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Exploring the past through lynchets landscapes in the Vosges Mountains and the Lorraine Plateau (France)

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Abstract

Lynchets are ridges formed by erosion and sediment accumulation downstream of agricultural plots and offer valuable insights into past agricultural activity. These microtopographies cover vast areas and serve as indicators of historical changes in land use. As a result, their ubiquity across Europe makes them particularly interesting. In this study, we propose a geoarchaeological approach to analyze six lynchets, four in the Vosges Mountains and two on the Lorraine Plateau (France). The lynchets can be considered soil archives with no stratigraphic organization or chronological sequence from bottom to top, making it difficult to determine the age of the lynchets and identify changes in land use over time. To this end, we propose the analysis of historical and geo-historical archives combined with the “pedosedimentary” archives of lynchets through charcoal identification and dating combined with near-infrared spectroscopy to determine the age, vegetation, and past land use changes associated with lynchets landscapes. By combining these multiple data sources, we are better able to show the chronological development of these ancient agricultural systems and uncover valuable information on landscape history. Charcoal dating suggests a higher frequency of fires from the Middle Ages. The dating aligns with the regional dynamics of anthropogenic fires, indicating a potential use of fire for cultural purposes. We also demonstrate the difficulty of extrapolating the dating of a lynchets to the entire lynchets system. Our results highlight the difficulties of interpreting the formation and dating of lynchets and the lynchets system on the sole basis of charcoal analysis. However, we highlight the value of applying pedoanthracology to lynchets to determine the dynamics of land use change in former fields.

KEYWORDS

charcoal, clearing forest, former field systems, geohistorical data, lynchets, NIRS landscape history

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1 | INTRODUCTION

The emergence of agriculture is key in the anthropization of European landscapes, particularly through land clearing (Williams, 2000). Determining the periods of cultivation and abandonment of field systems is essential in understanding anthropogenic landscapes (Brown et al., 2021). For several decades, the use of light detection and ranging (LiDAR) has made it possible to detect and map ancient field systems, especially under forest cover, more efficiently and on a larger scale (Georges-Leroy et al., 2009; Landois et al., 2019; Schwartz et al., 2020; Sittler et al., 2007, 2015). Reconstructing the history of land use and thus determining the ecological legacy associated with these land uses are essential benchmarks for more effective current environmental governance (Ellis, 2021).

In the Vosges mountain range, among the detected and mapped former field systems, lynchets represent a significant area (Keller et al., 2023). Lynchets are microtopographies that result from erosion and sediment accumulation downstream of an agricultural parcel, creating a ridge (Figure 1a). The soil bank or ridge results from aggradation of the soil profile by sediment accumulation at the bottom of a cultivated plot. Tillage erosion and runoff erosion are the two processes responsible for sediment transfer downslope (Nyssen et al., 2010). Lynchet systems can be dense, with the ridges almost parallel to each other and perpendicular to the direction of the slope (Figure 1c). These microrelief features are evidence of present or past agricultural use. They can form a dense spatial system, with numerous lynchets spaced from 10 to 50 m apart, and sometimes more, that can cover large areas exceeding hundreds of hectares (Keller et al., 2023). Each ridge or soil bank represents the boundary of a former crop field; hence, a crop field is bounded by two ridges. A lynchet results from a slow "pedosedimentary" accumulation, unlike an agricultural terrace, which is the result of excavating the soil from upstream to downstream (Figure 1b). A lynchet is the result of soil aggradation, which is partly dependent on the duration of plowing and, therefore, on the time spent in cultivation (Figure 1a). This sedimentary accumulation over several centuries or sometimes several millennia can be considered a pedosedimentary archive, allowing the trace of temporal trajectories of land use and landscape. From a soil science point of view, it can be described as cumulic soil; from a geomorphological point of view, it can be described as a colluvial deposit.

The morphology of lynchets has been wrongly attributed to a geological origin (Bracq & Delay, 1997; Evrard, 1951; Gosselet, 1906; Lasne, 1892). For Curwen (1939), this form is anthropogenic and the result of plowing. The discovery of traces of plowing at the base of the lynchet (Nyssen et al., 2000; Wood, 1961) and the opening of numerous pits and soil trenches confirm the anthropogenic origin (Bernard-Allée & Valadas, 1992; Ford et al., 1988; Froehlicher et al., 2016; Nielsen & Dalsgaard, 2017; Nyssen et al., 2014; Schwartz et al., 2020; Sillar et al., 2008). According to Wood (1961), the term lynchet comes from the Anglo-Saxon word *hlink*, often used to designate a natural shape such as a ridge or bank and sometimes that of a boundary marker. Lynchets are ubiquitous in northern European landscapes such as Germany (Larsen et al., 2016; Stolz et al., 2012),

England (Brown, 2009; Brown et al., 2020; Ford et al., 1988; Sillar et al., 2008; Vervust et al., 2020), France (Bernard-Allée & Valadas, 1992; Chartin et al., 2011; Froehlicher et al., 2016; Georges-Leroy, 2020; Georges-Leroy et al., 2009; Schwartz et al., 2020; Walter et al., 2003), Belgium (Nyssen et al., 2014), Denmark (Nielsen, 1984; Nielsen & Dalsgaard, 2017), the Czech Republic (Houfková et al., 2015; Zádorová et al., 2018), or Poland (Sobala, 2021). Lynchets are a footprint of past activities, which determine a new temporal reference to reconstruct landscape changes over long time scales (Keller et al., 2023). In France, despite the vast reparation ("grand remembrement") in the 1950s, lynchets are often preserved in areas of limited extensive agriculture.

Numerous relative dating techniques have been used to estimate the age of these microreliefs, such as annual estimates of pedosedimentary accumulation (Nyssen et al., 2014), the presence of artifacts and archaeological features (Brown, 2009; Ford et al., 1988; Georges-Leroy, 2020; Georges-Leroy et al., 2009), optically stimulated luminescence (OSL) (Froehlicher et al., 2016; Vervust et al., 2020), and carbon-14 (¹⁴C) dating of charcoal (Bernard-Allée & Valadas, 1992) combined with OSL (Larsen et al., 2016; Stolz et al., 2012). Nevertheless, few studies have performed tree species identification of charcoal collected from the pedosedimentary accumulation (Schwartz et al., 2020). Charcoal study not only allows for the estimation of lynchet age but also for the determination of land use trajectories and the identification of paleo-vegetation. The forest composition and temperate climate in northeast France do not favor natural fires (Krivtsov et al., 2009; Robin & Nelle, 2014). Therefore, the presence of charcoal in soils is a good indicator of the anthropization of an environment. Additionally, soil organic matter from the pedosedimentary accumulation analyzed by near-infrared spectroscopy (Ertlen et al., 2010) can provide information about past vegetation. Instead of producing an event archive like charcoal, it gives a more continuous image of past vegetation and is complementary to anthracology.

The purpose of this study is twofold. The first objective is to date the lynchets and lynchet agricultural systems. Although a number of lynchets, mostly in northern Europe, date to the Bronze Age (1800–800 years B.C.) or Iron Age (800–25 years B.C.) (Froehlicher et al., 2016; Nielsen & Dalsgaard, 2017; Sillar et al., 2008; Vervust et al., 2020) and the Gallo-Roman period (Ford et al., 1988; Nyssen et al., 2014; Ruffaldi et al., 2007), most landforms date to the Middle Ages (Bernard-Allée & Valadas, 1992; Brown, 2009; Froehlicher et al., 2016; Houfková et al., 2015; Larsen et al., 2016; Nyssen et al., 2014; Schwartz et al., 2020; Vervust et al., 2020). Additionally, many iconographic works from the 15th to 17th centuries, such as illuminations or engravings (Schwartz et al., 2019), depict lynchets, often materialized as hedges. By obtaining chronological data at a regional scale, we can better understand the chronology of these ancient agricultural systems. The second objective is to identify land use changes. By combining the identification of fire-clearing periods and tree species with soil, geohistorical, palynological, archaeological, and historical data from sites, it is possible to define the temporal trajectories of these landscapes.

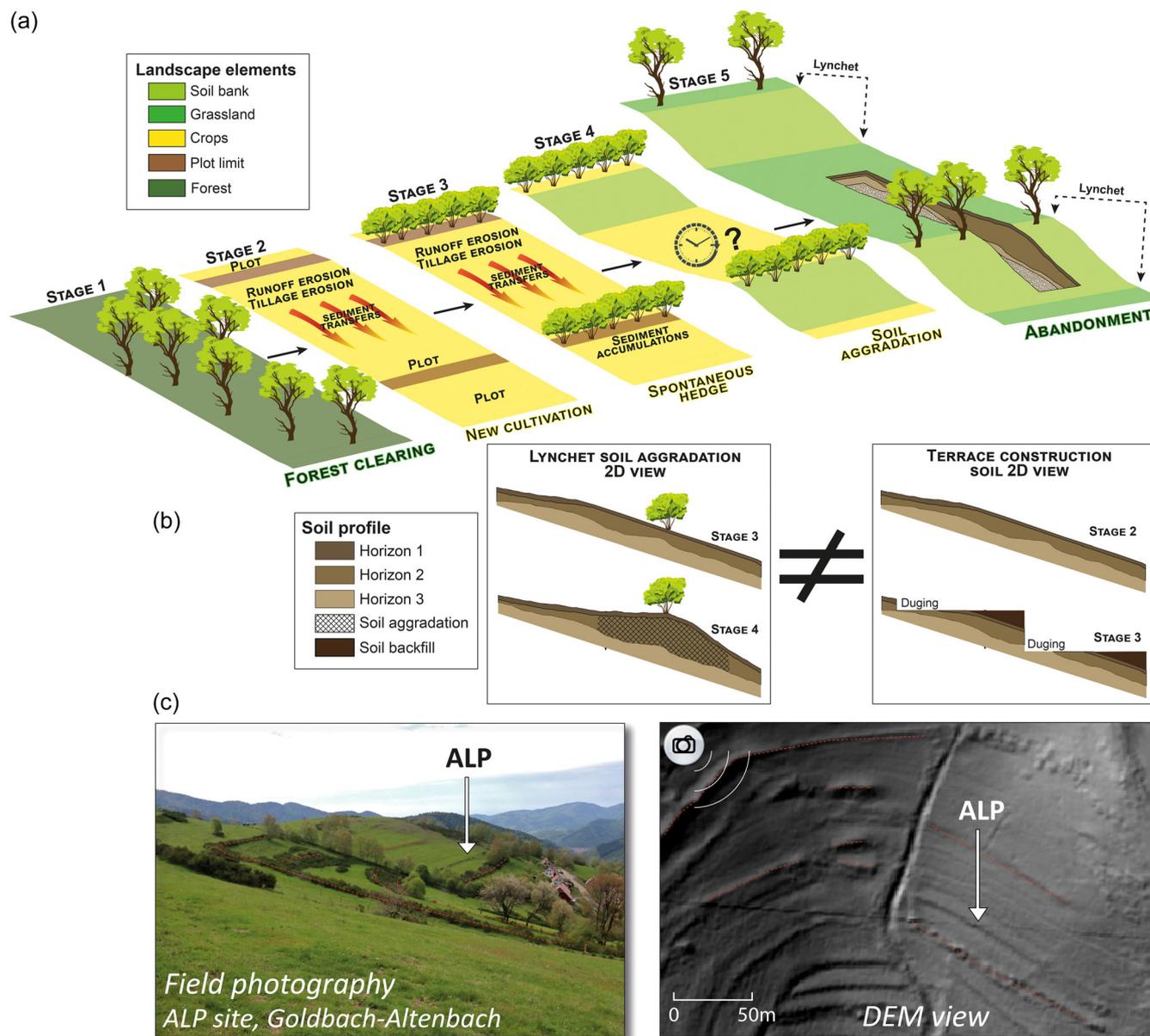


FIGURE 1 Description and identification of a lynchet. (a) Theoretical stages of lynchet formation a. Stage 1: Clearing of the forest (this stage can be repeated between Stages 3 and 5. Stage 2: Crop cultivation on small fields and beginning of erosion process transfers. Stage 3: Establishment of a hedge and accumulation of sediments upstream of it, beginning of soil aggradation. Stage 4: Soil aggradation depending on several factors (intensity of rainfall, time spent in cultivation, slope, intensity of tillage, edaphic characteristics, etc.). Stage 5: Abandonment of the lynchet system and conversion to forest or conversion to grassland. (b) Morphostratigraphic differences between a lynchet and an agricultural terrace; the terrace is the result of voluntary overburdening upstream and deposition of fill downstream visible in the soil profile. (c) Lynchet system in the Vosges mountain range Goldbach-Altenbach study site (ALP).

2 | STUDY AREA

2.1 | The Vosges Mountains and the Lorraine Plateau

The sites are in or near the Vosges Mountains, a low mountain range oriented from north to south located in northeast France. Its absolute elevations range from ~200 to 1424 m a.s.l. (Figure 2). Climate accordingly evolves from oceanic to almost

semicontinental, reflected by a very strong W-E rainfall gradient between the Lorraine Plateau (800 mm/year in Sarreguemines), the Vosges (the south >2300 mm/year; the north a maximum of 1600 mm/year), and the Rhine Graben (550 mm/year in Colmar and 665 mm/year in Strasbourg) located directly to the east. In the Vosges, at 1200 m, winters are cold and summers are mild, with 4–5°C annually on average, while in the Lorraine Plateau, average temperatures are around 9–10°C (Wahl, 2007). The Saales (SAA), Goutte au Rupt (GAR), ALP, and GOLF sites are located in the

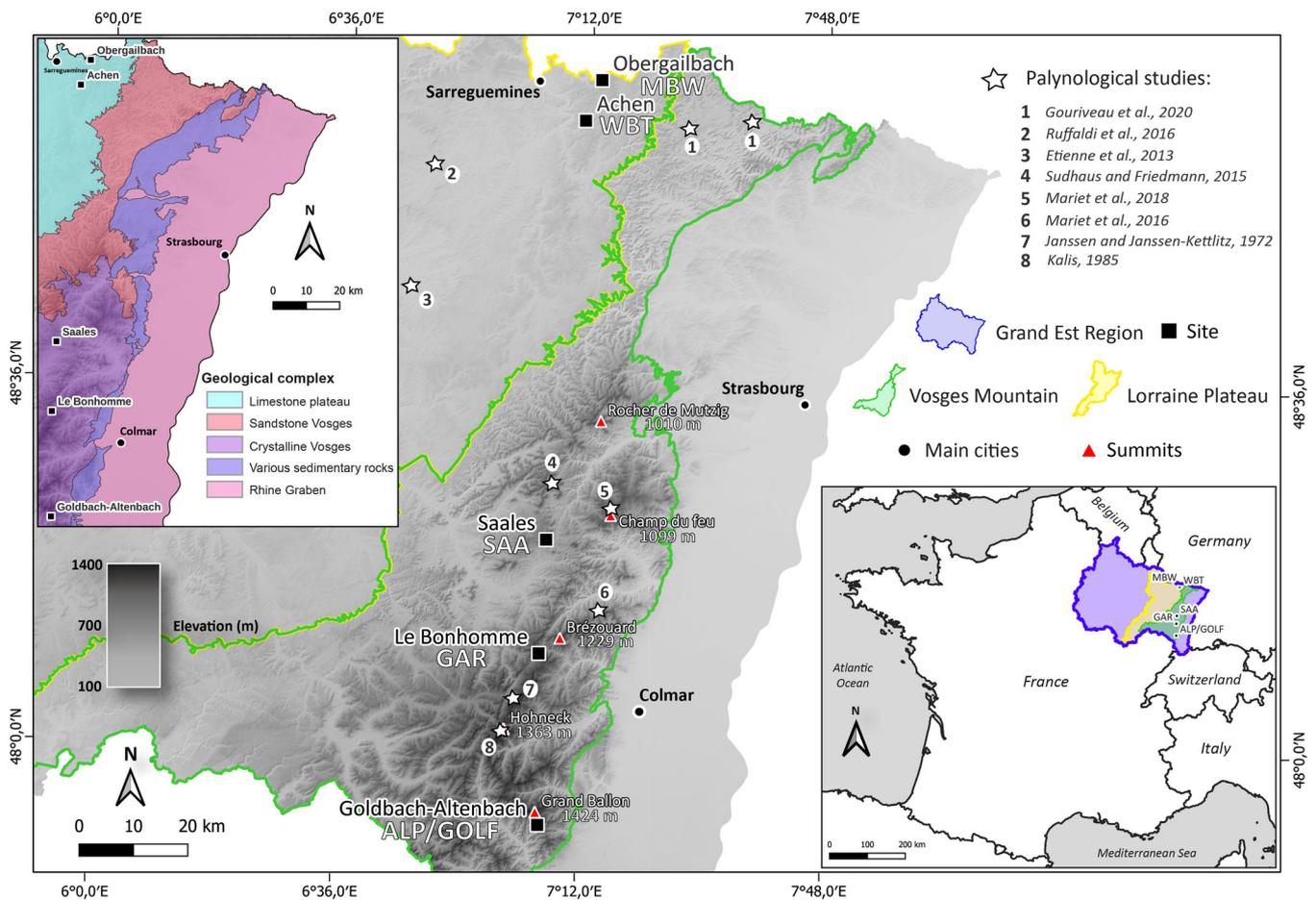


FIGURE 2 Location of study sites carried in or near the Vosges mountain range. Location of the Grand Est administrative region, the Vosges mountain range, and the Lorraine Plateau (bottom right of the image). Location of the geological outcrop (top left of the image).

Vosges, specifically the Crystalline Vosges. The Crystalline Vosges are dominated by granitic and metamorphic formations due to the uplift and erosion of sedimentary formations since the Mio-Pliocene, exposing the Hercynian basement, whose Quaternary glaciations contributed to the shaping of the relief. The Mittelbruckerwald (MBW) and Weidesheimer Berg (WBT) sites are in the direct vicinity of the Vosges in the Lorraine Plateau (Figure 2). The Lorraine Plateau, dominated by limestone formations, is a set of cuestas whose dip follows that of the sedimentary layers toward the east.

2.2 | MBW and WBT (Lorraine Plateau)

MBW lynchet, located in the municipality of Obergaillbach (57), is situated on a northern 9% gentle slope with an altitude of 352 m (Figure 3a). The site is currently located under a sparse forest. Land use is mostly dominated by grassland and crops. In the site vicinity, some lynchets are still preserved and often topped by hedges (enclosure). The vast reparation operation of the mid-20th century (Flatrès & Flatrès, 1997) may have erased a large part of the lynchet system.

WBT lynchet, located in the commune of Achen (57), is situated on a northeastern slope of 15% and an altitude of 283 m (Figure 3b). The site is currently on a grassland with a tree hedge (~15 m high) above the lynchets. Within a few years, the height of the trees could redefine the land use as a sparse forest with a significant herbaceous layer. The majority of lynchets are under grassland, while some are under forest. The lynchet network is dense and presents important homogeneity plots with ~20 m of space between each. Presumably, the vast reparation operation has removed a large majority of the lynchets present on this slope and in the village. A stone wall resulting from the removal of field stones is located a few meters from WBT. Near the site, land use is dominated by grasslands, with a much smaller forest on top of the slope and a few fields.

2.3 | SAA, GAR, ALP, and GOLF (the Vosges Mountains)

SAA lynchet, located in Saâles municipality (67), is situated on a southeastern slope of 12% and a moderate altitude of 582 m (Figure 3c). The site is currently on a grassland in the vicinity of a forest. A number of lynchet networks are well preserved and have

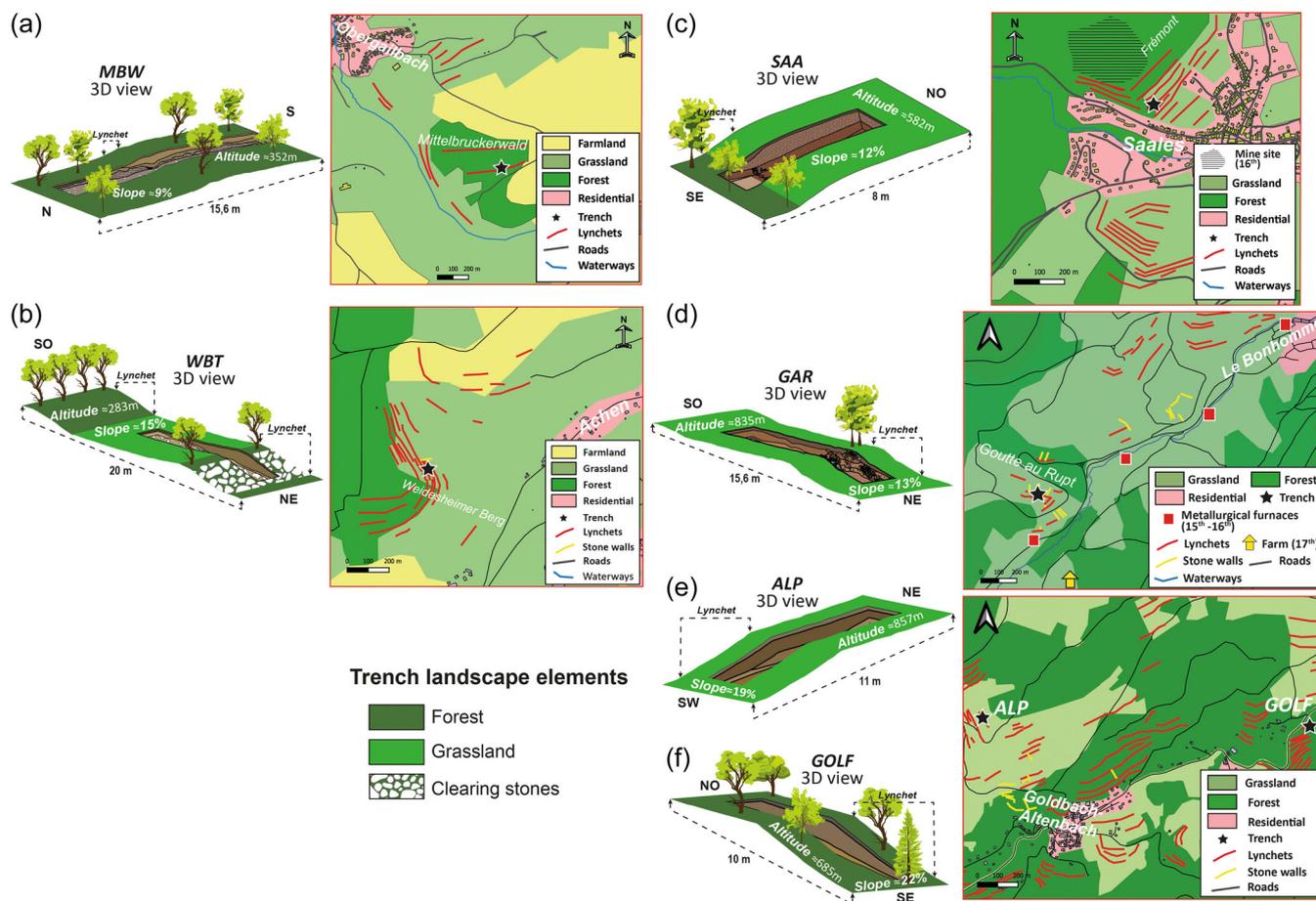


FIGURE 3 Land use map of the MBW (a), WBT (b), SAA (c), GAR (d), ALP (e), and GOLF (f) sites with the lynchets system (red line), some of which are associated with stone walls (yellow line). Location of the trench (black star) in the MBW lynchets in Obergailbach municipality (a); location of the trench (black star) in the WBT lynchets in Achen municipality (b); location of the trench (black star) in the SAA lynchets in Saales municipality with an archaeological site (c); location of the trench (black star) made in the GAR lynchets in Le Bonhomme commune with archaeological sites (d); and location of the trench (black star) made in the ALP and GOLF lynchets in the Goldbach-Altenbach commune (e, f). GAR, Goutte au Rupt; MBW, Mittelbruckerwald; SAA, Saales; WBT, Weidesheimer Berg.

been identified with important homogeneity plots. In the site vicinity, land use is dominated by grassland and forest. Archaeologically, the commune has numerous mining sites, including a 16th-century mining site located upstream from the site at ~150 m.

GAR lynchets, located in Le Bonhomme commune (68), is situated on a northeastern slope with an average of 13% and a high altitude of 835 m (Figure 3d). The site is currently on a grassland in the vicinity of a forest. In the GAR site vicinity, the identified lynchets network is moderate, with the presence of numerous stone walls perpendicular to the site. In addition, numerous stone walls and lynchets were identified ~1 km away. The land use is dominated by grassland and woodland. Archaeologically, the commune has numerous mining sites and metallurgical furnaces (4) dating from the 15th and 16th centuries. Two metallurgical sites are in the site vicinity at ~200 and ~400 m.

ALP and GOLF lynchets, both located in the Goldbach-Altenbach commune (68), are situated on a southwest and southeast slope, with significant slopes of 19% and 22% and high altitudes of 857 and 685 m (Figure 3e,f). The ALP site is currently on grassland near a forest, while

the GOLF site is under forest. The identified lynchets network is extremely dense and homogeneous, regularly spaced at 10–20 m apart depending on the slope, with the presence of numerous stone walls. Land use is dominated by forest and some grassland.

3 | METHODS

3.1 | Geoarchaeological research

3.1.1 | Pedological analysis (Figure 4)

Six soil profiles were sampled every 5 cm (e.g., 0–5, 5–10 cm, down to the bottom of the trench) in the part of the trench with the thickest pedosedimentary accumulation. The samples are between 100 and 400 g, depending on bulk density and coarse elements. All samples were oven-dried at 40°C and sieved through a 2-mm mesh. Total carbon (C(t)) analyses were carried out on ground samples using

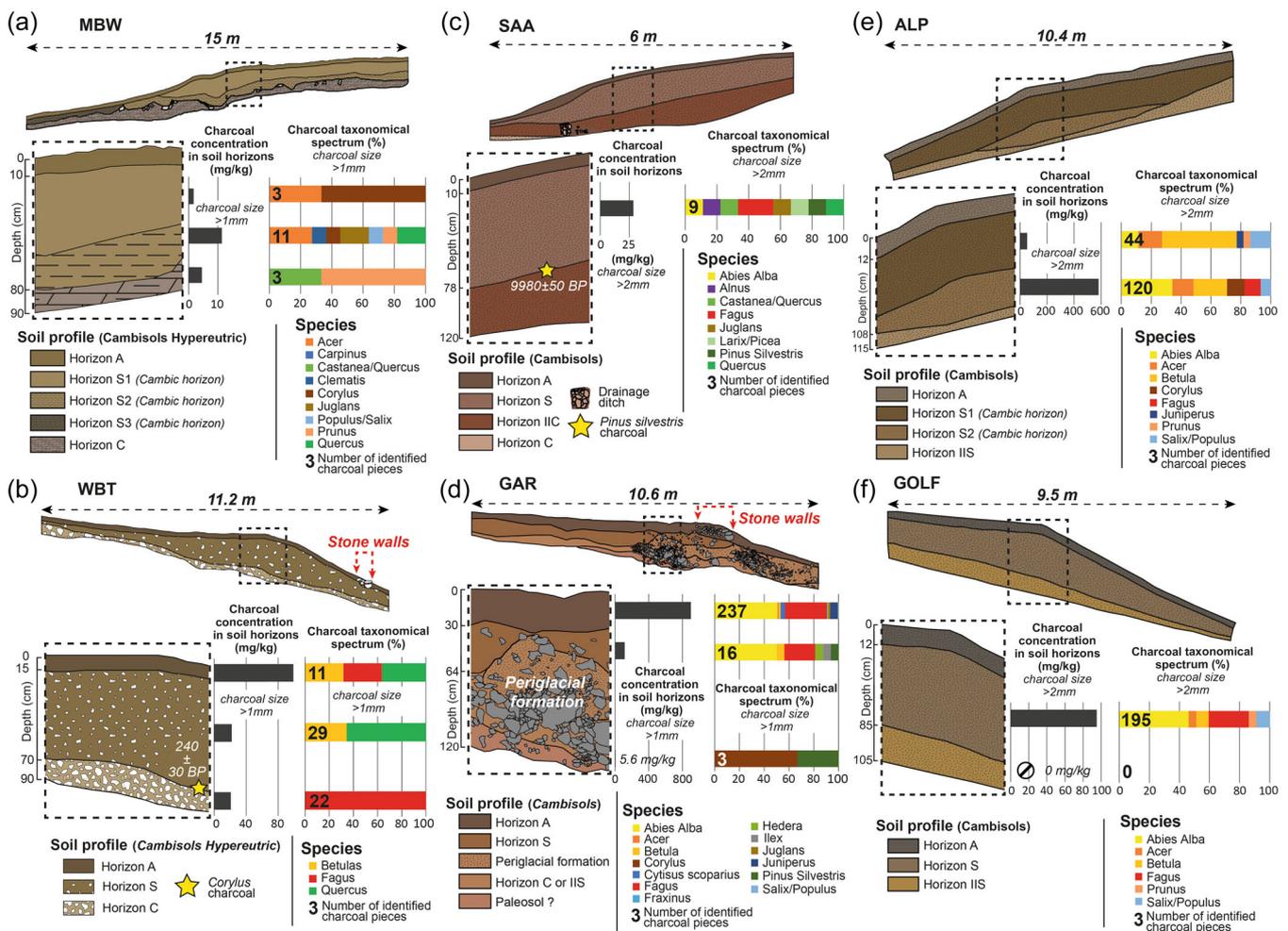


FIGURE 4 Trench soil profile with charcoal concentration in soil per taxa (mg/kg) per sampled horizon and the part (%) of charcoal pieces per species sampled in the lynchet at site MBW (a), WBT (b), SAA (c), GAR (d), ELP (e), and GOLF (f); some charcoal pieces were sampled opportunistically (yellow star) at site WBT (b) and SAA (c). GAR, Goutte au Rupt; MBW, Mittelbruckerwald; SAA, Saales; WBT, Weidesheimer Berg.

a Flash 2000 N and NC elemental analyzer, as well as the measurement of calcium carbonate (CaCO_3) to determine soil organic matter (OM). A particle size analysis was performed on each sample using a Beckman Coulter LS13 320 laser particle size analyzer. The texture of the soil profiles is determined from the United States Department of Agriculture (USDA) soil texture triangle. Micro-morphological and macromorphological analyses were carried out for the ALP and GOLF soil profiles (Schwartz et al., 2020).

3.1.2 | Pedoanthracology

In the six profiles, samples were taken from the soil horizons of interest from the upper to the lower limit to determine the clearing (forest) phases. Because bioturbation generates fragmentation as well as burial of charcoal, there is almost no stratification of charcoal in soils (Carcaillet, 2001; Carcaillet & Talon, 1996; Schwartz et al., 2005). We have therefore chosen to match the sampling of

the other indicators used in the study to be able to develop a general analysis that is as complementary as possible. Sampling the upper and lower limits of the soil horizons and those formed by pedosedimentary accumulation allows further discussion of the possible inherited charcoal by transfer to the slope. Surface horizons less than 15 cm thick were not sampled. This arbitrary limit is chosen to reduce the number of samples and potentially redundant analysis. A total of 14 soil samples between 1 and 7 kg were taken from the selected horizons of each lynchet. Charcoal >1 mm were extracted from the soil samples by wet sieving and recovered by flotation. Charcoal <1 mm were not considered in this study, as they are generally too small for taxonomic identification. We determined the total charcoal richness of the soil as the concentration of charcoal per unit of sediment: charcoal concentration in soil in mg/kg (Figure 4). This is the dry weight in mg of charcoal pieces larger than 1 mm divided by the dry weight of the soil profile in kilogram (Robin et al., 2014; Talon, 2010). This provides comparable quantitative data between the different soil horizons. We also obtained comparative data for soil

taxonomic assemblages. All charcoal fragments extracted from the soil samples were taxonomically identified using a diascopic microscope (Zeiss Axio Imager.M2m, $\times 100$, $\times 200$, $\times 500$) based on wood anatomy atlases (Schweingruber, 2016) and the reference collection of charred wood of the Image, Ville, Environnement Laboratory (LIVE UMR 762, University of Strasbourg). The results of the analysis are expressed as the number of the taxon in relation to the total number: charcoal taxonomical spectrum, expressed in % (Figure 4). In the WBT and SAA soil profiles, some charcoal >5 mm were extracted directly, identified, and dated and were not integrated with the analysis of the charcoal concentration in soil or the charcoal taxonomical spectrum (Figure 4). Currently, only the analysis of the fraction >2 mm has been completed on SAA, ALP, and GOLF. Enough dates for SAA have not yet been obtained.

3.1.3 | Radiocarbon dating (^{14}C)

Charcoal sent for dating were selected according to their species, the number of charcoal fragments in the profile, and sometimes the horizon in which the charcoal was located. Consequently, four charcoal were dated at the Beta Analytic Laboratory and 27 charcoal were dated at the Poznan Radiocarbon Laboratory using AMS (acid-alkaline pretreatment) radiocarbon dating. Calibrations were

calculated with the Calib 8.20 (Stuiver et al., 2022) calibration program using the IntCal20 atmospheric curve calibration (Reimer et al., 2020). A total of 31 charcoal were dated (Figure 5): 8 out of 17 identified in MBW, 6 out of 62 identified in WBT, 2 out of 9 identified in SAA, 9 out of 256 identified in GAR, 4 out of 164 identified in ALP, and 2 out of 195 identified in GOLF.

3.1.4 | Near-infrared spectroscopy (NIRS)

Qualitative NIRS (NIRS-qual) is an analytical method involving diffuse reflectance measurement in the near-infrared region (1100–2500 nm), allowing the determination of the vegetation source of soil organic matter. The NIR spectra are often considered as the fingerprint of the soil organic matter (Coûteaux et al., 2003; Palmborg & Nordgren, 1996). The use of NIRS for evaluation of the vegetational origin of the soil organic matter was established by Ertlen et al. (2010). The approach compares the NIR spectrum of a sample of an unknown origin with a library of reference samples using multivariate discriminant analysis. The spectral reference library of 1179 spectra was established based on samples from soil horizons or soil material with well-known organic matter origin. Two main vegetation groups are distinguished: forest and open landscape.

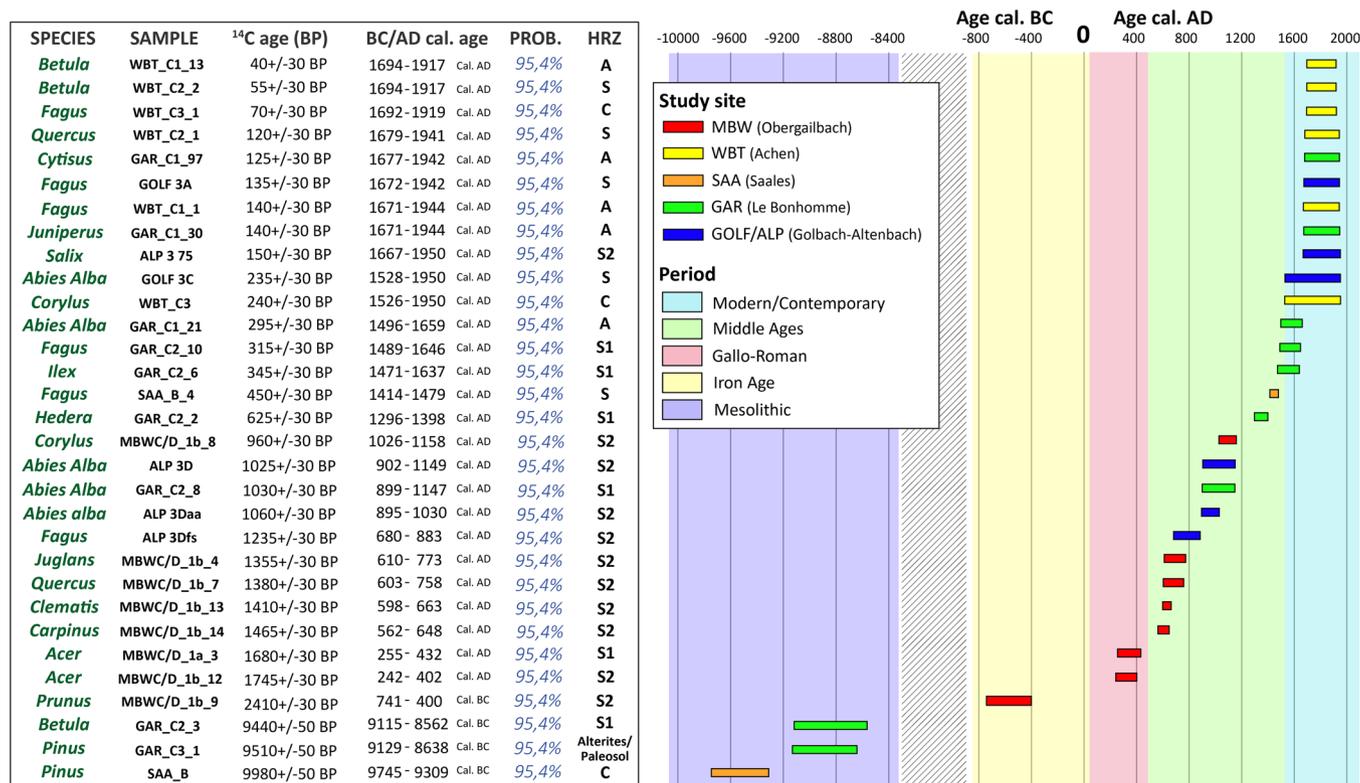


FIGURE 5 AMS- ^{14}C dates of the single charcoal pieces from the investigated sites MBW, WBT, SAA, GAR, ALP, and GOLF (left). Calibration in B.C. and AD based on the IntCal20 atmospheric curve calibration (Reimer et al., 2020). Timeline with each dating in chronological order (right) from the oldest on the left to the most recent on the right for each site: MBW (red), WBT (yellow), SAA (orange), GAR (green), GOLF, and ALP (blue). GAR, Goutte au Rupt; MBW, Mittelbruckerwald; SAA, Saales; WBT, Weidesheimer Berg.

Samples were taken from the same six profiles as pedoanthracology, but with a systematic vertical resolution from 5 to 10 cm. All samples were oven-dried and sieved through a 2-mm mesh, then placed one by one in a rotating cup (diameter 9 cm) and scanned in the wavelength range of 10,000–4000 cm^{-1} with a resolution of 2 cm^{-1} . An FT-IR Frontier Spectrometer (PerkinElmer) was used with a CaF2 beam-splitter, with an integrating sphere and an InGaAs detector. The measured reflectance (R) was transformed into absorbance (A) using the following equation: $A = \log_{10}(1/R)$.

For mathematical pretreatment and statistical treatment, we followed the methodology proposed by Strouhalová et al. (2019), supported by Ertlen et al. (2010) and Viscarra Rossel and Webster (2011). The resulting matrix has 1270 rows (1179 reference spectra +91 unknown samples; see Tables S3 and S4) and 737 columns (8 cm^{-1} wide wave number bands). The Mahalanobis distance is used to evaluate the discrimination between the two groups of reference samples (open landscape/forest). The calculated two-sided model of the reference library was applied on the set of 156 spectra samples from the six studied trenches with unknown history. The comparison of values from the multiple discriminant analysis (discriminant function score) of the unknown data with the reference library data enables an interpretation of the soil organic matter origin (open landscape or forest). To study the evolution of the vegetation over time, we examined the score of the multiple discriminant analysis of the NIR spectra at every sampled depth. This approach allows for the identification of relevant tendencies during the accumulation phase until present day (Ertlen et al., 2015).

3.2 | Geohistorical data

Geohistorical data are very valuable as they allow the estimation of land use over ~260 years. Several types of old maps from the mid-18th and mid-19th centuries can be used to determine land use before the 20th century:

1. The 1760 finage plans or Alsace cadastre (Figure 7) was produced between 1760 and 1764 at a scale of 1:5280 on the initiative of Jacques Pineau (Baron de Lucé). This tax cadastre was made in order to achieve a fairer compensation of the tax burden by the kingdom of France, to which the majority of Alsatian territory was attached after the treaties of Westphalia in 1648 (Tschaen, 2011).
2. The topographic atlas of Bitche County was completed in 1758. The purpose behind the creation of these maps was to facilitate forest development for the Duke of Lorraine (Rochel, 2017). These maps cover an area of 562 km^2 , partially in the Bitche region and partially in the northeastern Lorraine Plateau (Figure 2). They represent high-resolution information, as is the case with the Alsace cadastre, because of the ~1:2983 scale.
3. The Etat Major maps (Institut Géographique National [IGN], 2023) made between 1818 and 1866 cover the whole of France (in 273 sheets) at 1:80,000, and from 1830 at 1:40,000 (Figure 8). These

maps provide an accurate picture of land use, although this accuracy seems to deteriorate in mountainous areas (Dupouey et al., 2007).

For the post-20th century, aerial photographs (Figure 7) and the 1950 map of the IGN, (2023) allow land use to be determined accurately. For the 21st century, satellite images were used.

A timeline was created from these geohistorical data, delimited by a boundary between the mid-17th century and >2010 (Figure 7). The minimum threshold of 1648 was chosen because of the Thirty Years' War, which, for the sites located in the Vosges, led to a drastic fall in population between 1630 and 1634 (Garnier, 2004). For example, the village of Le Bonhomme (Figure 2) was decimated and left deserted for several years (Baradel, 2003; Jéhin, 1991). As a result, the end of the Thirty Years' War (1648) led to fields becoming overgrown, and some sites were abandoned. The repopulation of this part of the Vosges progressed slowly until the end of the 17th century, and numerous ordinances were promulgated under Louis XIV to encourage settlers to move onto abandoned lands (Garnier, 2004). The minimum threshold was also chosen according to the sites under forest, including a forest presence of at least >50 years.

4 | RESULTS

4.1 | Pedological and pedoanthracological data

4.1.1 | Trench analysis

The SAA, GAR, ALP, and GOLF sites are in the Vosges Mountains (Figure 2) and were developed on weathered periglacial slope formations. MBW and WBT are in the Lorraine Plateau (Figure 2) and were developed on marl-limestone slopes. The trench profiles all show soil sediment accumulation at the edge of the soil bank (Figure 4). This confirms that these former fields are lynchets.

The soil profile of the MBW trench (Figure 4a) does not present constant homogeneity (texture and structure; see Table S1 for all soil analysis). In fact, the texture of the soil is composed of a dominant silt loam (USDA) in the S1 horizon (Cambic horizon, WRB, 2015) and a dominant silty clay loam (USDA) in the S2 horizon with a massive structure. Texture is very similar to that of its parent material (marl-limestone). The downstream part does not have a silt loam horizon but a darker-colored S3 silty clay loam (USDA) horizon (more incorporated in organic matter). The downstream part of the trench has a poorly developed soil that has probably been truncated by erosion. This textural difference may be related to the transfer of soil materials by runoff or tillage erosion. The S1 horizon is, therefore, a colluvial horizon originating from soils (luvic cambisols) formed on loess veneers located at the top of the slope, loess being composed of 40%–70% silt (Smalley et al., 2011).

The soil profile of the WBT trench (Figure 4b) shows constant homogeneity (texture and structure) with a very marked thickening at the lynchet. The whole profile has a silty clay loam texture (USDA)

with a massive structure. The soil is very stony (10–15 cm in height), forcing the farmers of the time to remove the stones. The presence of a “small” stone wall in the terminal part of the trench and a more imposing stone wall slightly inclined in the axis of the slope near WBT (~5 m) (Figures 3b and 4b) should also be noted.

The soil profile of the SAA trench (Figure 4c) shows consistent homogeneity (texture and structure) with a thickening at the lynchet. SAA has a drainage furrow under the soil bank, probably put in place at the time of site cultivation. The whole profile has a sand texture (USDA).

The soil profile of the GAR trench (Figure 4d) is more complex, as a periglacial formation disrupted the profile. This formation is composed of a pile of boulders and centimetric stones of various sizes with a very fine interstitial matrix (silty–sandy–clay) and numerous gravels. The whole of the periglacial formation shows no pedological features. A stone wall is present at the level of the soil bank in the A horizon (probably due to the stone removal of the GAR site). The downstream profile of GAR, like MBW, appears to have been truncated by erosion (runoff or tillage). Textural analyses in the field revealed a sandy matrix in the A horizon and a sandy–silty matrix in the S horizon.

The soil profiles of the ALP and GOLF trenches (Figure 4e,f) show consistent homogeneity (texture and structure) with a significant thickening at the lynchet. The texture in both trench profiles is sandy loam (USDA). The only difference between these two profiles is the S2 horizon, which has coarser colluvial material (coarse sand and gravel in large numbers). Micromorphological analyses were carried out by Schwartz et al. (2020), revealing secondary dusty–silty linings, demonstrating that the soil surface had been exposed by plowing, stumping, or agricultural work (Deák et al., 2017). The analyses also showed that the base of the soil had clayey coatings typical of illuviation phenomena in the formation of a luvisol LV horizon laid down under forest cover. Macromorphological observation revealed levels richer in grass-like phytoliths, suggesting a prairie-type open landscape. The appearance of these phytoliths is blunt and has an isolated configuration attesting to mechanical tillage (Vrydaghs et al., 2017).

4.1.2 | Analysis of taxon and charcoal concentration in soil

Comparing the charcoal concentration in the soil of the six studied sites, it appears that the charcoal concentration of the sampled soils varies greatly within the sampled soil trenches and between the sites. This is a common observation about the soil charcoal records (Bal et al., 2010; Feiss et al., 2017; Robin et al., 2012, 2018; Talon et al., 2005). This is related to on-site conditions influencing the past fire regime and the possibilities of man-made fires (e.g., type of fuel, biomass to burn, and fire intensity), which then induce large heterogeneities of the on-site charcoal signal. Nevertheless, charcoal has been found on all the studied sites and permitted the identification of 703 charcoal pieces in total (Figure 4; see Table S2 for charcoal analysis).

In MBW, nine taxa were identified (Figure 4a). No single taxon dominates the whole profile. The profile consists of two pioneer species (*Clematis* and *Salix/Populus*), numerous postpioneer species (*Acer*, *Corylus*, *Carpinus*, *Juglans*, *Prunus*, and *Quercus*), and no mature forest species. The S2 horizon is composed of a greater number of charcoal (11) and taxa (8). The charcoal concentration in soil is highest in the S2 horizon with ~12 mg/kg, five times higher than that in the S1 horizon (~2.4 mg/kg).

In WBT, only three taxa were identified (Figure 4b). *Fagus* and *Quercus* dominate the whole profile. Oak is a postpioneer species (secondary species), while beech is a shade-tolerant species (Dumé et al., 2018). *Betula* is a pioneer species that can be found in relatively open or degraded forests (Dumé et al., 2018). The charcoal concentration in soil is very high in the A horizon (~100 mg/kg), that is, five times higher than that in the S horizon (~22 mg/kg), while the number of charcoal found is higher in the S horizon (29 compared to 22 in the A horizon). This indicates that the charcoal in the S horizon is more fragmented and smaller than that in the overlying horizon.

In SAA, eight taxa were identified (Figure 4c). No single taxon dominates the whole profile. The species spectra consist of pioneer (*Alnus*), postpioneer (*Juglans*, *Pinus sylvestris*, *Quercus*), and mature forest species (*Abies alba* and *Fagus*).

In GAR, 13 taxa were identified (Figure 4d). Many pioneer species are represented, such as *Betula*, *Salix/Populus*, *Cytisus scoparius*, and *Juniperus*, as well as postpioneer species (*Acer*, *Corylus*, *Fraxinus*, *Juglans*, and *P. sylvestris*) and mature forest species (*A. alba*, *Fagus*, *Hedera*, and *Ilex*). *Fagus* and *A. alba* largely dominate the species spectra. The A horizon has the highest total charcoal concentration in soil, with 897 mg/kg. The number of charcoal is also very high, with 237 charcoal identified. The charcoal concentration in soil decreases significantly in the S horizon, with 108 mg/kg, with only 16 charcoal showing the presence of some large charcoal. In the “alterites or paleosol” layer, the charcoal concentration in soil drops drastically to 5.6 mg/kg, consisting of three charcoal identified as *Corylus* and *P. sylvestris*. As pedological processes, mainly bioturbation, are almost nonexistent in the periglacial formation, the transfer of charcoal between horizons seems very limited.

In ALP, eight taxa were identified (Figure 4e). *Betula* dominates the S1 horizon and *A. alba* dominates the S2 horizon. The profile consists of three pioneer species (*Betula*, *Juniperus*, and *Salix/Populus*), three postpioneer species (*Acer*, *Corylus*, and *Prunus*), and two mature forest species (*A. alba* and *Fagus*). The S2 horizon is composed of many charcoal (120), which is three times as many as the S1 horizon (44). The charcoal concentration in soil is highest in the S2 horizon, with ~581 mg/kg, 11 times higher than that in the S1 horizon (~52 mg/kg).

In GOLF, six taxa were identified (Figure 4f). *A. alba* and *Fagus* dominate the S horizon. The profile consists of two pioneer species (*Betula* and *Salix/Populus*), two postpioneer species (*Acer* and *Prunus*), and two mature forest species (*A. alba* and *Fagus*). The S horizon is composed of a very large number of charcoal (195) and no charcoal >2 mm for the IIS horizon. The charcoal concentration in the soil is ~95 mg/kg.

4.2 | Charcoal dating (Figure 5)

Out of 31 charcoal, three dates from the Mesolithic period (9000–5000 B.C.). Three charcoal are dated to the ancient period (two charcoal from the Gallo-Roman period and one charcoal from the Iron Age), 11 charcoal are dated to the Middle Ages, 11 charcoal are dated to the modern/contemporary period, and three charcoal are dated between the medieval and modern/contemporary period (14–17th century). In total, 25 charcoal out of 31 (81%) are dated to the medieval or contemporary period.

4.2.1 | Dating and tree taxa

The charcoal dated to the Mesolithic period (*Pinus* and *Betula*) correspond to the regional palynological data from the Vosges Mountains (Gouriveau et al., 2020; Hatt, 1937; Sudhaus & Friedmann, 2015). The species dated to the ancient period all correspond to postpioneer species. Species dated to the medieval period show one pioneer species (*Clematis*), four postpioneer species (*Corylus*, *Carpinus*, *Juglans*, and *Quercus*), and six mature forest species (*A. alba* X3, *Fagus* X2, and *Hedera*). The species dated to the modern/contemporary period are pioneer species for five charcoal (*Betula* X2, *Salix*, *C. scoparius*, and *Juniperus*), postpioneer species for two charcoal (*Corylus* and *Quercus*), and mature forest species for seven charcoal (*A. alba* X2, *Fagus* X4, and *Ilex*).

4.3 | Organic matter origin

From the six analyzed profiles, the organic matter content was sufficient for interpreting NIRS analysis in all profiles for ALP, GOLF, GAR, and WBT (Figure 6, Table S1). On MBW, the organic matter was too low at the bottom of the profile and results were discarded. On SAA, no analysis of organic matter levels was carried out. The SAA profile shows negative values (open landscape) but largely outside the range of the reference spectrum, which makes interpretation difficult. GAR, ALP, and GOLF show a similar tendency with an open landscape signal or tendency on the first 15 cm and a clear tendency to forest vegetation at the bottom of the profile. However, the GAR profile shows a slight tendency to openness at around 80 cm depth (see Table S4 for NIRS analysis). The MBW profile shows a near forest signal at the top shifting quickly to an open landscape from 10 cm.

4.4 | Geohistorical analysis

The geohistorical data (Figure 7) show a bipartition of cultivated sites between ~1760 and today. The WBT and SAA sites are still cultivated during this period. WBT has been cultivated since at least ~1760. The SAA site was cultivated in the mid-19th century; unfortunately, no data are available for the earlier period, as the Alsatian cadastre of 1760 is missing in this commune. MBW, GAR, ALP, and GOLF have not been cultivated since at least ~1760. The land use of sites WBT, SAA, GAR, and GOLF has been changing since 1760, with at least one period under grassland. In contrast to the MBW and ALP sites, whose

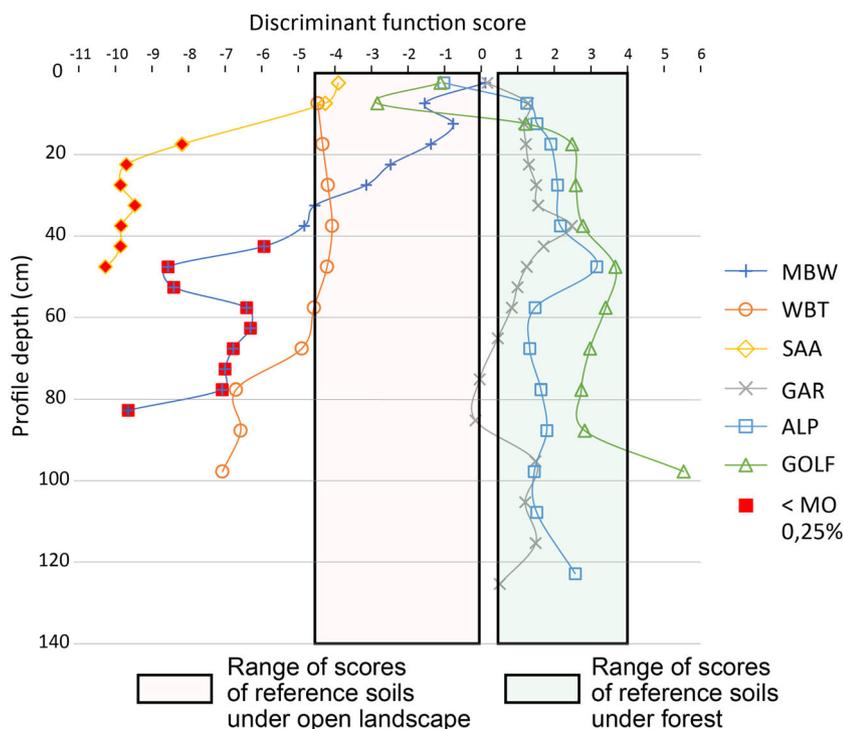


FIGURE 6 Discriminant scores obtained from the near infrared spectra measured on soil organic matter from the six pedosedimentary profiles. The two boxes are obtained from the reference library; the center of the box is the average score of the reference group and the width of the box is two times the standard deviation. GAR, Goutte au Rupt; MBW, Mittelbruckerwald; SAA, Saales; WBT, Weidesheimer Berg.

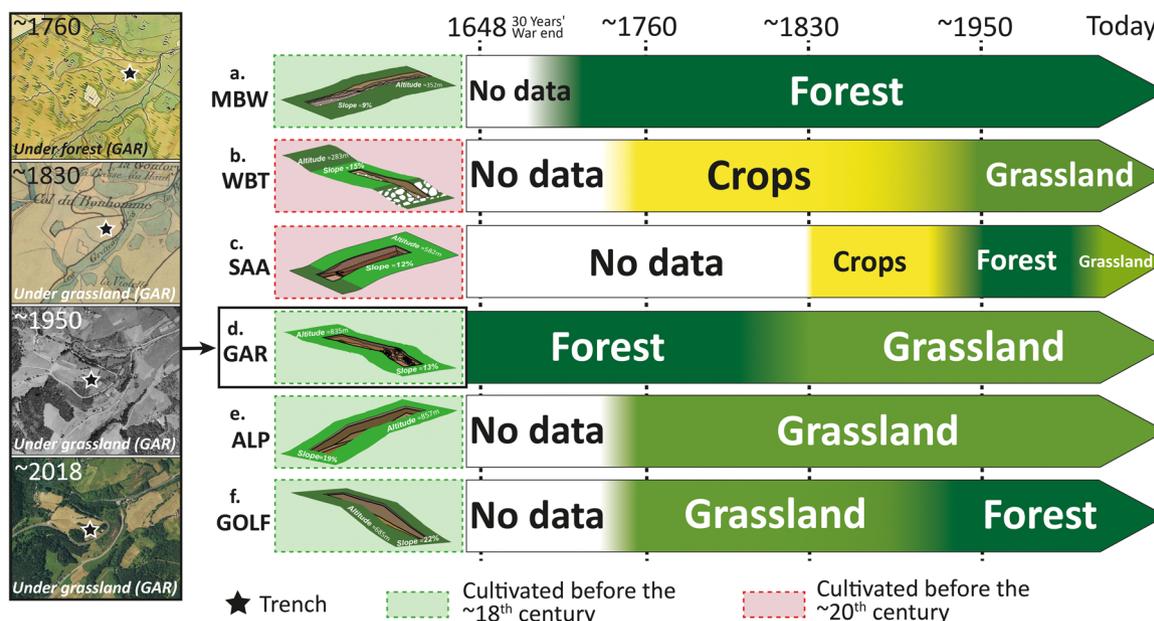


FIGURE 7 Timeline (right) of geohistorical data (example with site GAR, left, Section 2 part 2.3) for sites MBW (a), WBT (b), SAA (c), GAR (d), ALP (e), and GOLF (f). The sites are distinguished into two categories: cultivated before the ~18th century (green rectangle) and cultivated before the ~20th century (red rectangle). GAR, Goutte au Rupt; MBW, Mittelbruckerwald; SAA, Saales; WBT, Weidesheimer Berg.

land use has remained stable, under forest or grassland, since at least ~1760, SAA, GAR, and GOLF sites have been under forest at least once, unlike the WBT site. SAA is the only site that has had three land use changes in ~200 years.

5 | DISCUSSION

5.1 | Lynchet as an archive of past environment

From the geoarchaeological and paleoecological point of view, lynchets are hybrid objects between soil and sediments. From a geomorphological point of view, this is an accumulation of colluvial material. Profiles were selected where the soil bank is the thickest. Nevertheless, the profiles never clearly present a stratified deposit. On the contrary, the units described look like a succession of soil horizons. The processes of profile thickening depend on the importance of the dominant factors in the accumulation process (slope, tillage erosion, texture, etc.). Nevertheless, the accumulation process behind the hedge can be relatively slow. Consequently, sediments are never really buried and the pedogenetical process continues during the aggradation process. The analyzed material can be interpreted as cumulic soil (i.e., slow accumulation of sediment coincident with weathering; Johnson et al., 2015). While geomorphological processes are drastically reduced with the cessation of cultivation, the pedogenetical processes continue until present day, which favors the predominance of soil traits. For these reasons, the archives must be considered as a soil archive without stratigraphic organization, making it more difficult to establish a chronology from the bottom

to the top (Brasseur et al., 2022). The collected charcoal may be analyzed as a multiple fire assemblage at the profile scale and not at the layer scale. The NIRS approach is different because, despite bioturbation, soil organic matter presents a mean residence time gradient that allows a chronological interpretation (Ertlen et al., 2015). The lynchets allow us to determine the land use trajectories of a slope or at least the part upstream of the lynchet. As charcoal above 0.4 mm cannot be transported over long distances (Clark, 1988), it is a local paleo woody indication, unlike palynology (Feiss et al., 2017; Robin et al., 2018). Using only pedoanthracology limits the interpretation of the dates. As already demonstrated by Bal et al. (2010) on agricultural terraces in the Pyrenees (France), it is possible to hypothesize how land use has changed over time by combining several data (Figure 8).

5.2 | Lynchet medieval origin

Among the 31 dated charcoal, three date from before the arrival of the first cultivators in Europe, ~5500 B.C. (Kalis, 1985). The charcoal dated to the Mesolithic period do not provide any relevant information to this study (Figure 6). They can either be inherited from the paleosol buried under the lynchet, especially when they were found at the bottom of the profile, or they can be discharged from the soils upstream and transported with erosion processes. This process can also concern younger charcoal that match the history of agriculture and could mislead the interpretation. Nevertheless, charcoal dating shows a higher frequency from the Middle Ages onward (Figure 5), and geohistorical data suggest that MBW, GAR, ALP, and GOLF were abandoned before the middle of the 18th

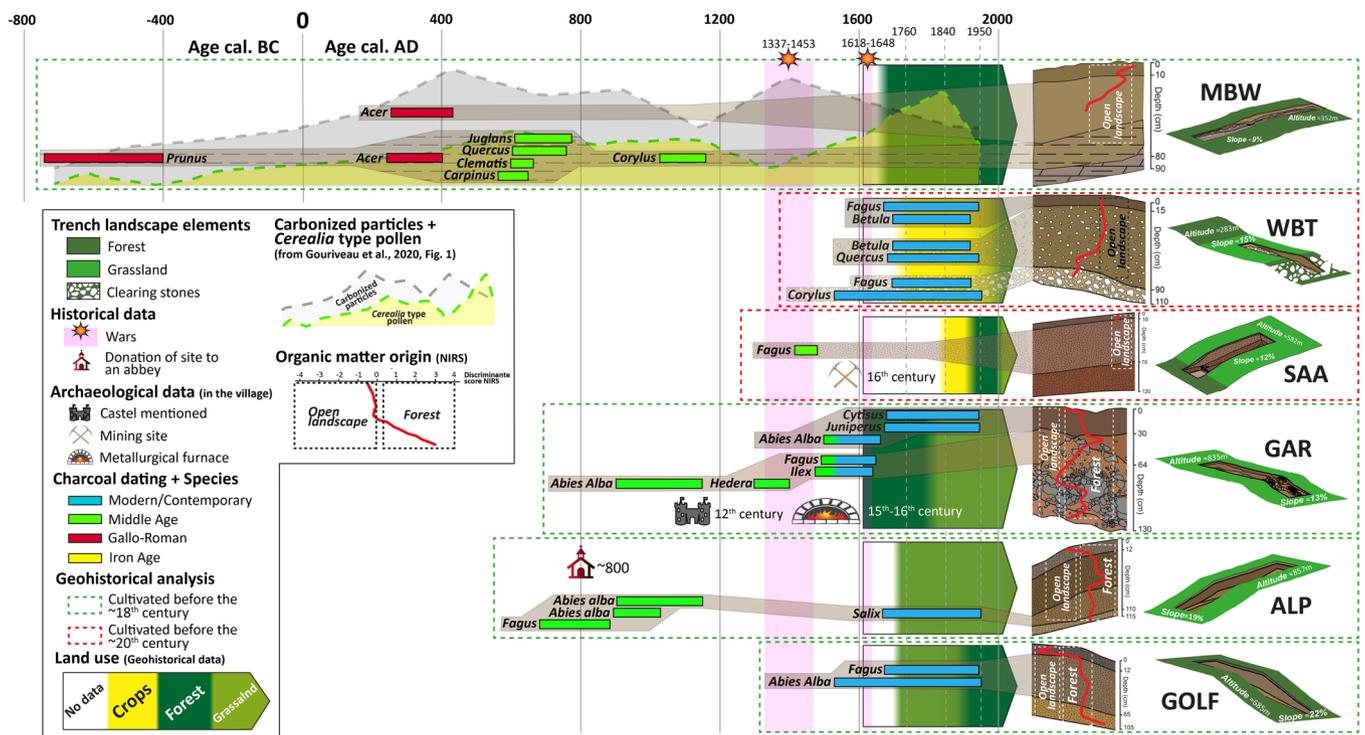


FIGURE 8 Timeline per site combined with geohistorical data, archaeological/historical data, pedoanthracological data (charcoal dating), and near infrared spectroscopy data. Cerealia-type pollen data and carbonized particles (Gouriveau et al., 2020) data used only for MBW and WBT. GAR, Goutte au Rupt; MBW, Mittelbruckerwald; SAA, Saales; WBT, Weidesheimer Berg.

century (Figure 8). However, from these data, asserting a medieval origin of the lynchets systems in the study area is not straightforward. The regional history and paleoecological data, which show a very different chronology of anthropization between the Vosges Mountains and the Lorraine Plateau, can strengthen the medieval hypothesis.

5.2.1 | The Vosges Mountains

Archaeological evidence from the Crystalline Vosges before the medieval period is weak. In the Vosges Mountains, many abbeys were founded between the end of the sixth and eighth centuries. In the southern Vosges, four abbeys were founded: Saint-Amarin around 623 A.D., Murbach around 728, Liepvre in 770, and Masevaux around 780 (Bornert, 2008). Through royal donations and great lords, the abbeys quickly acquired large properties. For example, Murbach received from Charlemagne, around the year 800, the upper half of the Thur Valley, of which the ALP and GOLF sites are a part. At a time when feudalism was in its infancy, the abbeys exercised control over most of the land outside the royal and ducal domains in the 9th and 10th centuries (Parmentier, 2012). This suggests that it was the ecclesiastical powers that were at the origin of this mode of land exploitation. Nevertheless, cereal pollen reached its peak in the middle of the Middle Ages between the 11th and 12th centuries (Janssen &

Janssen-Kettlitz, 1972; Kalis, 1985; Mariet et al., 2018; Sudhaus & Friedmann, 2015), parallel to the construction of numerous castles (>45) and other abbeys between the 10th and 12th centuries (Bornert, 2008; Koch, 2012). Large-scale mining of the Vosges Mountains also took place between the 8th and 12th centuries.

This period between the 8th and 12th centuries probably marks the establishment of lynchets systems. The end of the Middle Ages and the beginning of the modern period are marked by social disorganization, leading to a decline in agricultural activities and a concomitant forest reconquest according to pollen records (Gouriveau et al., 2020; Mariet et al., 2018). This could have been caused by several Black Death epidemics during the 14th century, as well as successive disastrous wars (e.g., the Hundred Years' War from 1337 to 1453), and reached its peak during the Thirty Years' War (1618–1648), so that the population of Alsace, the former easternmost region of the Grand Est, was halved by 1640 (Vogler, 1998). After 1648, it was progressively annexed by the Kingdom of France with the edicts of Louis XIV (1662, 1682, and 1687) to repopulate the devastated areas (Emig, 2012; Garnier, 2004). Since the last mountain range wide deforestation phase in the 18th century (Gebhardt et al., 2015), forestry and supporting industrial and pastoral activities have prevailed in the Vosges until the 20th century (Garnier, 2004). The regional history of the Vosges supports the hypothesis of a medieval origin of the majority of lynchets.

5.2.2 | Lorraine Plateau

Agricultural development of the Lorraine Plateau seems to start well before the Middle Ages (Etienne et al., 2013; Gouriveau et al., 2020). The MBW and WBT sites are located at low elevations (Figures 2 and 3), where numerous archaeological sites, such as burials, villae, and a Roman city, dated to the Iron Age and Gallo-Roman period, are also present (<4 km, Boulanger, 2021; Petit & Santoro, 2016), indicating a probable continuity of anthropization since at least the Iron Age. The Gallo-Roman period in the Lorraine Plateau already reaches a forest minimum, with some areas dominated by grasslands and others by cereal cultivation (Etienne et al., 2013). In contrast to the Hautes-Vosges, the intensity of cereal cultivation does not only reach a maximum during the medieval period but also seems to vary according to location (Figure 2). The palynological data in the vicinity of the MBW and WBT sites show a cereal maximum during the Middle Ages in ~1100 and a maximum deforestation in ~1150 (Figure 2, Gouriveau et al., 2020). This intensification coincides with the appearance of numerous abbeys during the Merovingian period (fifth–eighth century, Gaillard, 1993) and the presence of funerary sites in this same period (Schmit et al., 2017). The diocese of Metz had a dozen abbeys in the ninth century (Gaillard, 1993). Two abbeys are located in the northeast of the Lorraine Plateau ~10 km from the MBW and WBT sites. The late medieval period in the northeastern plateau is marked by reforestation (Gouriveau et al., 2020). This decrease in anthropization can be explained by the same social unrest, such as epidemics, famines, and wars, observed in the Vosges Mountains. The regional history of the Lorraine Plateau shows that anthropization, and especially the presence of cereal cultivation, is proven as early as the Iron Age. The establishment of the lynchet systems in this region may have a medieval origin according to the charcoal that we studied in MBW, but this is not clearly confirmed by historical and pollen data.

5.3 | Land use trajectories

5.3.1 | MBW site: Lorraine Plateau

The dating in the MBW site profile shows four different periods. A *Prunus* is dated to 741–400 cal. B.C., an *Acer* is dated to 255–432 cal. A.D. in the S1 horizon, six charcoal are dated to 242–402 cal. A.D. and 562–773 cal. A.D. in the S2 horizon, and a *Corylus* is dated to 1026–1158 cal. A.D. (Figure 8). The dating of the charcoal in the MBW site seems to be consistent with the regional dynamics of anthropogenic fires determined from carbonized microscopic particles and ashes found in a peat bog (~20 km from the sites) in the Northern Vosges (Figure 2). The study by Gouriveau et al. (2020) shows a strong increase in fires from the Iron Age onward, with two marked intensifications in the late Gallo-Roman period (~460) and during the Late Middle Ages (~1385) (Figure 8). The curves of crop pollen and charred particles show a strong similarity until the 12th/13th century (Figure 8), indicating the potential use of fire to create

cultivation areas. Nevertheless, the four dates obtained from the Iron Age, the Gallo-Roman period, and the Central Middle Ages are too scattered and not consistent enough to date the lynchet. In fact, the accumulation of colluvial material should have favored the contribution of numerous charcoal dated to the same periods (recall that seven charcoal have been dated out of 11 identified in the S2 horizon, Figures 4 and 8). The dispersion of 14C ages in soils is often large. This may be related to three factors, the first being that charcoal can originate from different fire episodes and are intensively stirred and mixed in soils by bioturbation (Carcaillet, 2001; Goepf, 2007; Goepf et al., 2007; Robin et al., 2014; Schwartz et al., 2005). This is probably the case of *Acer* located in the S1 horizon, which the date inversion seems to point to. The data indicate that the two *Acer* charcoal (242–402 and 255–432 cal. A.D.) come from the same tree. The second is influenced by slope, as erosion and transport downslope can lead to a mixture of charcoal assemblages that can generate inconsistencies in fire interpretation (Robin & Nelle, 2014). It is possible that the *Prunus* and *Acer* charcoal are linked to the destocking by runoff during the cultivation of the site and stored in the lynchet. The third is the “old wood” problem (Gavin, 2001). The two *Acer* charcoal dated between 242 and 432 cal. A.D. could correspond to the same *Acer* tree that can live up to 150 years (Dumé et al., 2018). The two Gallo-Roman charcoal could be contemporary with the charcoal dated between 562 and 773 cal. A.D. Finally, there are two hypotheses that remain speculative but not impossible, concerning certain chronologically erratic charcoals such as *Corylus* (dated between 1026 and 1158 cal. A.D.). The first hypothesis is that these charcoals are the result of an amendment due to the use of ash as fertilizer (Fournier, 2019; Poirier & Nuninger, 2012), but ash seems to be used more in food gardens (Koerner et al., 1999), rather than large plots. The second is the cause of an unintentional fire, which some historical sources mention during the modern period (Garnier, 2004).

In addition, the maximum cultivation period appears to be reached in the ~7th century and was maintained until the end of the ~12th century (Gouriveau et al., 2020). This period corresponds to the four charcoal found in the S2 horizon dated between 562 and 773 cal. A.D. (~650 cal. A.D.). The number of dated charcoal corresponding (4 charcoal out of 11 identified, Figure 4) to the same period, the heterogeneity of the species, and the paleoenvironmental data support the interpretation in favor of a Merovingian origin for the lynchet. The burnt species (*Carpinus*, *Clematis*, *Quercus*, and *Juglans*) are all postpioneer, indicating a logged or more recent forest. It is possible that the forest has been managed since at least the Iron Age. In fact, the MBW forest (Figure 3) is still managed and has been for at least 250 years and shows the same vegetation community. This testifies in favor of a forest exploited well before the Merovingian period and explains the presence of charcoal dated to earlier periods. However, we cannot say whether all the lynchets present in the vicinity of the site are dated to the Merovingian period. It is possible that the charcoal dated before this period come from sites exploited upstream from MBW. The presence of luvisols formed on loess may have favored the establishment of culture

well before the Merovingian period. Moreover, some lynchets were still under cultivation in the 18th century, not allowing an *ante quem* date.

5.3.2 | WBT site: Lorraine Plateau

In contrast to MBW, the dating of charcoal at WBT sites shows a homogeneity of fire periods. The dating of the entire soil profile of the WBT site shows that all the charcoal are of modern/contemporary origin (Figure 8). Soil with a texture of more than 30% clay greatly limits the intensity of soil erosion (Cerdan et al., 2006). It is likely that this is limiting the removal of charcoal from upstream of the lynchet. In addition, we believe that bioturbation could not have removed charcoal from recent amendment or clearing over the entire profile (90 cm). Moreover, the *Corylus* charcoal collected at the upper limit of the C horizon (Figure 4) is located under a large stone. This evidence indicates that the charcoal could not have been positioned postdeposition under this stone. This charcoal would date the beginning of the lynchet formation. Data from the Bitche topographical atlas of 1758 seem to confirm this hypothesis. The map indicates that the forest at the top of the WBT site (Figure 3) was “a few years ago much more considerable, a large part of it was cleared on the western side...” (ADM Archives départementales de Metz, 1758, p. 145). The atlas specifies that this is mainly the western slope and not the eastern slope on which the WBT site is located. However, the atlas does not specify that the eastern part has not been cleared, but it does specify that it is mainly a large area to the west, possibly indicating the most impacted area. The WBT lynchet would have formed between ~1700 and 1950 in less than 250 years. This hypothesis is possible according to the work of Nyssen et al. (2014), who estimate the aggradation of lynchets in Belgium based on estimated erosion rates by nonmechanical plowing, in addition to cross-sectional area, average slope gradient, and soil bulk density. This study shows that lynchets can form between 217 and 585 years in sufficiently steep slopes. According to the formula proposed by Nyssen et al. (2014), the WBT lynchet would have formed between 209 and 376 years ago, periods depending on the contribution of tillage erosion (50% or 90%). The lynchet system at the WBT site could date from the modern period (~18th century). Moreover, palynological data near the site (Figure 2) show a peak in crop pollen in 1850 (Gouriveau et al., 2020, Figure 8), which could be related to the expansion of the cultivation areas as realized at the WBT site. In addition, the homogeneity of the lynchets plot (Figure 4) argues in favor of the synchronization of all plots during the same period.

5.3.3 | SAA site: The Vosges Mountains

The SAA site is located in the extreme north of the Vosges Mountains, at the lowest altitude (Figures 2 and 3), which, unlike the GAR, ALP, and GOLF groups, may have favored continuous occupation of the site. Moreover, the village of Saâles (Figure 3c) has

significant mining resources exploited since at least the seventh to eighth century (Magar, 2021), which may indicate continuous anthropization of the site since this period. Unfortunately, we have not yet been able to date any more charcoal in the SAA lynchet. In addition, geohistorical data from the 18th century are missing. This is a very complex site due to the presence of a mine and smelter site in the vicinity. The late medieval charcoal (Figure 8) may be the result of mining dated to the 16th century (Leypold, 1995), located above SAA (Figure 3). The SAA site, however, appears to have remained under grassland or cultivation for a long time.

5.3.4 | GAR site: The Vosges Mountains

The dating of the GAR site shows several periods of fire as does that of the MBW site. The possibility of charcoal transport due to erosion is limited, as the GAR site is almost at the top of the slope. The presence of a charcoal (*Betula*) dated between 8562 and 9115 cal. B.C. in the S1 horizon (Figures 5 and 6) located above the periglacial formation is probably the result of bioturbation. Like MBW, there are two erratic charcoal: *Hedera* dated to 1296–1398 cal. A.D. and *A. alba* dated to 899–1147 cal. A.D. (Figure 8). In contrast to the MBW site, a large amount of archaeological, historical, and, to a lesser extent, palynological data allows us to further discuss the potential age of the lynchet and land use changes. *A. alba* and *Hedera* charcoal dated to the medieval period with a gap of ~250 years. As *A. alba* can live ~200–300 years (Dumé et al., 2018), it could be contemporary with *Hedera* charcoal. *Hedera* can be a contemporary of *Ilex*, *Fagus*, and *A. alba* (dated between 1471 and 1659). It is also possible that *Hedera*, which likes to settle in hedges, is the result of hedge maintenance (Dumé et al., 2018).

The age of *A. alba* charcoal (899–1147 cal. A.D.) corroborates with palynological data showing an increase in cultivation in the Central Middle Ages (between 11th and 13th century) in the Crystalline Vosges (Janssen & Janssen-Kettlitz, 1972; Kalis, 1985; Mariet et al., 2016, 2018; Sudhaus & Friedmann, 2015; Figure 2), and mostly an abrupt decrease of *Abies* after 1000 A.D. (Mariet et al., 2018). This period corresponds to the dating of *A. alba*.

Additionally, Le Bonhomme commune seems to have been inhabited well before the 14th century, since a castle, the Jutenburg, is mentioned in 1162 as belonging to the Count of Eguisheim (Jéhin, 1995). However, there is no historical source to indicate whether the surrounding land was farmed during this period. Only one farm is mentioned in 1675 located on the opposite slope of the GAR site (Figure 3) belonging to the Ribeaupierre seigneurie (Litchle, 1989). This farm is probably older, since the Ribeaupierres acquired the usufruct of the land and the castle in 1325 (Jéhin, 1991), and the farm may have already belonged to the Counts of Eguisheim in the ~11th century. Le Bonhomme village experienced a demographic expansion in the 16th century (Jéhin, 2000), probably induced by the boom in silver production (Bonnamour et al., 2010; Fluck & Florsch, 1996).

Numerous metallurgical workshops are attested to in the vicinity of the GAR site (Figure 3), installed between the end of the 15th and the end of the 16th centuries (Figure 8, Bonnamour et al., 2010; Fluck & Florsch, 1996; Jéhin, 1991), before a decline at the beginning of the 17th century and a definitive stop at the end of the Thirty Years' War (Fluck & Florsch, 1996; Jéhin, 2010). The establishment of this "industry" led to massive deforestation (Fluck & Florsch, 1996) in order to produce charcoal (Garnier, 2004).

On the boundary plans of 1760, the GAR site is indicated as being part of the Louschbach forest. This same forest was made available in ~1550 to meet the wood needs of the four nearby foundries (Figure 3, Garnier, 2004). A historical archive from 1571 indicates that the Louschbach forest was almost exhausted (Fluck & Florsch, 1996) and possibly already so in 1558 (Garnier, 2004). The Louschbach forest was an important resource for the lordly foundries. The lords of Ribeaupierre would probably not have allowed their tenant to exploit GAR after the clearing in ~1550. Moreover, a 100 years between ~1550 and the ravages of the Thirty Years' War would have been necessary to form the lynchet, which seems insufficient insofar as the erosive phenomena are limited because of the almost summit situation of GAR. In addition, the Alsatian cadastre (1760) specifies that the Louschbach forest is a "high fir forest on good soil" (<https://archives.haut-rhin.fr>, Archives départementales du Haut-Rhin, 2023), indicating a forest ≥ 100 years old. According to historical data, Le Bonhomme commune had 41 arpents of cultivated land in 1632 (Litchle, 1996) and 64 arpents in 1760, showing very little increase in cultivated area over this period. In addition, the land and grasslands exploited by the farm located in front of GAR have been recorded since 1689 (Litchle, 1989) and correspond perfectly to those recorded on the Alsatian cadastre of 1760. Moreover, some of the uncultivated land was cleared in 1689 (Litchle, 1989). This historical data show that if GAR had been exploited before the Thirty Years' War, the farmer would have re-exploited this land.

These data indicate two things about the site. First, the GAR site was probably used for charcoal production between ~1550 and ~1571, which corresponds to the dates of *Ilex*, *Fagus*, and *A. alba* (dated between 1471 and 1659). This change in land use has also been observed in central Germany (Larsen et al., 2016). Furthermore, this could explain the high charcoal concentration in the soil in the A horizon. In charcoal production areas, there is a risk of carbonized residues being dispersed (Bal et al., 2010, 2023). Second, the site was under forest from the 16th century and probably already during the 15th century until the 19th century. During the 19th century, the GAR site passed under grassland (Figure 8). In the Vosges, the beginning of the 18th century was marked by a major demographic boom, which resulted in significant clearing of land, culminating in 1770 (Garnier, 2000). Le Bonhomme commune was no exception: according to estimates, in 1720, the village had ~136 inhabitants (Jordan, 1996), in 1790, the village had 888 inhabitants (Baradel, 2003), and in 1831, the village had 1431 inhabitants (Jéhin, 1991). This demographic surge led to numerous constructions in 1758, generating massive land clearing (Jéhin, 1991). Moreover, in 1778, to compensate for this demographic increase and the need for wood, a

third of the seigneurial woods were given to the communities of the valley, of which Le Bonhomme village was one (Baradel, 2003). It was, therefore, during this period at the end of the 18th century that the high fir forest, still shown as a seigneurial wood on the 1760 plans, was cut down. Subsequently, *Cytisus* and *Juniperus* became established on the forest plot sometime after the logging. After a clearing, probably at the beginning of the 19th century, the GAR site was converted into grassland. This is consistent with *Cytisus* and *Juniperus charcoal* dated to the modern/contemporary period (≥ 1671 A.D.). These two pioneer species are the first to recolonize newly deforested areas or abandoned grasslands in the Crystalline Vosges (Goepf, 2007). During this period, Le Bonhomme seems to have turned to cheese production. The number of dairy cows increased between 1797 and 1805 from 463 to 650 (Baradel, 2003), necessitating an increase in the number of pastures or grasslands.

Based on historical analysis and dating, the origin of the lynchet system at the GAR site dates from the medieval period. For the moment, a precise date is still unknown, but it seems that its origin is situated between the 10th and 13th centuries. The site then passed under forest before the 16th century and was exploited for its timber and charcoal production. The site probably fell under forest during or after the 14th century. Repeated famines, epidemics like the Black Death, and war-like incursions like the Hundred Years' War led to a demographic decline in the Le Bonhomme region (Baradel, 2003). At the beginning of the 19th century, the forest was cut down and turned into grassland or pasture.

5.3.5 | ALP and GOLF site: The Vosges Mountains

As we have shown, the MBW and GAR sites show a relative dispersion of 14C ages. A notable exception to this pattern is represented by the case of the Goldbach-Altenbach commune sector (GOLF and ALP). Here, only two periods were dated. A first phase of clearing took place between 680 and 1149 cal. A.D. and seems to correspond to the establishment of the land plot (Figure 8). At that time, the Upper Thur Valley, of which Goldbach-Altenbach is a part, belonged to the abbey of Murbach, the most powerful abbey in Alsace, to whom it had been bequeathed around the year 800 (Schwartz et al., 2020). The clearing was thus conducted under its authority, probably around 900. A second series of ages is between 1526 (terminus post quem, 14C) and 1760 (terminus ante que, on the Alsatian cadastre), corresponding to a reopening after the abandonment of the sector during the Thirty Years' War, between 1634 and 1760. As for the GAR site, this period is marked by an abandonment of the sites in favor of the grasslands.

6 | CONCLUSION

This study demonstrates the benefits of using pedoanthracology for lynchet analysis. We identify that the majority of these Lynchets have a medieval origin, probably High Middle Ages (5–10th century) for

three of the landforms (MBW, ALP, and GOLF). We show that some sites, such as the GAR site, have a complex chronology with land use changes that are sometimes centennial, demonstrating socio-economic variations. Pedoanthracology has been used to highlight these land use changes, sometimes supported by other data. We thus show that dating and identification of charcoal species are essential for understanding the temporal trajectories of ancient cropping systems, even if the temporal variability of the dates needs to be complemented by historical, archaeological, and palynological data. We also highlight the homogeneity of medieval and modern/contemporary dates in the Vosges Mountains (GAR, SAA, ALP, and GOLF). This raises the question of the late persistence of vast forest areas, between the Vosges summits and the Rhine plain and the valley bottoms, all of which were largely cleared from the Neolithic period. It is possible that in these intermediate areas, late forest clearings were carried out under the aegis of monastic authorities, as seems to be the case in the Rhine Graben region, where the presence of abbeys created between the seventh and eighth centuries coincides with the existence of vast lynchet plots (Schwartz et al., 2019, 2020). Nevertheless, as we were able to demonstrate with the WBT site and as already demonstrated by Vervust et al. (2020) and Georges-Leroy et al. (2012), the change in scale between the dating of a lynchet and that of a lynchet plot raises questions, even when the 14C dates do not show dispersion, and especially when very little additional information is available. The dispersion of 14C dates that we were able to note within the MBW and GAR soil profile, some of which come from inherited charcoal (either present before the formation of the lynchets or accumulated by colluvium) and others from later clearing episodes when the environments were reopened, would be important to be able to determine the date corresponding to the formation of the lynchet.

In the case of the WBT site, we have shown that it is not easy to determine the age of the lynchet system, even when this system shows a high degree of homogeneity that may indicate a synchronic construction. If in the case of Goldbach-Altenbach the attribution to the Early Middle Ages was relatively simple (Schwartz et al., 2020), the general dispersion of the ages requires the use of other geochronological methods that could provide additional information than only 14C dating on charcoal. The use of OSL has already been carried out in the southern Rhine Graben with convincing results (Froehlicher et al., 2016; Larsen et al., 2016; Stolz et al., 2012). Nevertheless, luminescence dating has certain limitations, including the risk of incomplete bleaching (Sanderson & Murphy, 2010), especially as bioturbation in soils prevents stratification. However, prospective applications of OSL dating using a portable OSL reader (PR), developed by Sanderson and Murphy (2010), could allow the evaluation of luminescent signal intensity changes in the soil profile and to assist in choosing the sample dating. This method has already been successfully used in agricultural terraces or lynchets to obtain a detailed chronology of sediment accumulation (Porat et al., 2019; Turner et al., 2021; Vervust et al., 2020).

AUTHOR CONTRIBUTIONS

Benjamin Keller: Investigation; writing—original draft; methodology; visualization; writing—review and editing. **Robin Vincent:** Methodology; validation; writing—review and editing; supervision. **Dominique Schwartz:** Supervision; conceptualization; validation; investigation. **Damien Ertlen:** Conceptualization; investigation; funding acquisition; writing—original draft; methodology; writing—review and editing; supervision; project administration.

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DATA AVAILABILITY STATEMENT

Data are available in the Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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