté *et al.*, 2000).

5.2.2.2 Abandonment phases

Three abandonment phases (AP1, AP2 and AP3, Fig. 4, Tab. 3) occur between these occupation phases, indicating that the Waldeck watershed was more or less permanently occupied. The first phase (AP1) was identified by a decrease in crops, APIs, carbonized particles and erosion indices, and marks the beginning of the second Iron Age, from 2350 to 2150 cal. BP. The second phase of decline, from 1410 to 1280 cal. BP (540–670 AD) (AP2), is probably the consequence of the Great Invasions, as well as a phase of climate deterioration characterized by a cooler and moister climate between 270 and 600 AD (1680–1350 cal. BP) (Kalis, 1985, Ruffaldi *et al.*, 2007, Le Roy Ladurie, 2009, Mäckel *et al.*, 2009). In the Vosges, the Black Forest and the Alsace Plain, as on the Lorraine Plateau, the Early Middle Ages was a period of anthropogenic decline (Rösch, 2007, Ruffaldi *et al.*, 2007, Mäckel *et al.*, 2009, Etienne *et al.*, 2013, Bégeot *et al.*, 2019). Finally, a further decline occurred between 1160 and 950 cal. BP (790–1000 AD) (AP3), during which all human activities seemed to cease: complete disappearance of crops, decrease in coprophilic fungus spores, very few carbonized particles, colonization of abandoned land by Ericaceae and further expansion of beech and hornbeam. From 900 to 1300 AD, the climate became milder throughout Europe, during the Medieval Climate Optimum (Mann, 2002, Le Roy Ladurie, 2009). Nevertheless, at that time, historical archives in Alsace and Lorraine indicate several extreme winters and floods (Beck, 2011). These meteorological events led to numerous crop failures, severe famines and epidemics (Beck, 2011). The

Waldeck site, located in a very narrow and peaty valley bottom, with poor soil, bordered by sandstone reliefs, may have experienced the same weather events. These would have been unsuitable for crop cultivation and living conditions and would have pushed the inhabitants of the region to migrate to more favourable areas. In phases AP1 and AP3, the increase in Pb and Zn inputs in the peat bog suggests that, while the Waldeck region was abandoned, ore extraction and/or metallurgy increased elsewhere in the region. The presence of mining activities during the AP1 phase, the Iron Age, is coherent with the hypothesis of iron ore extraction in the Mouterhouse forests (6 km SW of Waldeck, Fig. 1A) at that time (Schmit *et al.*, 2017).

5.2.3 End of High Middle Ages and Late Middle Ages (Fig. 4, WAL 5a-5b)

5.2.3.1 Intensification of activities

The first wave of monasteries and abbeys on the edges of the Vosges massif (seventh-ninth centuries, *e.g.*, Marmoutier, Graufthal, Neuwiller-lès-Saverne, Fig. 1A) did not reach the heart of the Northern Vosges massif. However, the second wave, during the eleventh-twelfth centuries, is observed in the core of the forests. The eleventh century is known as a period of increased anthropogenic pressure and population growth everywhere in the surrounding regions (Etienne *et al.*, 2013, Ruffaldi *et al.*, 2015, Mariet *et al.*, 2016, Bégeot *et al.*, 2019). In the Pays de Bitche, Sturzelbronn Abbey (6 km northeast of our study site, Fig. 1A) was founded in 1135 AD and occupied by Cistercian monks (Beierlein *et al.*, n.d.). Around Waldeck peat bog, human activities reappear and intensify from 800 cal. BP (1150 AD) (HOP7), indicating that the climate became milder and marking the onset of the Medieval Climate Optimum in the region. The landscape began to open up significantly, mainly affecting beech and pine (Fig. 3). On the other hand, oak increased until it reached a first maximum (39%), and was probably kept to provide acorns for livestock (*i.e.*, pannage), as observed on the Lorraine Plateau and in the Vosges Mountains (Lemée, 1955, Behre, 1988, Ruffaldi *et al.*, 2007, Sudhaus and Friedmann, 2015). Cultivated crops became more diversified with the appearance of rye (*Secale-t.*), a hardy species that adapts well to poor soils. The opening of the landscape exposes the soil to erosion and farm work leads to an increase in erosion processes. Hay meadows with Anthemideae, Cichorioideae, *Plantago lanceolata* (narrowleaf plantain) and *Rumex* develop while coprophilous fungus spores prove the presence of livestock on the bog. It would therefore seem that a hamlet was established near the Waldeck bog during the High Middle Ages.

5.2.3.2 Building of Waldeck Castle

Around the Waldeck peat bog, the opening of the landscape accelerates from 770 cal. BP onwards (1180 AD, HOP 7), undoubtedly related to the construction of Waldeck Castle which overlooks the peat bog and was first mentioned in 1227 AD, under the name of *Waldeske* (Rudrauf, 2008, Mengus, 2009). Around 1227 AD (720 cal. BP), pollen indices show significant human activities around the castle, with APIs and crops reaching a first maximum (11 and 3% respectively),

which may be due to agricultural farmyard-related activities, which extended below the tower, on its east side, *i.e.*, opposite the peat bog (Mengus, 2009). The maximum opening of the forest occurs around 620 cal. BP (AP at 31%), with a drastic and unprecedented decrease in pine (1.4%), followed by the second maximum of APIs and crops (12% and 3.5% respectively).

This period of agropastoral expansion and intensified land use activities was of short duration and is limited to the construction of Waldeck Castle and related activities.

5.2.3.3 Decrease in anthropogenic pressure during the fourteenth-fifteenth centuries

From 570 cal. BP (1380 cal. AD), the forest colonizes the environment again and anthropic pressure decreases giving rise to a new phase of abandonment (AP4). On the Lorraine Plateau, and generally throughout France but also in Germany, the fourteenth century is seen as a phase of decline in human activities (Rösch, 1992). At that time, the Hundred Years' War broke out and the black plague epidemic spread throughout the West, leading to the desertion of many villages. In Lorraine, this was most prevalent between 1411 and 1439 AD. In Waldeck, a decrease in agropastoral activities (especially agriculture) can be observed between 1380 AD (570 cal. BP) and 1470 AD (480 cal. BP) (AP4), along with a return of the forest, which almost attains its original percentages. This decrease in anthropogenic pressure could also be related to the onset of the Little Ice Age, which began in Europe around 1300 cal. AD and may have been felt in the peaty valley bottoms of the Pays de Bitche (Le Roy Ladurie, 2009).

After 480 cal. BP (HOP8), the forest continues to flourish around Waldeck Castle, agriculture develops again and cattle are still present. Then, erosion phenomena intensify in the watershed, resulting in increased mineral fraction inputs in the sediment. The increase in Pb inputs can indicate the development of ore mining and metalworking activities, consistent with the rise in metallurgical activities during the sixteenth century at the instigation of the Duke of Lorraine (Jacops *et al.*, 1990; Jehin, 2005).

5.2.4 The Modern Period: wars, renewal and then decline (Fig. 4, WAL 6)

The seventeenth century is marked by unrest in the form of the Thirty Years' War between 1618 and 1648 AD, and an attack on the Bitche region by the Swedes around 1632 AD (Jehin, 2005). Thus, around 360 cal. BP (1590 AD) (AP5), agropastoral activities decline around Waldeck Castle, which is described as ruined in 1594 AD and dismantled by French troops in 1635 AD. Erosion indices also decrease, indicating stabilizing soils in the peat bog watershed. After the Peace of Ryswick, in 1697 AD, Duke Leopold promulgated edicts and ordinances, promoting the repopulation of the Duchy of Lorraine through immigration, as well as land clearing (Jehin, 2005). This period of demographic growth affected the Pays de Bitche from 1720-1730 AD, and Waldeck became a village in the eighteenth century. In 1754 AD, forest inspectors note that, on the edge of the pond at the foot of the remains of Waldeck Castle, a "considerable clearing" had been already cleared

(Jehin, 2005). At that time, many activities developed along the Falkensteinerbach stream (sawmills, forges (Fig. 1A), paper mills, mills) (Jacops *et al.*, 1990). Waldeck Forest was exploited for industrial and building activities, such as for example, transporting pines from the forest to Holland for shipbuilding (Jehin, 2006). Around the Waldeck peat bog, from 235 cal. BP (1715 AD) (HOP9), agriculture seems to have developed, but not to the same extent as crop percentages during the HOP8 occupancy phase. Crops reached 1.6%, then APIs and coprophilous fungus spores increased, but activities were still limited compared to previous times. A rapid retreat of the forest also occurred from 235 cal. BP, when Poaceae developed. The forest then reached a second minimum (63%) around 200 cal. BP (1750 AD), illustrating the impact of pre-industrial fuel-powered activities (forges, glass factories).

The rest of the Modern Period is characterized by a constant but reduced human presence compared to previous phases of occupation, with a low impact on the environment. Crop cultivation seems to be limited around the Waldeck peat bog, while the presence of livestock is still documented (*Sporormiella*, *Sordaria*, *Cercophora*, *Plantago lanceolata*, *Urticaceae*). Soil erosion continued to decrease around the peat bog. Around 160 cal. BP (1790 AD), the environment closed again with the spread of pine and the development of spruce (*Picea*), two widely planted species in the Northern Vosges during the nineteenth century.

5.3 The impact of human activities on past plant diversity

The evolution of estimated pollen richness $E(Tn)$ can be divided into several units (Fig. 5) (Berglund *et al.*, 2008, Miras *et al.*, 2015). In general, the rarefaction analysis shows, in the light of the multidisciplinary study, that the impact of human activities increases floristic diversity around the peat bog. As a result, the average $E(Tn)$ is 12% at the base of the sequence (U1) and 22% at the top (U7).

The first increase in floristic richness dates back to the Neolithic period (U2), when the first significant opening of the forest environment coincides with the appearance of the first crop pollen grains and an increase in APIs. Neolithic impacts on the landscape remain very limited, but they nonetheless generate a change in vegetation with new open herbaceous areas, leading to the establishment of a more heterogeneous landscape. Thus, around the Waldeck site, a weak anthropisation of the environment leads to a tenuous diversification of vegetation cover. From the end of the Neolithic period to the Early Middle Ages (U4 and U5), the alternation of more intense phases of human occupation gives rise to a growing, progressive and oscillatory trend in plant diversity, which is clearly visible in the U5 zone. During this unit, three phases of increase in floristic richness correspond exactly to phases of agropastoral development, and in particular to opening phases; the development of *Calluna*, an increase in APIs and the presence of coprophilic spores. U6 is characterized by remarkable increases in $E(Tn)$ which correspond to the construction of Waldeck Castle and the settlement of populations around it. These events thus generated unprecedented floral diversity (25), with the highest estimated floral richness of the sequence. However, the $E(Tn)$ curve oscillates, suggesting that the successive phases of occupation

and abandonment (Tab. 3) impacted floristic richness around the peat bog.

However, some units show that variations in $E(Tn)$ do not only seem to be related to anthropogenic impacts but also to the history of regional vegetation. In this sense, unit U4 shows that the floral diversification confirmed by the rarefaction analysis corresponds not only to intensified anthropogenic pressure, as mentioned above, but also to many changes in forest composition, such as the replacement of diversified oak forests by beech wood, with fir and the appearance of hornbeam. Similarly, the loss of floral richness in unit U3 corresponds to the return of the forest and in particular, the marked development of hazelnut (30%) and pine (48%). According to Berglund *et al.* (2008), a decrease in pollen richness during the Neolithic period could be due to a low, but nonetheless sufficient anthropogenic impact to generate an increase in pollen production from trees, leading to an under-representation of herbaceous plants. In addition, the dominance of a taxon, especially a tree taxon (here pine and hazelnut), also tends to reduce pollen richness (Berglund *et al.*, 2008). Unit U7 also shows a decrease in plant diversity due to the low anthropogenic impact around Waldeck Castle in recent times, as well as to the reconquest of forests and pine and spruce plantations in the nineteenth century in the Pays de Bitche.

6 Conclusion

The palaeoecological study of the Waldeck site broadens our knowledge of the evolution of landscapes in these mid-mountain areas of the Northern Vosges. It reveals the first very tenuous traces of human presence in these densely forested landscapes during the Neolithic period, which then increased in the Bronze Age and then again in the High Middle Ages. Human land use over the past seven millennia is characteristic of these regions with acidic soils which are not suitable for the development of widespread agriculture. Periods such as the Upper Neolithic, the Gallo-Roman or the last two centuries had little impact on the landscape and the forest dominated throughout the sequence. Phases of clearly visible human activity are linked to the construction of Waldeck Castle during the High Middle Ages. Even during phases of strong population growth and the establishment of metallurgy and glassmaking activities in the seventeenth and eighteenth centuries, the site was mainly exploited for its dense oak and pine forests.

The study also shows the re-conquest of the forest in the watershed between each occupation phase. Each period of decline in human activities effectively shows the return of the forest with almost identical percentages to those of previous periods. The only exception is the Middle Ages when the total return of forest cover was no longer possible after the significant opening of the environment as a result of human activities linked to the castle. The recent increase in percentages of tree pollen is attributed to eighteenth century plantations. Consequently, the forest has lost some of its resilience to human disturbance over time.

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