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Late Holocene sedimentation and palaeoagronomy in a carbonate dry valley system using OSL, sedaDNA and geochemistry: Implications for understanding anthropogenic slope-sediment transfer in fluvial headwaters

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ABSTRACT

The understanding of landscape stability and erosional regimes from carbonate geological areas has traditionally been limited to fluvial areas due to the lack of lakes and the predominance of clastic-dominated valley fills. The combination of novel Optically Stimulated Luminescence (OSL) dating and sediment ancient DNA opens up new possibilities to study these geomorphological, ecological and agrarian changes in clastic-carbonate landscapes. Here, we use OSL dating and sedaDNA analyses alongside traditional geoarchaeological techniques to examine potential anthropogenic and palaeoclimatic drivers of sediment transfer within a loessic-dominated dry valley with agricultural lynchets at Sint Martens-Voeren, eastern Belgium, through the late Holocene.

Cultivation of loess-dominated sediments across the dry-valley hilltop occurred from the Bronze Age (1900–700 BCE), with lynchet formation on the steep valley sides occurring from later prehistory (Iron Age 700–50 BCE). Major erosion and valley bottom sedimentation began in the early medieval period (450–1000 CE) and accelerated in the medieval and post medieval periods (1000–1750 CE) in line with an intensification of arable cultivation, particularly beet and hops, the development of open three-field agrarian diversity, landscape connectivity and increased climatic variability. This pattern of late Holocene slope-sediment erosion, transfer and storage mirrors other dry valley sites in the Voer catchments, especially in relation to lynchets, and accelerations in sedimentation in other eastern Belgian fluvial catchments, driven by high-intensity palaeoagronomic systems.

1. Introduction

Understanding of the drivers of landscape change in carbonate-dominated terrains has always been hampered by problems of geochronology, environmental reconstruction and land use change, all related to the lack of suitable organic sediments for radiocarbon dating and palaeoecology. This paper approaches this problem by combining the now well-developed dating methodology of optically stimulated luminescence (OSL) with the well-established method of sedimentary ancient DNA (sedaDNA) metabarcoding, alongside traditional environmental analytical techniques.

In areas dominated by carbonate geology (e.g. limestones and chalks), organic deposits are however rare, limiting radiocarbon dating and palaeoenvironmental reconstructions. However, many of these

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areas, including NW Europe, are also characterised by a cover of Pleistocene wind-blown loess sediments (Catt, 1988, 2001; Lehmkuhl et al., 2021). The fine-grained medium to coarse silt to fine sand texture of loess and loess-derived sediments make them ideal for OSL dating (Lang and Hönscheidt, 1999; Fuchs and Lang, 2009; Vandenberghe et al., 2025), particularly in relation to agricultural lynchets (Pears et al., 2024) and for the relatively new environmental technique, sedaDNA (Brown et al., 2025).

The majority of environmental reconstructions using sedaDNA have been based on permafrost samples and undisturbed lacustrine environments from cold regions (Garcés-Pastor et al., 2023; Revéret et al., 2023; Alsos et al., 2024) In contrast, mid-latitude temperate landscapes have been significantly under-represented due to concerns about the environmental and depositionary conditions required to ensure preservation and successful extraction (Brown et al., 2025).

However, developments in the sedaDNA methodology, specifically

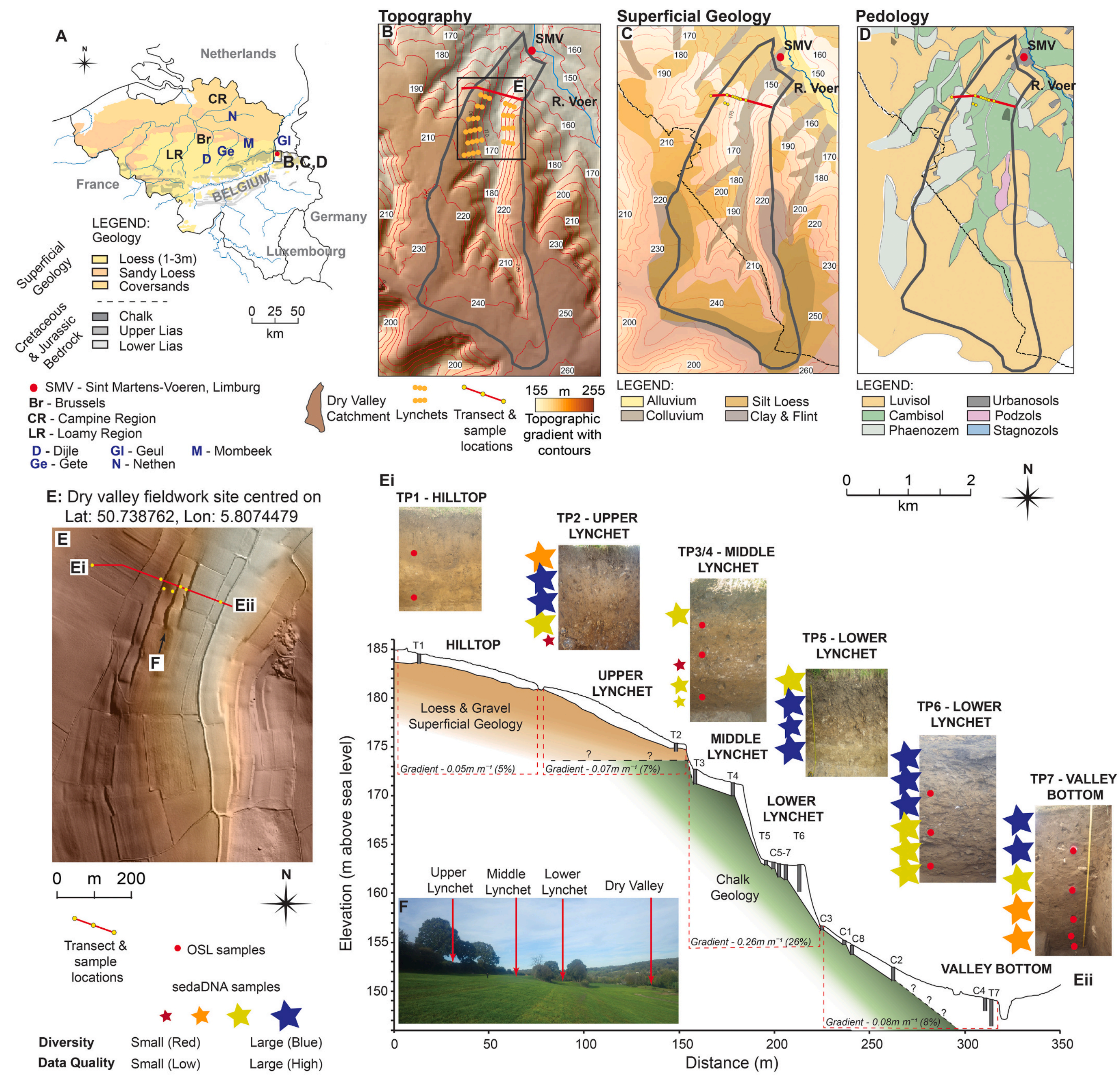

Fig. 1. A, Location map of Sint Martens-Voeren within eastern Belgium alongside dominant carbonaceous solid lithologies and superficial geology; B, Topography and geomorphology of the dry valley south of Sint Martens-Voeren and the River Voer showing catchment area, extent of lynchets and transect and sampling locations. Base map uses 1m hillshade model and coloured topographic gradient derived from 1m DTM Lidar data (Flanders Information Agency, ALS, 2014); C, Extent of mapped superficial geology within the dry valley dominated by colluvium in valley bottom (Ondergrond Vlaanderen, 2021) with 10m contours; D, Extent of mapped soils within the dry valley dominated by cambisols and luvisols (Ondergrond Vlaanderen, 2021); E, Topography of landscape around sample transect, demonstrating extent of lynchets, centred on Lat: 50.738762, Lon: 5.8074479. Base map uses 1m hillshade model and coloured topographic gradient derived from 1m DTM Lidar data (Flanders Information Agency, ALS, 2014). Valley cross section (Ei-Eii) shows major sampling locations across hilltop (TP1), agricultural lynchets (upper TP2, middle TP3/4, lower TP5, TP6) and valley bottom (TP7) with OSL sampling positions and sedaDNA sampling positions with ecological diversity and data quality; F, Photograph of sample transect shows lynchets and contemporary vegetation and land use. Photo taken by the authors.

improvements in the amplification of DNA bound to fine sediment (Alvarez et al., 1998; Giguet-Covex et al., 2014; Garcés-Pastor et al., 2022), and the development and improvement of Polymerase Chain Reaction (PCR) and Next Generation Sequencing (NGS) (Taberlet et al., 2007, 2012) have now made it possible to extract reliable results from temperate soils and sediments with a requisite clay and silt texture. This has expanded its utilisation into low-energy, fine sediment dominated terrestrial locations, including floodplains and archaeological deposits (Brown et al., 2021; Hudson et al., 2022, 2023).

The development and utilisation of sedaDNA in the clastic and calcareous dominant nature of colluvial sediments within chalkland dry valleys provides a valuable development in our understanding of these areas which traditionally have a poor preservation of pollen (Wilkinson, 2003; Bell et al., 2020). Furthermore, traditional environmental indicators e.g., terrestrial mollusca, can only provide a limited and generalised interpretation of vegetation cover (Evans et al., 1992). As a result, our understanding of geomorphic forcing and trigger factors in these, generally densely populated landscapes has largely been derived from hinterland pollen sequences from alluvial deposits, both on, but more often, off the limestone bedrock (Barreto et al., 2024).

Multiproxy studies of geomorphological change on the chalkland scarp landscape and central loessic belt have been a major theme of research across central Belgium, with particular focus on fluvial contexts (Rommens et al., 2007; Verstraeten et al., 2009a, 2017; Notebaert and Verstraeten, 2010; Notebaert et al., 2009, 2018, 2011a, 2011b; Broothaerts et al., 2013, 2014, 2021; Hoevers et al., 2022a, 2022b). However, there has been less focus on headwater contexts and dry-valley locations due to issues with suitable environmental proxies and dating. This paper utilises the specific physical and chemical properties of in situ and reworked loess from a dry valley sequence at Sint Martens-Voeren, Belgium (Fig. 1) combining OSL dating, sedaDNA and sedimentological analysis, to better understand sediment erosion and slope transfer through time in relation of changes in historic land cover, land use and climatic variation. Thereby addressing the key temporal, hillslope-floodplain interconnectivity, sedimentological-hydrological and human impact research problems outlined by (Broothaerts et al., 2021).

2. Study location

The case study site of Sint Martens-Voeren, is located on the eastern edge of the extensive central Belgian loess belt in the province of Limburg (Fig. 1). The dry valley catchment forms part of the fluvial system of the River Voer with chalk basal geology overlain by silt loessic luvisols and clay-with-flints across the catchment margins and colluvial cambisols in the valley bottom. The study sample area lies at the junction of the steepest mid-valley chalkland slopes with a series of large lynchet features, modelled in detail with LiDAR, UAV-SfM photogrammetry and TLS (Cucchiaro et al., 2021). The topography of the sample transect has gradients which range from 0.06 to 0.08 m m^{-1} [6–8 %] across the smooth hilltop and broad-sided dry valley bottom to 0.26 m m^{-1} [26 %] across the agricultural lynchets (Supplemental Material S1). Despite no direct relation to in-situ archaeology at this site, the nature of the historic agricultural landscape in the wider Voer valley is captured by the presence of widespread hedged boundaries within the contemporary landscape and presented in the extensive historic maps and archaeological record of the area highlighting the extent of the cultivated landscape in the mid-18th century across open field systems which were created in the medieval period.

3. Sampling and methods

The sediment stratigraphy of the valley transect at Sint Martens-Voeren, Belgium was investigated with seven machine excavated 1.5 m square test pits positioned at the hilltop, across the upper, middle and lower lynchets and within the dry valley bottom (Fig. 1). The stratigraphy was interpolated between these locations using additional hand-augered boreholes (Supplemental Material S2), and age determination conducted in five tests pits using 14 OSL samples (Supplemental Material S3, Supplemental Table S1). OSL dating utilised fine-silt quartz-extracts following Mauz and Lang, 2004. All OSL ages show low analytical uncertainties and are stratigraphically consistent. Chronological modelling of the OSL dates was conducted using OxCal, v.4.4 with IntCal20 program (Bronk Ramsey, 2008, 2009, 2017), using the OSL setting and relevant requirements [U = linear, k-perameter = 1, Poisson interpolation rate = 0.3, General outlier model = 0.05] to calculate calendrical dates at 2σ [95.4 %] confidence (Supplemental Material S4, Supplemental Fig. S1). To establish further confidence in the chronological modelling and provide additional cryptostratigraphy sensu Staff et al. (2024) portable Optically Stimulated Luminescence (pOSL) was conducted (Supplemental Material S5). By extracting and analysing samples between 1 and 5 cm resolution the pOSL provided strong confirmation of the nature of the age depth models along with minor variations in the levels of feldspar and quartz mineralogies and small peaks caused by the influx of older sediment into the core profile (Pears et al., 2020; Pears et al., n.d.).

At the excavation positions on the sample transect, sediment sequences were hand excavated back to clean, undisturbed layers prior to graphical and descriptive recording. This was followed by in situ analysis and monolith extraction for sediment analyses under field and laboratory conditions. Stratigraphic and sedimentological variations at each test pit were analysed in the field and under laboratory conditions using a Niton XL3t GOLDD+ portable X-Ray Fluorescence (pXRF) analyser. A full methodology of that procedure is included in Supplemental Material (S6). The chemostratigraphic results determined by the field and laboratory pXRF were scrutinised against organic and textural characterisation determined using loss on ignition (LOI), magnetic susceptibility (MS) and particle size analysis (PS) (Supplemental Materials S7 to S9).

Following data collection, quality and checking was conducted on the 39 identified elements to determine which examples were paramount to determining sediment provenance and post burial alteration. This process highlighted 11 key elements which provided chemostratigraphic variations associated with coarse clastic sediment (Ti, Si, Zr), fine grained sediment (Al, K, Rb), carbonate (Ca, Sr), redox (Fe, Mn) and proxy organic content (S), which could be compared with other sedimentological analyses (Supplemental Sections S7, S8, S9). These elements were mapped across each test pit sequence by Inverse Distance Weighting (IDW) interpolation using QGIS 3.40.8 (Bratislava) to produce modelled chemostratigraphic profiles (Supplemental Figs. S2, S3, S4 and Figs. 2, 3, 4, 5). The remaining 28 elements including heavy metals and trace elements did not provide any additional information to the formation or erosional process.

In addition to the chemostratigraphic modelling further Principal Component and Variable Factor Analysis alongside Pearson's (n) Correlation statistics were also conducted on seven key elements as these represented the main formation elements associated with coarse clastic sediments (Ti, Si, Zr), fine clastic sediments (Al, K, Fe) and carbonates (Ca). This was conducted using XLStat 2019.3.2 to demonstrate variation between in situ loess and base carbonate geology. For each test pit the pXRF data were clustered into horizon averages based on field recording and sedimentological analyses and plotted on individual distance biplots and Varimax rotation plots with an automated coefficient (Supplemental Table S2, Supplemental Fig. S5).

Palaeoecological reconstruction of vegetation cover and crops was conducted using sedaDNA analysis. Sampling took place across six test pits and a total of 24 samples were taken covering the upper lynchet (TP2, x5 samples), the middle lynchet (TP3, x3 samples and TP4, x1 sample), the lower lynchet (TP5, x4 samples and TP6, x6 samples) and the valley bottom (TP7, x5 samples). At each sample location, the trench section was cleaned with a bleach-sterilised trowel to remove potentially contaminated material and sediment extraction was conducted with a new, sterile 50 ml falcon tube pushed directly into the section and

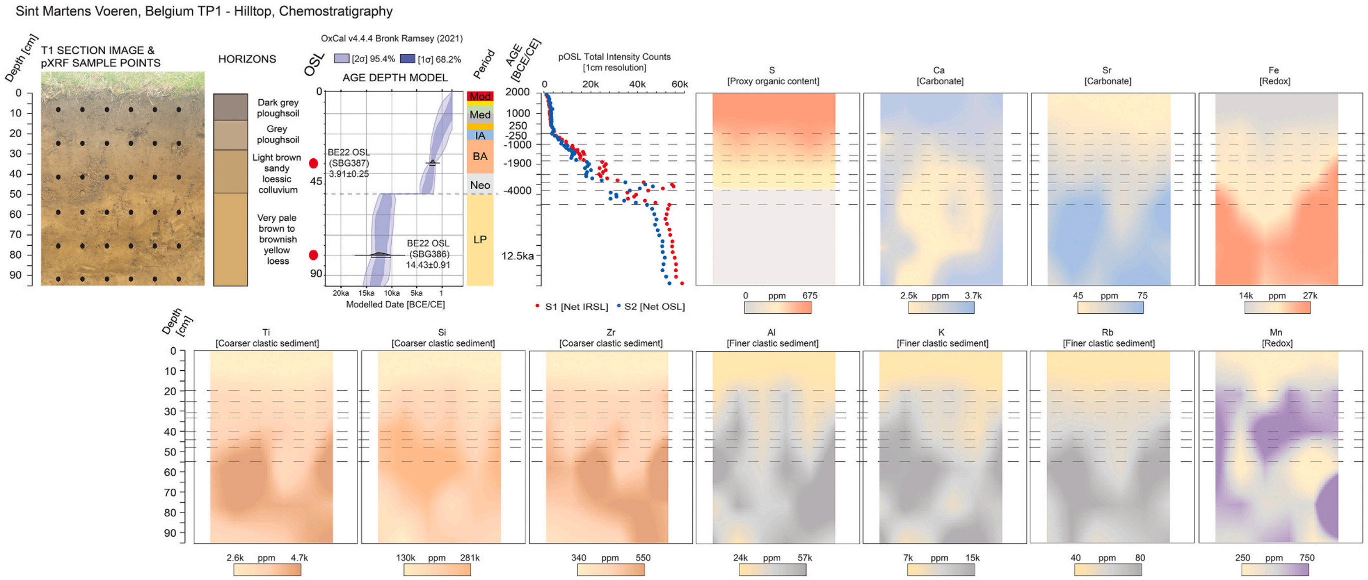

Fig. 2. Hilltop sediment sequence (TP1) at Sint Martens-Voeren, Belgium including section image with pXRF sampling points; horizon descriptions; OSL age-depth model and interpolated periods (see Supplemental Table S1 for period details); pOSL net intensity counts highlighting sediment stability and/or mixing across the infrared – feldspar and blue light – quartz spectrum; and interpolated chemostratigraphy in parts per million [PPM] by specific element for proxy organics (S); carbonate (Ca, Sr); coarse clastic sediment (Ti, Si, Zr); fine clastic sediment (Al, K, Rb) and redox conditions (Fe, Mn).

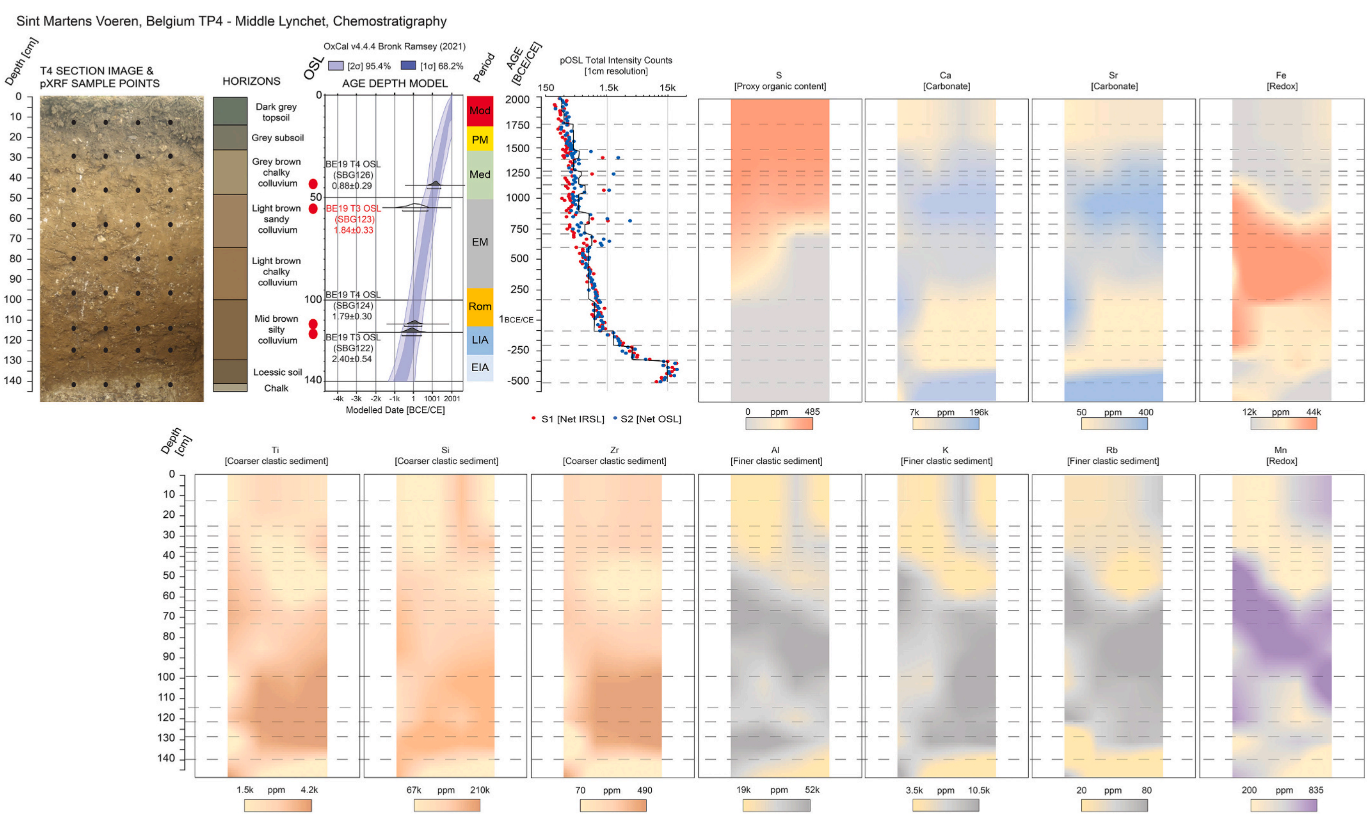

Fig. 3. Middle agricultural lynchet sediment sequence (TP4) at Sint Martens-Voeren, Belgium including section image with pXRF sampling points; horizon descriptions; OSL age-depth model and interpolated periods (see Supplemental Table S1 for period details); pOSL net intensity counts highlighting sediment stability and/or mixing across the infrared – feldspar and blue light – quartz spectrum; and interpolated chemostratigraphy in parts per million [PPM] by specific element for proxy organics (S); carbonate (Ca, Sr); coarse clastic sediment (Ti, Si, Zr); fine clastic sediment (Al, K, Rb) and redox conditions (Fe, Mn).

immediately removed, sealed with a sterilised lid, labelled and then stored at 4 °C. Following sampling, DNA extraction was conducted under dedicated ancient DNA laboratory conditions at the Tromsø University Museum, UiT – The Arctic University of Norway. Extraction and quality checking of the P6 loop of the trnl (UAA) intron with taxa from the PhyloNorway database (Alsos et al., 2020), provided a total dataset of 24 samples containing 5,084,332 reads and 5925 polymerase chain reaction (PCR) repeats of 420 taxa. As we ran eight PCR repeats

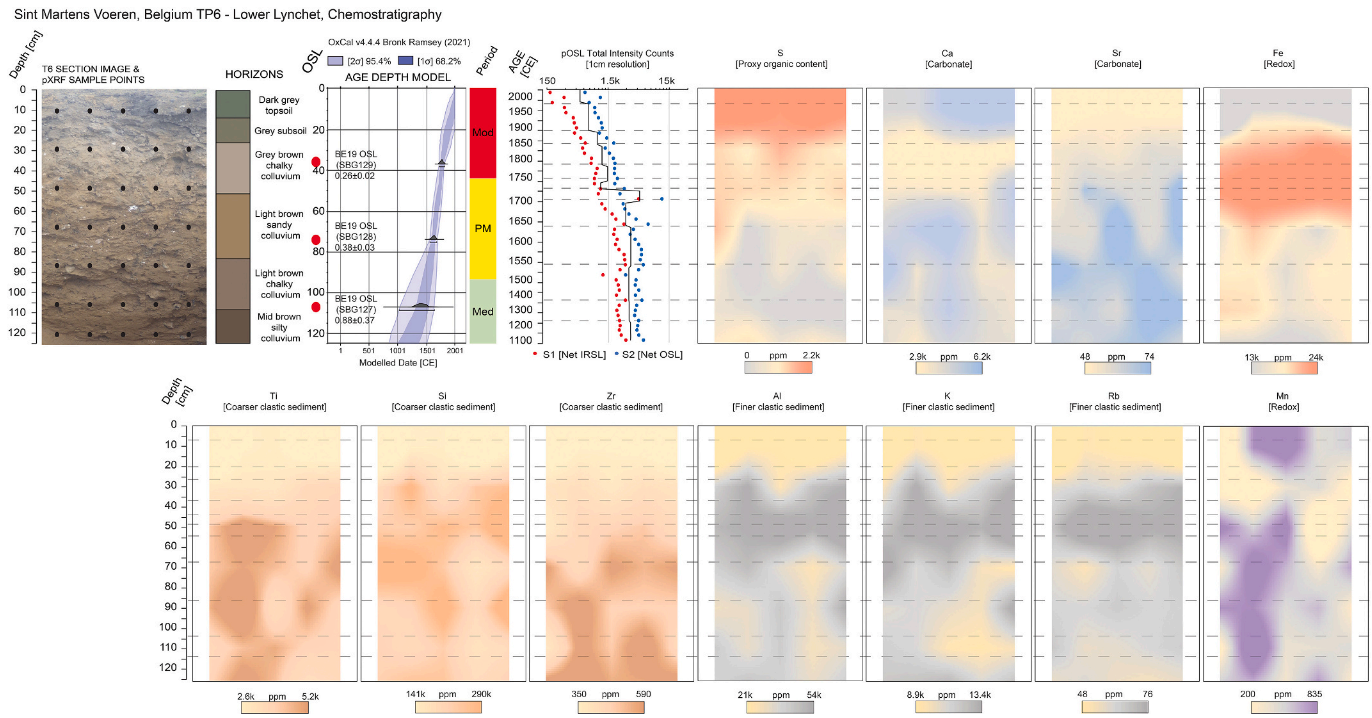

Fig. 4. Lower agricultural lynchet sediment sequence (TP6) at Sint Martens-Voeren, Belgium including section image with pXRF sampling points; horizon descriptions; OSL age-depth model and interpolated periods (see Supplemental Table S1 for period details); pOSL net intensity counts highlighting sediment stability and/or mixing across the infrared – feldspar and blue light – quartz spectrum; and interpolated chemostratigraphy in parts per million [PPM] by specific element for proxy organics (S); carbonate (Ca, Sr); coarse clastic sediment (Ti, Si, Zr); fine clastic sediment (Al, K, Rb) and redox conditions (Fe, Mn).

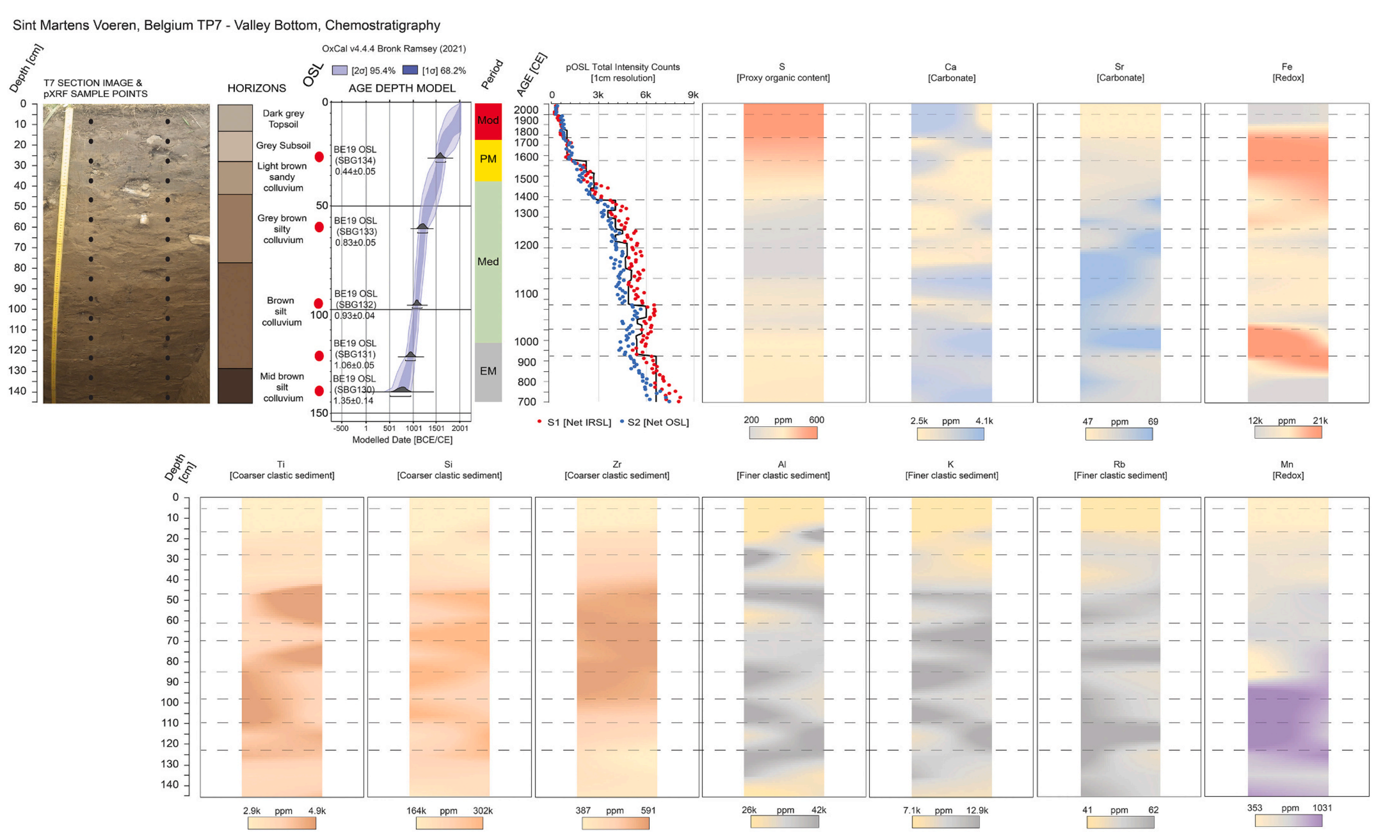

Fig. 5. Valley bottom sediment sequence (TP7) at Sint Martens-Voeren, Belgium including section image with pXRF sampling points; horizon descriptions; OSL age-depth model and interpolated periods (see Supplemental Table S1 for period details); pOSL net intensity counts highlighting sediment stability and/or mixing across the infrared – feldspar and blue light – quartz spectrum; and interpolated chemostratigraphy in parts per million [PPM] by specific element for proxy organics (S); carbonate (Ca, Sr); coarse clastic sediment (Ti, Si, Zr); fine clastic sediment (Al, K, Rb) and redox conditions (Fe, Mn).

per sample, we used these replicates as a proxy for taxon abundance. A full methodology of that procedure is included in Supplemental Material (S10).

Statistical analysis (following Rijal et al., 2021) was also conducted on each of the sedaDNA data (Supplemental Material S11) including the determination of total reads and replicates, average reads and replicates, total taxa (TT), average number of taxa, the average metabarcoding analytical quality (MAQ), and descriptive MAQ (to determine data quality) lastly the Pearson's correlation coefficient (r) to determine whether the data quality (MAQ) correlated with taxonomic diversity (TT) (Supplemental Table S3).

In order to contextualise the sedaDNA palaeoecological information, contemporary ecological diversity and conditions were recorded on each of the narrow risers between the lynchets (Supplemental Table S4). In the field the contemporary vegetation of each lynchet riser was recorded at 30 m intervals and this also enabled the use of an additional hedgerow dating methodology (Hooper et al., 1971). This information could then be compared to the range of historic and modern land use maps of the area for a more comprehensive analysis of the landscape change through time.

Finally, sediment volume and transfer calculations were made across the sample transect using the mean recorded sediment depth at each test pit and core location to be compared against research in other dry-valley catchments with lynchets (Supplemental Table S5). Sediment volume calculations were extrapolated out to the dry-valley catchment scale, by land use division, by multiplying by the calculated area determined from the Lidar data by an average bulk density of 1.6 t m^{-3} to give the volume in [t km^{-2}] and then by the sediment accumulation rates to give the sediment storage at the Hill Top, Hillside with lynchet, Hillside with no lynchets and Valley Bottom in [t km^{-2} yr^{-1}] (Supplemental Table S6). The resultant values could then be compared to volumetric data from additional fluvial sites by landscape position through time (Supplemental Table S7).

4. Results

4.1. Transect stratigraphy and chemostratigraphic (pXRF) profiling

Sedimentological analysis across the valley transect revealed a complex depositional history. Across the hilltop (TP1) (Fig. 2, Supplemental Fig. S6) 1 m of stratigraphy was excavated which included 0.15–0.2 m of organic topsoil and subsoil above a 0.15–0.2 m clay silt loam agricultural soil, dominated by organic material and lack significant clastic elements (Ti, Zr, K, Al, Si, Fe), the base of which presented an Early to Middle Bronze Age OSL date 1870–1390 BCE. These pedological horizons were located directly upon +0.5 m of very pale brown to brownish yellow sandy silt loess superficial geology dated to the late Pleistocene [12,29–10,95 ka BCE]. Detailed textural analysis of this loess indicated a dominant uniform modal coarse silt fraction [40 μm] with low clay content and 24–32 % fine sand composed primarily of Si with a geochemistry also consisting of Fe, Al, K and Ti with minimal Ca, but enhanced pOSL intensity readings, between c.35-40 k, compared to the overlying pedological deposits [c. 5 k].

At the edge of the hilltop, the land dropped gradually away to the east and formed the upper lynchet. This was investigated at TP2 where 0.10 m of topsoil overlay a grey subsoil [0.10–0.25 m] and several mid to light brown sandy colluvial deposits [0.25–0.50 m] (Supplemental Fig. S4). OSL dates could not be determined from this sample location, however the pOSL results of the lower colluvial deposits [2-8 k] fall into the same intensity range as the later prehistoric and historic horizons in TP1. Unlike TP1, the basal superficial geology in TP2 consisted of very coarse clay gravels, which demonstrated a stable pOSL signature [c.2 k]. Chemostratigraphic profiling of TP2 demonstrates a remnant degraded dark yellowish brown reworked loess [0.46–0.61 m]. This deposit contained lower concentrations of Ti, Zr, K, Al and Si than the loess in TP1, but maintained a very high Fe level and almost complete decalcification. The elemental character of the overlying colluvial and current surface soil mirrors that of TP1, including raised organic content (S) and raised coarse and fine clastic indicators.

The sediment sequence within the middle lynchet, sampled in TP3 and 4 (Fig. 3, Supplemental Fig. S7), was deeper than the hilltop test pits, ranging from 1.4 to 1.6 m directly above the chalk geology. Beneath an organic dominated (from S and LOI) topsoil and subsoil [0–0.26 m] the stratigraphy consisted of distinctive dark yellowish, grey-brown sandy-silt layers and lighter yellowish brown sandy silts dating from the Early Iron Age (550 BCE). Between [0.26–0.75 m] the organic content had stabilised at 3 % and carbonate levels (Ca and Sr) increased alongside a more gradual increase in clastic element indicators. Baseline pOSL intensity values also increased [450–600] but were interspersed with sediment of increased values [to 3 k]. From 0.75 to 1.00 m there is a distinctive increase in coarse/fine clastic indicators and redox elements (Fe and Mn) alongside a marked reduction in organic and carbonate content and a stabilisation of pOSL intensity values [750–1000]. Between 1.00 and 1.30 m there is a dominance of clastic elements (Ti, Si, Zr, Al, K and Rb) and a distinct rise in pOSL values from 1 to 3 k. In contrast organic, carbonate and redox values were very low. At the base of the sequence [1.30–1.45 m], above the basal chalk, there is a major rise in pOSL values [to 15 k] with a rise in carbonate indicators (Ca, Sr) and clastic indicators alongside further reductions in Fe and Mn.

Across the lower lynchet features sampled in TP5 and 6 there was a much greater disparity in sequence depth. TP5 was shallow with 0.55 m of topsoil, subsoil, and thin agricultural horizons above a pale grey to white chalky clay silt (Supplemental Fig. S5). The proximity of the sediment sequence to the grey to white chalky clay silt basal material resulted in the chemostratigraphy of TP5 being dominated by Ca, particularly below 0.29 m. The uppermost horizons between 0 and 0.20 m maintained the elemental signature typical of the topsoil and subsoil deposits found across the other sample locations. The elemental signature within TP5 illustrated low levels of Ti, Zr and Al and raised concentrations of Ca and Sr with little variation down-profile. Greater stratigraphic variation was evident in K, Si and Fe between 0.21 and 0.29 m. No direct dating was ascertained from this sample location, but the enhanced pOSL intensities throughout [c. 5 k–500 k] indicate the sequence has been largely undisturbed and is of some antiquity.

Coring between TP5 and TP6 showed that the lower lynchet deposits rapidly deepened so that at the toe-end at TP6 2.45 m of cultivation deposits were present yet with less distinctive horizonation than in the TP3 and 4. The textural character of the sediments in TP6 (Fig. 4) consist of dark yellowish brown and yellowish grey brown sandy silts and silty sand loams with greater proportions of fine to medium sands alongside reduced pOSL intensities ranging from 150 to 1500 associated with much younger sedimentation from the medieval to modern periods (from c. 1100 CE). Chemostratigraphic modelling of the lower lynchet at TP6 revealed a range of variable depositional phases but overall, the stratigraphy analysed contained geochemical composition most statistically comparable with that of the in-situ loess in TP1, particularly below the contemporary topsoil, subsoil and uppermost horizons, which contained higher organic content. High concentrations of coarse clastic elements Ti and Zr occurred throughout alongside more variable levels of K, Al and Fe and reduced carbonate (Ca and Sr) concentrations. Below the surface sediments, there are higher concentrations of K, Al and Fe, and reduced Ca between 0.29 and 0.62 m. From 0.62 to 1.26 m the sequence maintains increased evidence of coarser sediment deposition (Ti, Zr and Si) compared to lower K, Al and Fe levels and decalcified conditions.

In the valley bottom (TP7), a 2.50 m sediment sequence was identified with sedimentological analysis conducted in the uppermost 1.50 m (Fig. 5, Supplemental Fig. S8). The basal chalk geology was not identified at this location, but additional coring from the bottom edge of the lower lynchet indicated the chalk substrate at 0.30 m below ground level, and this sloped away towards TP7. The sediment sequence comprised much finer grained, light yellowish grey-brown medium silts with higher clay content [c. 4 %] and lower sand percentage [5–15 %] consisting primarily of fine sand. Unlike the lynchet features the valley bottom also illustrated a less well-defined variation in horizonation and consistently low pOSL intensity levels [to 7 k] throughout suggesting progressive, slow deposition (OSL dated from c. 700 CE-present.).

Chemostratigraphic analysis within the valley bottom highlighted a distinctive elemental signature akin to heavily weathered, clastic Zr and Si dominated source material with reduced Ca, Sr and Fe with distinctive phases of deposition visible through distinct horizonation marked by increases and decreases of fine-grained clastic indicators (K and Al). Beneath a distinct yet shallow topsoil [0–0.11 m] with a raised organic content (S and LOI) akin to the surface sediments across the rest of the area a deeper subsoil is present [0.12–0.29 m] with increasing Ti, Zr, K, Al and Si and reduced Fe levels. Between 0.30 and 1.48 m there is evidence of rhythmical variation in accretion in the valley bottom at c.0.1 m resolution with distinct phases of dominant finer (K, Al) clastic deposition over time with less obvious changes in Ti and subtle down profile decreases in Zr and Si. The reduced Ca and Sr levels throughout the sequence also demonstrate widespread but variable decalcification, particularly towards the base.

4.2. SedaDNA results

4.2.1. The upper lynchet (TP2)

In the upper lynchet at TP2 (Fig. 6, Supplemental Fig. S9) dryland trees and tall shrubs are dominated by *Quercus* and Betulaceae (*Corylus/Carpinus*) throughout with 6–8 repeats, suggesting a constant presence of oak trees alongside a hazel/hornbeam and a *Sambucus* (elder) understory, with more sporadic levels, 1–7 repeats, of other canopy-forming trees including *Pinus*, *Juglans*, and *Ulmus*, alongside wet woodland species *Salix* and *Populus*. Dominant hedgerow shrub species include Maleae and *Prunus*, 7–8 repeats, with 4–8 repeats of *Cornus, Clematis*, *Hedera helix* and *Rubus* all indicative of a diverse ecology in the local landscape.

The upper 25 cm of TP2 contained a distinctive range of cultivars, with a distinctive reduction in diversity in the lower part of the sequence. The most common crops are Triticeae, *Hordeum* and Solanoideae, with 4–7 repeats, alongside a prominence of *Humulus lupus* (Hops), 8 repeats, in the uppermost sample.

The graminoids identified in TP2 represent a wide range of grassland habitats. They do increase in relative abundance of replicates up-profile, relating to meadow-grasses (*Poa*, *Poinae*), 8 repeats, becoming more common as pasture becomes more improved and more disturbed with more intensive modern farming regimes. Common forbs include *Ranunculus*, *Rumex* and *Plantago* in the upper 15 cm, all 8 repeats, with an increase in species diversity between 15 and 30 cm, including *Trifolium*, *Prunella vulgaris*, *Rumex* and *Urtica dioica*, all 7–8 repeats, reflecting a combination of arable weeds, pastoral herbs, and hedgerow border herbs.

4.2.2. The middle lynchet (TP3/4)

Despite the presence of very low data quality from samples from TP3 and TP4, broad localised vegetation diversity across the middle lynchet can be determined (Fig. 7, Supplemental Fig. S10). Dryland trees and tall

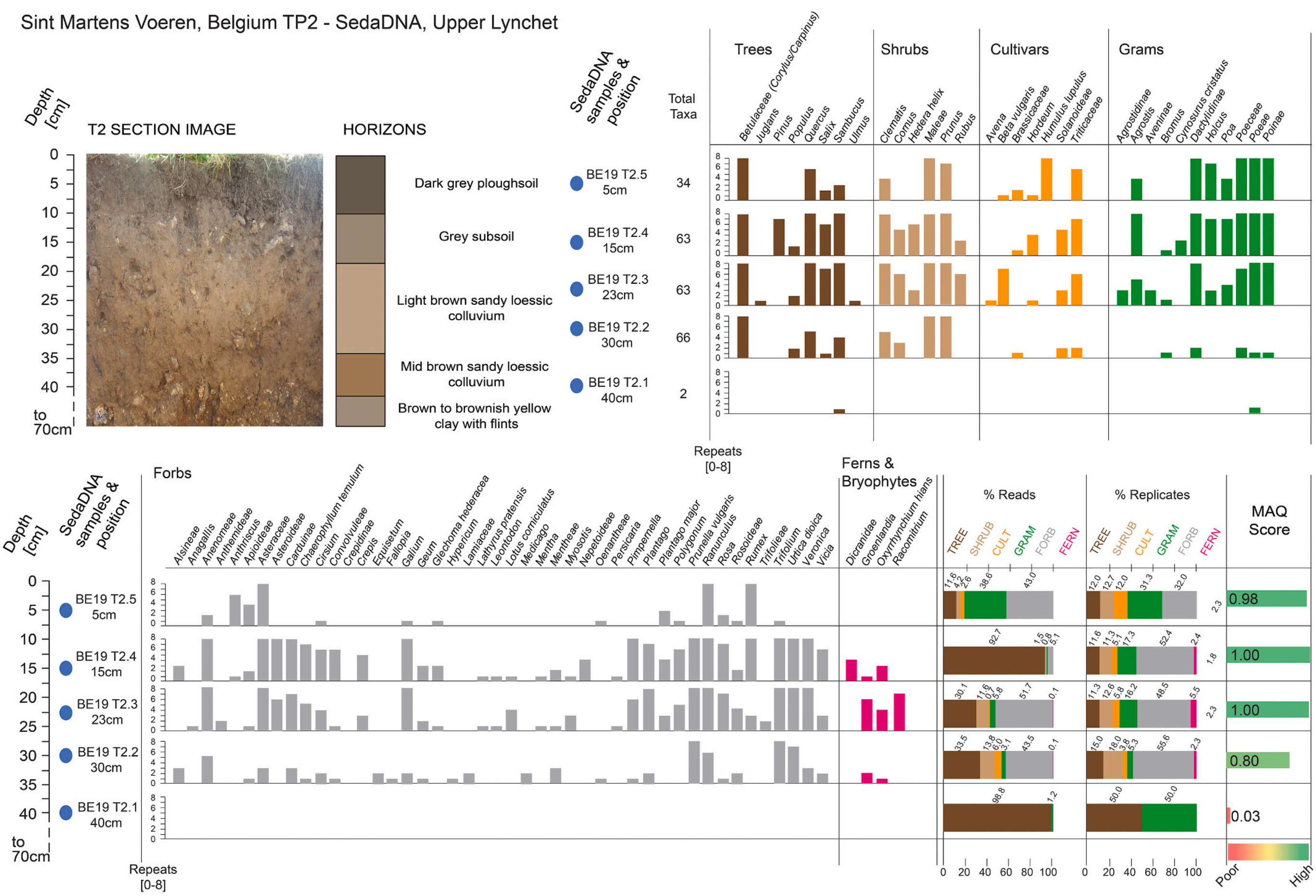

Fig. 6. Summary sedaDNA model of the upper agricultural lynchet sediment sequence (TP2) at Sint Martens-Voeren, Belgium including section image with horizon descriptions; sedaDNA sample positions (blue dots); total number of taxa per sample location; Data presented as number of repeats [0-8] for Trees (brown), Shrubs (light brown), Cultivars (orange), Grams (green), Forbs (grey) and Ferns/Bryophytes (purple); sedaDNA % Reads by the six categories, with individual % demonstrated; % Replicates by the six categories with individual % demonstrated and the metabarcoding analytical quality (MAQ) score [0-1 scale].

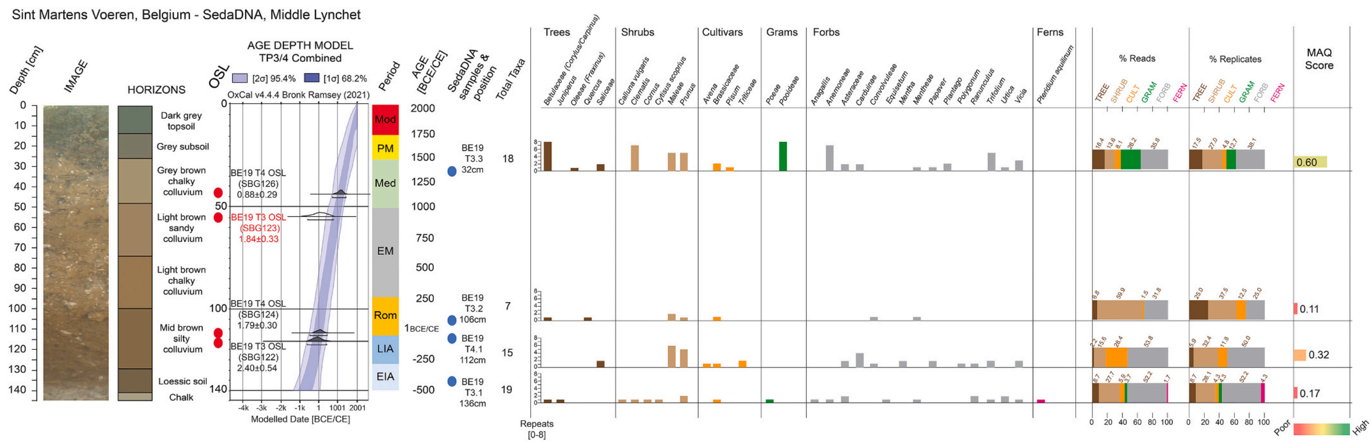

Fig. 7. Summary sedaDNA model of the middle agricultural lynchet sediment sequence (TP3/4) at Sint Martens-Voeren, Belgium including section image with horizon descriptions; OSL age-depth model and interpolated periods (see Supplemental Table S1 for period details); sedaDNA sample positions (blue dots); total number of taxa per sample location; Data presented as number of repeats [0-8] for Trees (brown), Shrubs (light brown), Cultivars (orange), Grams (green), Forbs (grey) and Ferns/Bryophytes (purple); sedaDNA % Reads by the six categories, with individual % demonstrated; % Replicates by the six categories with individual % demonstrated and the metabarcoding analytical quality (MAQ) score [0-1 scale].

shrubs are dominated by the presence of Betulaceae (*Corylus/Carpinus*), 8 repeats, associated with hazel woodland or hedgerows alongside rarer occurrences of *Oleeae* (*Fraxinus*), *Quercus* and Saliceae, 1–3 repeats, with shrub species dominated by high numbers of *Maleae* and *Prunus* with *Clematis*, 6–8 repeats, and an increase in heath taxa (*Calluna*, *Juniperus, Cytisus* and *Cornus*), 1–2 repeats, in the basal sample.

Cultivars include *Avena* and *Triticeae*, 1–3 repeats, from cereal cultivation in the Late Iron Age, and the presence of Brassicaceae and *Pisum*, 2–3 repeats, also indicates fodder and garden crops were being grown.

Graminoids are represented by high levels of *Poeae* and *Pooideae*, 8 repeats, and there is a greater diversity of open, scrub forbs including pastoral species (*Plantago*, *Rumex*, *Trifolium* and *Carduinae*, 1–4 repeats, disturbed ground species including *Anagallis*, *Papaver* and *Urtica dioica*, 1–4 repeats, and the fern *Pteridium aquilinum*, 1 repeat, at the base of the sequence.

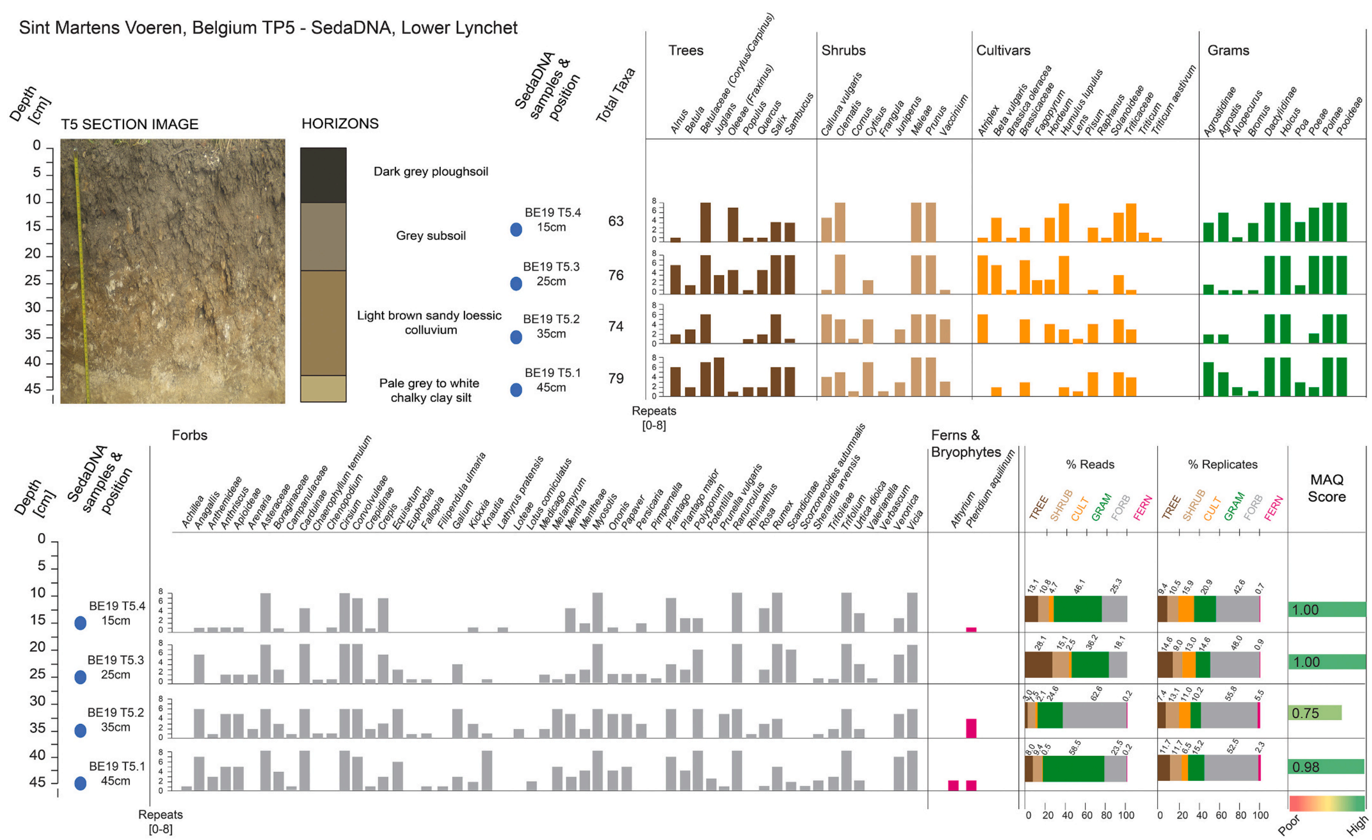

Fig. 8. Summary sedaDNA model of the lower agricultural lynchet sediment sequence (TP5) at Sint Martens-Voeren, Belgium including section image with horizon descriptions; sedaDNA sample positions (blue dots); total number of taxa per sample location; Data presented as repeats [0-8] for Trees (brown), Shrubs (light brown), Cultivars (orange), Grams (green), Forbs (grey) and Ferns/Bryophytes (purple); sedaDNA % Reads by the six categories, with individual % demonstrated; % Replicates by the six categories with individual % demonstrated; the metabarcoding analytical quality (MAQ) score [0-1 scale.

4.2.3. The lower lynchet (TP5/6)

Across the lower lynchet (TP5, Fig. 8, Supplemental Fig. S11 and TP6, Fig. 9, Supplemental Fig. S12) dryland trees and tall shrubs were dominated by Betulaceae (*Corylus/Carpinus*) and *Quercus*, 7–8 repeats, with smaller amounts of *Oleeae* (*Fraxinus*), *Fagus*, *Pinus*, *Tilia*, *Juglans* (walnut), 6–8 repeats, and *Sambucus* present in moderate to smaller amounts, 2–7 repeats, alongside a number of wetland trees including *Alnus, Betula, Populus* and *Salix*, 1–8 repeats. Alongside trees, shrub species identified included common hedging and fruit bearing taxa (Maleae and *Prunus*), 7–8 repeats, as well as *Cornus, Frangula, Pyrus* and *Rubus*, 1–3 repeats. Climbing species are limited to *Clematis* in BE5, 7–8 repeats, but also include *Lonicera periclymenum* and *Hedera helix* in BE6, 1–3 repeats. Both sequences also include a number of heath species including *Calluna vulgaris, Cytisus, Juniperus* and *Vaccinium*, 1–8 repeats.

Cultivar evidence across the lower lynchet includes *Beta vulgaris, Fagopyrum, Humulus lupus, Lens* and *Solanoideae* in the upper sequence samples, 2–8 repeats (which could relate to either potato, nightshades or henbanes). Other crops occur from the very base of the sequence in high amounts; these include 'staple' crop cultivars *Avena, Brassicaceae, Hordeum, Raphanus, Pisum* and *Triticum/Triticeae*, 2–8 repeats. The presence of *Cannabis sativa*, 2–8 repeats, in almost every sample also indicates the cultivation of hemp.

The graminoids species found across the lower lynchet are common to a wide range of grassland and meadow habitats. Both TP5 and TP6 contained high levels of meadow-grasses (*Poa*, *Poeae*, *Poinae, Pooideae*), 8 repeats, as well as *Dactylidinae*, *Holcus,* 2–8 repeats, alongside lower levels of Agrostidinae, *Agrostis*, *Alopecurus* and *Bromus*, 2–8 repeats. Wetland species *Juncus, Carex,* and *Scirpus* were also identified, 1–3 repeats, albeit firmly in the minority as there were only in low numbers of reads and replicates.

The record of the forb community across the lower lynchet is extensive (71 taxa), with similar records highlighted in TP5 and TP6, and these can be grouped into at least three major habitats. There are a large number of disturbed ground and arable weed taxa, including: *Anagallis, Arenaria, Atriplex, Cerastium, Chenopodium, Fallopia, Fumaria, Kickxia, Papaver, Persicaria, Pimpinella, Polygonum, Sherardia arvensis, Valerianella, Verbascum*. Most of these appear in the top 65 cm in low repeats, 2–4, but some, such as *Anagallis, Polygonum,* and *Papaver* appear as high repeats, 7–8, throughout.

Another clear grouping of forbs, and perhaps the most dominant, are those associated with grassland/meadow and/or pastoral communities. These include Carduinae*, Cirsium,* Crepidinae*, Lathyrus pratensis, Leontodon,* Loteae*, Lotus corniculatus, Medicago, Ononis, Plantago, Plantago major, Rhinanthus, Rumex, Scorzoneroides autumnalis,* Trifolieae*, Trifolium* and *Veronica*. Of these, common species of grazed ground dominate, such as Carduinae, *Cirsium*, *Plantago,* and *Trifolium*, 7–8 repeats. Other taxa that appear as moderate-high repeats include Convolvulae, *Lotus corniculatus* and *Lathyrus pratensis*, 6–8 repeats, all common on well-drained, chalk grassland with the former also associated with disturbance.

Thirdly, many forbs seen are associated with hedge, border, and wetland communities. These include *Anthriscus, Glechoma hederacea,*

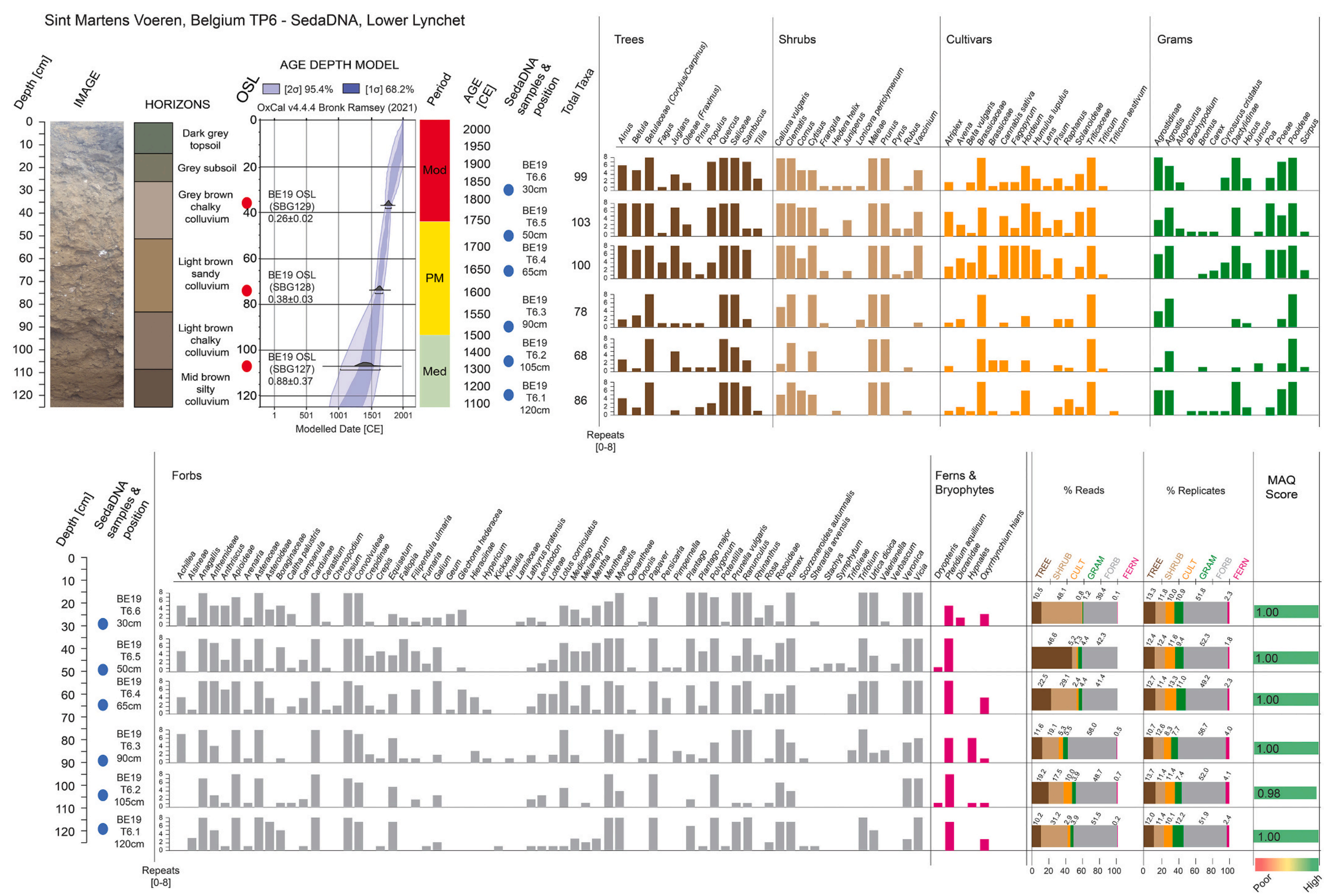

Fig. 9. Summary sedaDNA model of the lower agricultural lynchet sediment sequence (TP6) at Sint Martens-Voeren, Belgium including section image with horizon descriptions; OSL age-depth model and interpolated periods (see Supplemental Table S1 for period details); sedaDNA sample positions (blue dots); total number of taxa per sample location; Data presented as repeats [0-8] for Trees (brown), Shrubs (light brown), Cultivars (orange), Grams (green), Forbs (grey) and Ferns/ Bryophytes (purple); sedaDNA % Reads by the six categories, with individual % demonstrated; % Replicates by the six categories with individual % demonstrated and the metabarcoding analytical quality (MAQ) score [0-1 scale].

Geum, Vicia, Caltha palustris, Equisetum, Filipendula ulmaria, Ranunculus, and *Mentha*, 7–8 repeats. Taxa such as *Anthriscus, Vicia* and *Glechoma*, 2–8 repeats, can be associated with hedgerows, partially shaded areas (also represented by the presence of the fern species *Athryrium* and *Dryopteris*, 2–4 repeats) and damper environments.

4.2.4. The valley bottom (TP7)

In the valley bottom at TP7 (Fig. 10, Supplemental Fig. S13) trees and tall shrubs are dominated by Oleaceae (*Fraxinus*) with Betulaceae, 6–8 repeats, *Quercus*, and *Salicaceae*, 2–6 repeats, alongside *Alnus, Populus, Juglans* and *Sambucus*, 2–6 repeats, with *Ulmus* and *Pinus*, 1–3 repeats, at the base. Shrubs include *Maleae* and *Prunus*, 2–8 repeats, as the usual major taxa, with smaller amounts of *Clematis, Cornus, Calluna vulgaris, Vaccinium* and *Cytisus*, 1–6 repeats.

Cultivars in the valley bottom are dominated by the generic Triticeae assignment, 8 repeats, associated with both domesticated and wild grass species, and it is not possible to distinguish between them at this resolution. *Hordeum* is also very common, 4–8 repeats, and is case-specific to the cultivation of barley. Other cultivars include *Beta vulgaris, Pyrus* and *Pisum*, 2–8 repeats, with less sporadic occurrences of *Fagopyrum, Lens, Raphanus* and *Avena*, 1–3 repeats, in moderate amounts in the upper part of the sequence, and 4 replicates of *Sorghum* possibly great millet (*Sorghum bicolor*) at a single sample location (63 cm).

Graminoids typical of grassland and meadow habitats are present in variable amounts, including Agrostidinae, *Agrostis, Bromus, Dactylis, Holcus, Poa, Poeae,* and *Pooideae*, 2–8 repeats. Forbs present in the valley bottom also represent a mix of pastoral herbs, arable weeds with 8 repeats of *Asteraceae, Carduinae, Convolvulaceae, Rumex, Trifolium* throughout the sequence alongside 6–7 repeats of a range of other forbs and occasional levels of wetland and shady woodland margin and hedge taxa including *Juncus* and *Equisetum*, 4–8 repeats.

5. Discussion

5.1. Sedimentology & chemostratigraphy

The presence of c.0.50 m of in situ loess within TP1 demonstrates the degree to which physically unaltered material is retained upon the

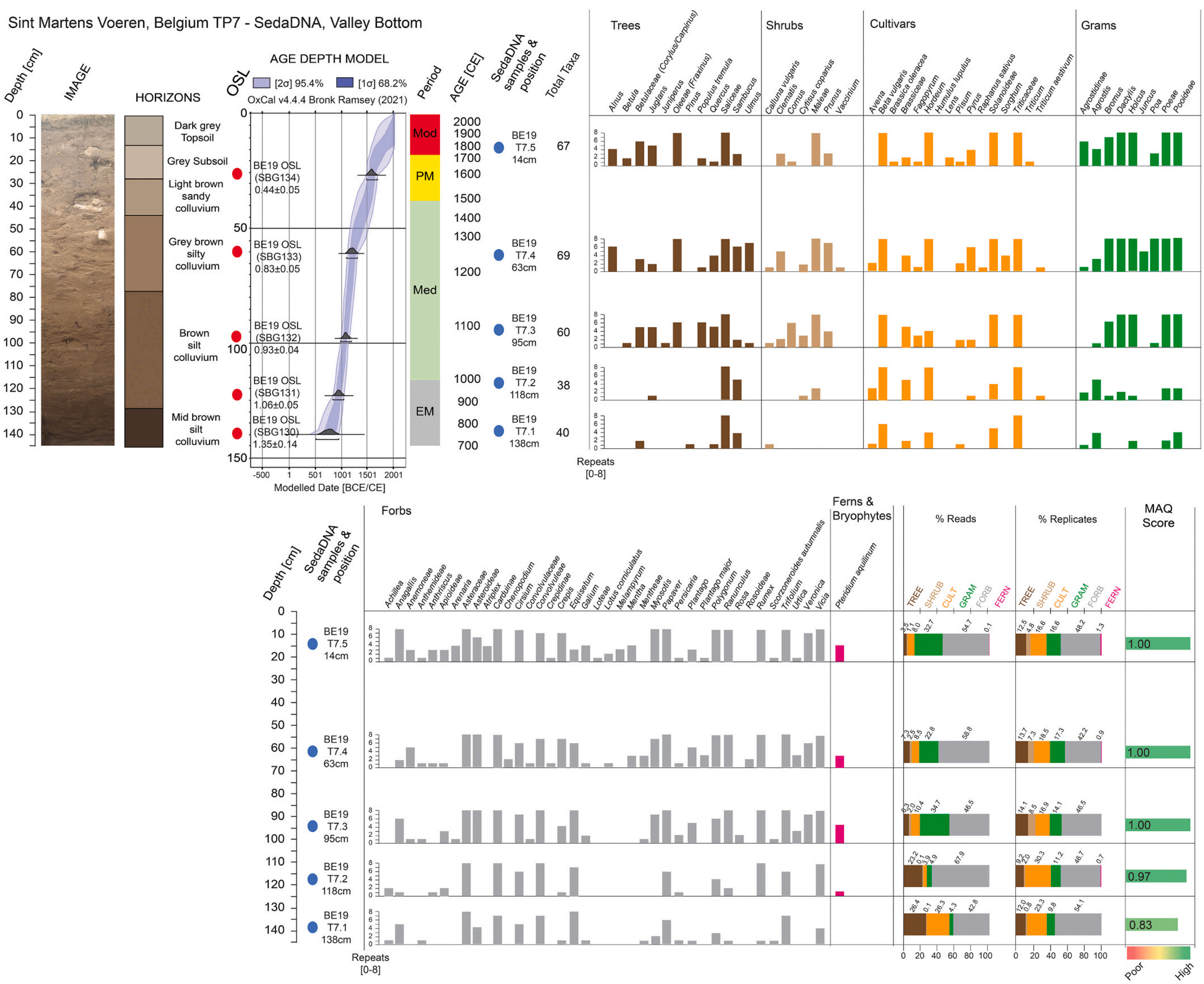

Fig. 10. Summary sedaDNA model of the valley bottom sediment sequence (TP7) at Sint Martens-Voeren, Belgium including section image with horizon descriptions; OSL age-depth model and interpolated periods (see Supplemental Table S1 for period details); sedaDNA sample positions (blue dots); total number of taxa per sample location; Data presented as repeats [0-8] for Trees (brown), Shrubs (light brown), Cultivars (orange), Grams (green), Forbs (grey) and Ferns/Bryophytes (purple); sedaDNA % Reads by the six categories, with individual % demonstrated; % Replicates by the six categories with individual % demonstrated and the metabarcoding analytical quality (MAQ) score [0-1 scale].

contemporary hilltop, despite being decalcified. The dominance of loessic originated sediments across the valley transect and the variation in sequence depths indicates however that significant weathering and erosion of loess has occurred through time (Fig. 11). Chemostratigraphic and PCA analysis have demonstrated that horizons across the toe ends of the three lynchet features (TP2, TP4 and TP6) contain material with the greatest elemental similarity to the in-situ loess in TP1. Variations in the OSL chronologies alongside differences in the physical and chemical character of the stratigraphic sequences indicate varying degrees of erosion and slope transfer rate in the later Holocene driven by increases in cultivation resulting in major colluviation and significant valley bottom sedimentation with distinctive sediment retention within valley edge lynchets.

More specifically, in the shallow soil profile of the upper lynchet in TP2, the removal of Ca and Sr demonstrates significant decalcification as a result of mixing through cultivation and also provides a record of gradual downslope movement of cultivated loess from across the hilltop landscape. In contrast the greater profile depths of the middle and lower lynchets provides a more substantial record of sedimentation and land use change.

In the middle lynchet, there is evidence for some initial loessic reworking during early prehistory, but the increase in sediment variation from the Middle/Late Iron Age onwards suggests an intensification of cultivation and sediment transfer across the lynchet, with the mixed pOSL results demonstrating the repeated addition of older sediment. The major difference here is the continued raised concentrations of both Ca and Sr and this could have derived from the original carbonate held within a basal in situ loess, formed part of deliberate chalk addition through the manuring process, derived from the basal chalk itself, or occurred as a result of increased downslope carbonate transfer from increased surface weathering. It is clear that the prolonged process of cultivation has led to a significant alteration of a former undisturbed basal loess horizon through intensive agricultural mixing, resulting in a heavily modified loessic horizon.

From the early medieval period onwards there is a significant shift in the degree of sedimentation, downslope erosion and land use activity across the lynchets and valley bottom locations. The chemostratigraphic analysis shows that in TP3, 4 and 7, there is a distinctive increase in reworked loess derived sedimentation which derives from an intensification of arable activity across the landscape as a whole. This agrarian activity accelerates in the medieval period, with the onset of the open field cultivation system, and is reflected by a major period of loessic reworking, erosion and colluviation across the lynchets and valley bottom.

By the post-medieval period sediment transfer and colluviation appear to have slowed despite a continuation of arable activity across

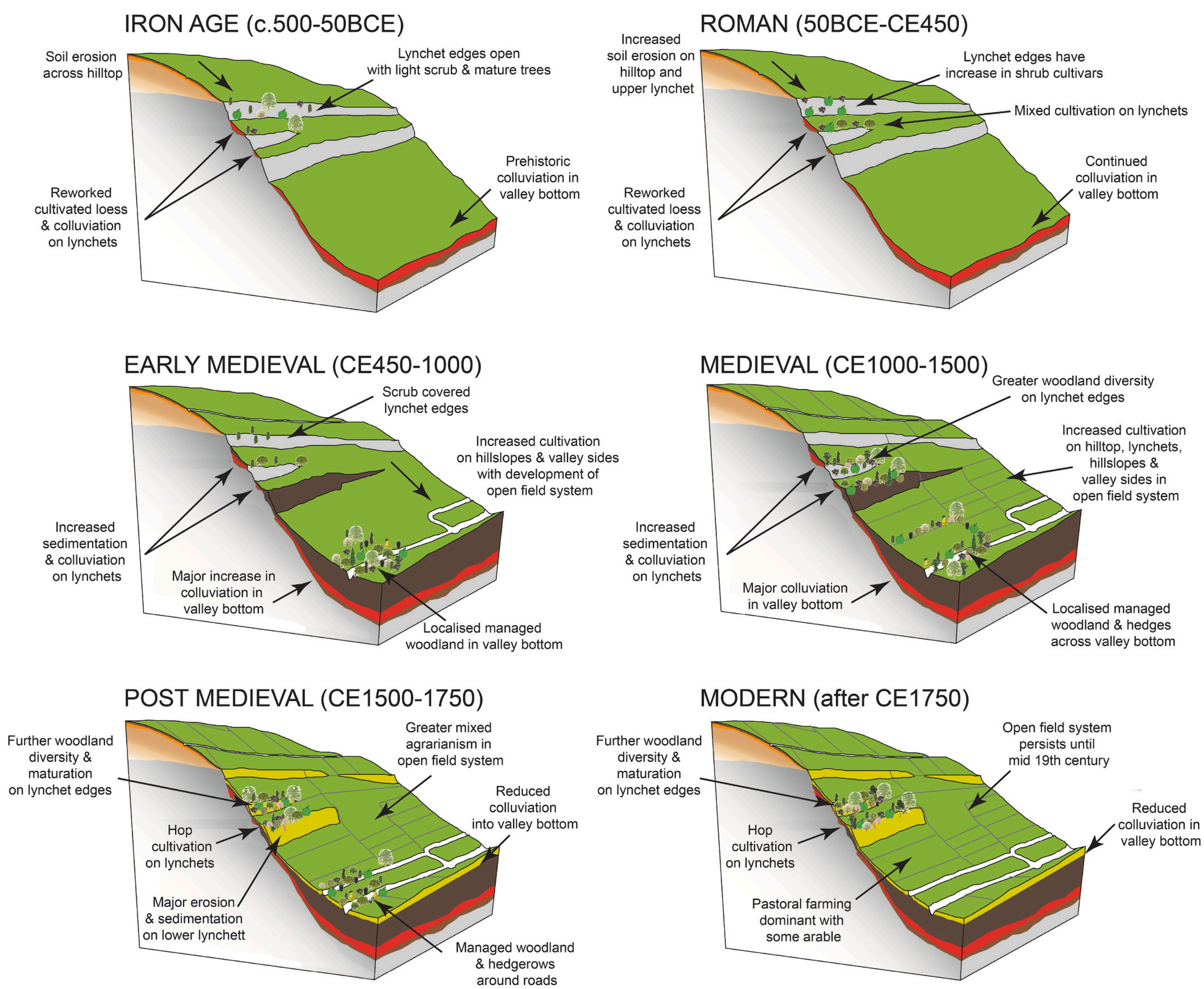

Fig. 11. Sedimentation and palaeoecological reconstruction model through time across the valley transect landscape at Sint Martens-Voeren, Belgium.

the valley side possibly due to an increase in the enclosure of farmland with trees and hedges. That said, sediment erosion across TP6 significantly increases at this time, perhaps as a result of the degree of gradient at this location and in response to significant climatic deterioration and increased rainfall through the Little Ice Age (Büntgen et al., 2011; Wanner et al., 2022). This activity, though, does appear to be clearly constrained to this particular part of the slope system (the steepest section) as similar degrees of weathering and erosion are not seen in either at the base of the middle or lower lynchets, or in colluviation in the valley bottom. In contrast, regular, progressive sedimentation in the valley bottom marked by broad rhymical patterns in the fine-grained clastic indicators (K and Al) indicate a different deposition process to that on the lynchets with colluvial transfer occurring from the wider, steeper slopes of the valley catchment.

5.2. Palaeoagronomy and land use

Palaeoagronomic and palaeoecological characteristics of the upper, middle and lower lynchets, defined by the sedaDNA and contemporary vegetation survey, demonstrated key similarities and differences, and present perhaps the best rural palaeoecological sequence outside of an urban, archaeological context such as Brussels (Speleers and van der Valk, 2017). Overall, the localised palaeoecology of the upper lynchet (TP2) was similar to the other lynchets through the variety of dryland trees and shrubs, oak, ash and hazel, present on the risers and hedgerows. The typical woodland characteristics were observed across the lower lynchet (TP5, 6). Of these, TP6 had greater depth and chronological framework (from medieval to present) but demonstrated relative homogeneity in vegetation type throughout, suggesting that any changes in land use since the medieval period were on a fine scale. Oak woodland was a persistent presence, growing on the toe edge and risers of the adjacent lynchets. *Fagus* also becomes present from the post-medieval period onwards, though as a rarer occurrence. The presence of a large number of hedgerow species is also clear from the data, with some of these (e.g. *Pyrus* and *Prunus*) managed for their fruit, and *Juglans* may also have been planted for walnut consumption from the Roman period onwards (Pollegioni et al., 2017). The TP5 sequence acts as a continuation of the TP6 one in that we see more recent changes to vegetation, notably a slight decrease in diversity (as seen in lower numbers of taxa) despite similar quality scores of the samples. From the contemporary ecological survey, 32 species of vascular plants were recorded from the narrow risers between the lynchets. Of these, 17 were either trees, tall shrubs or woody epiphytes (Supplemental Table S4). Hooper et al., 1971 hedgerow dating methodology suggests an age for the hedge-covered risers of just over 1000 years due to the presence of an average of 10 woody species per 30 m. Whilst this is certainly not a definitive and fool-proof method (Cousins, 2004) the species mix from the contemporary count demonstrates the longevity and great age of some of the epiphytes suggesting that this result is reasonable and that the risers have acted as reservoirs for some of the agricultural activities on the treads (e.g. the cultivation of shrub cultivars) since medieval times. Indeed, the presence of additional species such as *Juniperus*, *Maleae*, *Pyrus*, and *Juglans* in the sedaDNA results suggests an even greater diversity of shrub cultivar evidence through time on the lynchets and dry valley slopes.

The palaeoecology of the valley bottom was very similar in its composition to the lower lynchet and together the three sequences provide an excellent record of ecological diversity and historic land use over the last 1000 years. The record of dryland trees is similar to those found at all the sample locations across the sample transect, particularly the lower lynchet which may be due to their closer proximity. The higher relative abundance of Saliceae, *Alnus* and *Populus* as well as the notable appearance of *Juncus* and *Equisetum* suggests a greater proportion of wet woodland and wetter ground conditions in the valley bottom from the later medieval period (c. 1250 CE). The presence of *Juglans* across most of the sequence suggests a localised presence of walnut in the valley bottom landscape from the medieval period onwards (its absence in the basal sample may be due to data quality) and could have been deliberately grown and managed within hedgerows, alongside other shrub cultivars (*Maleae, Pyrus* and *Prunus)*. Alternatively, its presence could support its identification in the lower lynchet assemblage, and DNA presence due to the extensive erosion and colluviation of sediment in the early medieval and medieval periods.

A greater understanding of land use variability on the lynchets can be seen in the varieties of cultivars. Across the upper lynchet, the dominance of cereal crops *Triticeae* and *Hordeum* and lack of fodder and garden crops (*Pisum*, *Lens*, *Raphanus* and *Fagopyrum*) in this location may reflect the lynchets larger area and closer proximity to the hilltop where increased sunlight would made it more suitable for cereal crop cultivation compared to the middle and lower lynchets.

On the middle and lower lynchets there is more variability between the quality of sedaDNA data, but there are some ecological patterns that exist, such as the detection of garden/fodder crops supported by a collection of arable weeds, disturbed ground indicators, which from a chronological point of view potentially demonstrate cultivation from the Middle/Late Iron Age onwards.

In the later historic period, the presence of *Humulus lupus* (hops) and *Cannabis sativa* (hemp) across the upper and lower lynchets suggest a possible shift to the cultivation of specialist cultivars, however it is also possible that these species indicate a record of the persistence of wild derivatives which would have grown within hedgerows.

Similarly, the presence of *Solanoideae* in the uppermost parts of the sequences, could point towards the cultivation of potato in the recent past. However, this also occurs in the lower parts of TP6, and as this subfamily also includes nightshades and henbanes this is not necessarily an anachronistic identification of potato cultivation, but if it is then could demonstrate possible DNA leaching via earthworm bioturbation, particularly as the common presence of arable weeds *Anagallis*, *Polygonum*, and *Papaver* demonstrate a prolonged phase of intensive cultivation through time.

The presence of arable weeds, disturbed ground indicators and a significant component of pastoral taxa all reflect direct cultivation and pastoralism across the lynchet from the medieval period onwards. In the vegetation survey, some of the epiphytes were also old and there were several that had probably originated from previous crops including *Humulus lupulus* (hops), identified to species level in the sedaDNA in TPs 2, 5, 6 and *Prunus padus* (bird cherry), identified to genus level in the sedaDNA at all locations. Many of the plants have also been managed for food and/or hurdling or fuel, and nearly all the species are typical of anthropogenically influenced habitats.

In the valley bottom profile, the dominance of *Triticeae* and *Hordeum* suggests that the arable processes at this location were akin to those across the upper lynchet and possibly the hilltop, due to larger field sizes and fertile soil depth. That said, the presence of other cultivars: *Beta vulgaris, Pisum, Lens, Raphanus, Fagopyrum,* and *Avena* suggests a high degree of cultivation variety and crop rotation between cereals, fodder and garden types, required in two- or three-field agrarian systems typical of the early and later medieval periods. The relative abundance of arable and arable weeds is high in the bottom two samples, which could suggest that arable cultivation was higher in the early medieval period. However, this signal could also be an artefact of data quality with, and due to, a greater number of false negatives from other ecological groupings at these depths. Otherwise, arable cultivation remained stable in the upper three samples, indicating continued levels of arable farming in this location for much of the last 1000 years. The presence of Sorghum at a single sample location (63 cm), may also demonstrate rare evidence of the cultivation of great millet (*Sorghum bicolor*) typical of the medieval period particularly the period 1200–1300 CE (Livarda, 2011).

Across large parts of the survey area, the presence of extensive graminoid DNA evidence indicates a wide range of grassland habitats across the upper lynchet. The increase in relative abundance of replicates up-profile is probably due to meadow-grasses (*Poa, Poinae*) becoming more common as pasture becomes more improved and more disturbed with more intensive modern farming regimes and also the likelihood of greater seed contaminants from the wider landscape, which can been seen in the cartographic record of the landscape from the mid- 17th and 18th centuries onwards, particularly the 1842–79 map which provides excellent detail of the remnant and fossilisation of the medieval open field system, the dominance of grassland areas and increase in pastoralism, recorded in annual land use maps (Fig. 12), and witnessed first-hand in the contemporary vegetation survey (Supplemental Table S4).

5.3. Sedimentary processes in the local landscape

This research within the Sint Martens-Voeren chalkland dry-valley system and agricultural lynchets follows former landscape analysis which looked at the form, function and chronology of these anthropomorphic features (Van den Balck and Durinck, 2012; Nyssen et al., 2014), and the conclusions of which can be compared to results from the current research to assist with discussion of sedimentary processes over a broader landscape context (Supplemental Table S5).

The nature and topography of the lynchets on the northern side of the village of Martleburg and Groensdael (in the River Voer valley), were compared with those from El Tawe in the River Meuse valley, to the west (Nyssen et al., 2014). The form of the analysed lynchets varied between the three analysed sites, with variations in number [between 1 and 6], total vertical interval [between 7 and 35 m] and average slope gradient, 0.16 m m^{-1} at Groensdael, and steeper at Martleburg [0.22 m m^{-1}] and El Tawe [0.28 m m^{-1}], gradients which were comparable to the lynchets in the current study which averaged 0.26 m m^{-1} compared to between 0.05 and 0.08 m m^{-1} on the hilltop and in the valley bottom. The average slope gradient for the three risers at Sint Martens-Voeren ranged from 0.625 m m^{-1} at the top to between 0.69 and 0.71 m m^{-1} for the lower lynchets, each of these well within the calculated average riser gradient for the area 0.83 ± 0.17 m m^{-1}, but well above the average height of 2.96 ± 1.66 m (Van den Balck and Durinck, 2012).

At each of the lynchet sites within the Voer catchment, colluvial deposits were recorded on both valley slopes and lynchets to between 1 and 2 m, whereas at El Tawe colluvium was present on the lynchets only. The results gathered from Sint Martens-Voeren are comparable with those from Martleburg and Groensdael and confirm the conclusion that the colluvial deposits are derived from arable cultivation, topography and well-defined historic land use characterisation and arable cultivation (Nyssen et al., 2014), in dry valleys across the Voer valley. Nyssen's lynchet chronologies were formulated using the calculated volumes of increased colluviation and rates of non-mechanised tillage translocation. The sites would have required cropping agriculture for a total of 217–585 years on steep, and 1037–1867 years on gentle slopes.

6. Sediment storage and transfer in dry-valleys and larger loessic fluvial catchments

The determination of chronology, sedimentology, palaeoecology and palaeoagronomy across the sample transect at Sint Martens-Voeren provides the basis for determining a model of the budget and transfer of sediments within chalkland dry valleys and comparison with research conducted in loessic fluvial catchments across Belgium, the Netherlands and further afield.

A greater understanding of the sediment processes in small,

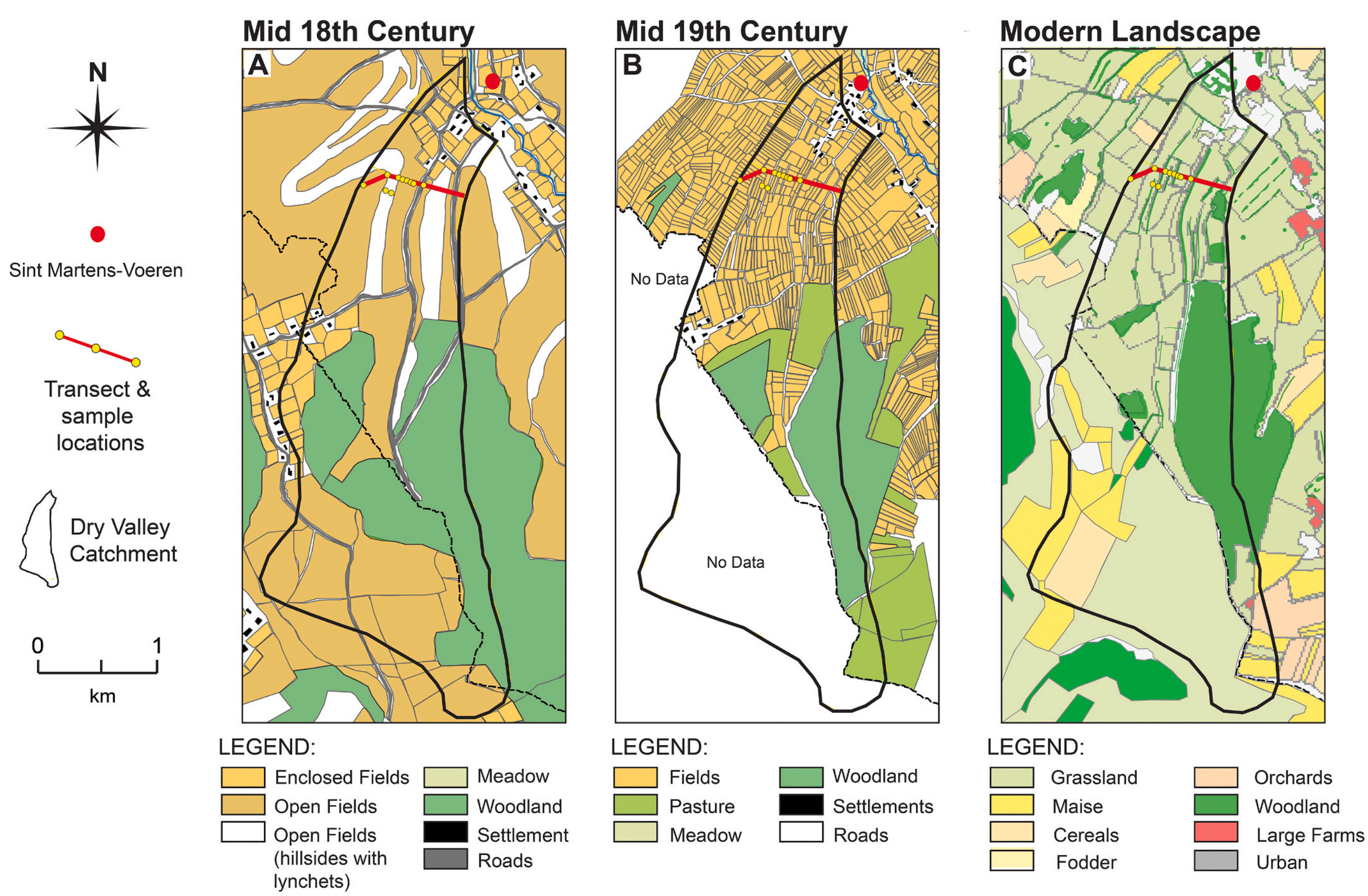

Fig. 12. Historical landscape change across the dry valley research area south of Sint Martens-Voeren, Limburg, Belgium. (A), Mid-18th century rural land use with woodland (adapted from the Villaret Kaarten 1745-48 [Ondergrond Vlaanderen, 2021]); (B) Mid-19th century rural land use with woodland (adapted from the Popp Kaarten, 1842-79 [Ondergrond Vlaanderen, 2021]); (C), Modern urban and rural land use with woodland (Ondergrond Vlaanderen, 2021).

headwater and dry valley catchments such as that at Sint Martens-Voeren which are extremely sensitive to localised variations are essential for the fuller interpretation of landscape trends in riverine areas. Together, these allow for a wider remit of variations in climate and land use through time. In north central Europe, and particularly the agriculturally rich loessic belt area, the progressive development and intensification of woodland clearance, management and cultivation which began in the Neolithic (Lüning, 1996), ultimately resulted in significant degrees of soil and sediment erosion and the creation of widespread colluvium and alluvium (Lang and Bork, 2006).

Calculations of sediment storage across the sample transect at Sint Martens-Voeren (Fig. 13, Supplemental Table S6) demonstrates that the valley bottom landscape [109.82 t km^{-2} yr^{-1}] holds in excess of 2.75 times more sediment than the hilltop [40.10 t km^{-2} yr^{-1}] and over 4.5 times more sediment than the hillside without agricultural lynchets [24.41 t km^{-2} yr^{-1}], but only 1.3 times the amount held in the lynchets themselves [82.71 t km^{-2} yr^{-1}].

When we look at the sediment budgets by landscape position through time we can see this pattern more clearly, and relate these changes to similar patterns within the loessic fluvial catchments of the Nethen and Dijle systems (Supplemental Table S7). Despite the major scale factor, hillslope soil erosion is the major contributing factor to sediment deposition in all cases through time with a minor increase from the medieval period [1.67–1.94 Mt], a pattern replicated in the larger fluvial examples. This is mirrored by a decrease in colluvial storage on hilltops especially between prehistory and the medieval period [0.81–0.31 Mt]. In the case of colluvial storage on hillslopes the Sint Martens-Voeren site shows a similar decrease to the hilltop [0.95–0.38 Mt], however in the Nethen and Dijle there are significant increases in the medieval to modern periods [5.03 Mt and 75.9 Mt, respectively] (Verstraeten et al., 2009a, 2017; Notebaert et al., 2011a) reflecting the significantly reduced gradient and lack of lynchets in the downstream locations. In contrast to sediment storage on hillsides, the colluvial retention in lynchets increases to over 0.50 Mt from late prehistory onwards.

Calculations of sediment storage from dry valleys through time form the most comparable data sets. At all locations there is a marked increase in colluvial storage between late prehistory and the medieval period, and again between the medieval to modern periods.

The onset of agricultural activity at Sint Martens-Voeren in the Bronze Age (1900–700 BCE) and lynchet formation from the Iron Age 700–50 BCE (Pears et al., 2024), mirrors the commencement of soil erosion and sedimentation in the Nethen catchment (Rommens et al., 2006, 2007) and the Geul River, where the expansion of arable agriculture and grasslands led to localised deforestation and the onset of major soil erosion and colluviation on valley slopes in prehistory (De Moor et al., 2008).

Colluviation in the Dijle started in the Neolithic around c.4000 BCE and increased during the Iron Age (2000–500 BCE (Notebaert et al., 2011b), with palynological research demonstrating the nature of landscape conditions and the increasing role of human impact in the landscape (Broothaerts et al., 2013). At a broader scale, the use of REVEALS on pollen data from fluvial catchments in the central loess belt and sandy Campine regions of Belgium (summarised in Fig. 13) demonstrated a linear reduction in woodland and onset of anthropogenic impact on soil erosion and sediment transfer into fluvial systems across the loamy loess belt of the Dijle and Mombeek catchments from the Bronze Age onwards with accelerations in the Iron Age (from c. 2700 BP) (Hoevers et al., 2022a). In contrast, woodland cover in the Campine region fluctuated and the shallow, sandy nature of the soils was more conducive to pastoralism resulting in localised scrub woodland regeneration despite low level arable cultivation from the end of the Iron Age (ca. 2050 cal. BP) (Hoevers et al., 2022a).

Despite a minimal Roman sedimentological and palaeoecological record at Sint Martens-Voeren the presence of several large villas on the lower slopes of the Voer (Gierts and Desmet, 2020) demonstrate the presence of major centres of the agro-urban economy, where agricultural product was grown across the local landscape and managed by the local elite and wealthy regional landowners. Roman agricultural sites in the Voeren area fall into a wider catchment of villa sites located in the highly fertile central sandy loam region of Belgium with agricultural products regularly transported between larger civitas at *Tongrorum* (centred on what is now Tongeren) and *Nerviorum* (across northern France and central Belgium) and beyond. The intensification of arable cultivation is also marked in accelerations in extreme soil erosion and fluvial sedimentation across the regional rivers, including the Geul (De Moor et al., 2008), an increase in dry valley sedimentation in the Nethen catchment (Rommens et al., 2006, 2007) and the commencement of alluviation in the Gete catchment during the 1st or 2nd centuries as a non-linear response to vegetation clearance, driven by land use intensification (van Zon et al., 2025). At the same time, palynological shifts after CE 50 also suggest a continued acceleration in human impact in the Dijle catchment, although crucially, variations in results from different topographic locations also suggest differences in floodplain-hillside interconnectivity (Broothaerts et al., 2013).

Intensification of erosion in the dry valleys may have also risen as a result of broader climatic variability (Büntgen et al., 2011) and recorded in alluvial records. For example, increased Roman alluviation in the central German loess catchments may have been exacerbated by extreme rainstorms leading to colluvial reworking, although overall climatic trends appear to have had a minor role (Lang et al., 2003).

Following the end of the Roman period, the shift to Frankish control (from 481 CE) led to the almost total removal of the widespread (villa-vicus-civitas) agro-urban economy. Despite this change an agrarian dominant society remained, known as (*Raumkontinuität*-spatial continuity), but occurred over a more localised scale. In the Voer valley, untestified evidence suggests that the Frankish and Carolingian monarchs maintained a royal farm or '*curtes/domus*' here but its location is unknown. These sites would have played an important role in the economic and political structure of the region reflecting the focus on agriculture and the cultivation of a range of grains, fruits and vegetables.

The political situation during the medieval period in the Voer valley may have also played an important role in the nature and degree of sedimentation across the sample location. From the 11th century, two-thirds of the territory of the present municipality of Voeren was in the county of Dalhem, (now in Wallonia), which was a possession of the dukes of Brabant (as part of the medieval 'Lands of Overmaas' (13th to 18th centuries) alongside the other one-third of the Duchy of Limburg, which also belonged to Brabant after 1288). Crucially, the feudal land rights were not abolished until 1795 (Waelkens, 2015).

The medieval period saw a resurgence in the intensification of agrarian practice across large parts of contemporary Belgium, in part as result of urban redevelopment in the 11th to 12th centuries, although this originated in the pre-existing rural agricultural economic framework, seigneurial land management, regional specialisation and soil quality (Thoen, 1997).

At Sint Martens-Voeren OSL dating in the valley bottom indicates that the vast majority of this deposition occurred from the early medieval period onwards, alongside significant erosion of the lowest lynchet feature, corresponding with periods of accelerated colluviation and 80 % of the total sediment production was stored as colluvium (De Moor and Verstraeten, 2008), further reconciling the idea that most sediment did not move into main river valleys and instead was retained on valley sides and upper tributaries (c.f. Verstraeten et al., 2009b; Houben et al., 2013). In addition, the high rate of sediment storage on slopes [88 %], in the medieval period, may have been partly as a result of the development of lynchets (Macaire et al., 2002).

More specifically, sediment storage in the Nethen catchment (summarised in Fig. 13) was calculated at 18.0 ± 2.2 t ha^{-1} yr^{-1} in the medieval period, with 50 % of Holocene sediments in the Nethen valley stored as colluvium in upper catchment locations and dry valleys, with around 21–29 % within lower order streams and rivers (Rommens et al., 2006, 2007). In the Dijle catchment, a total sedimentation budget for

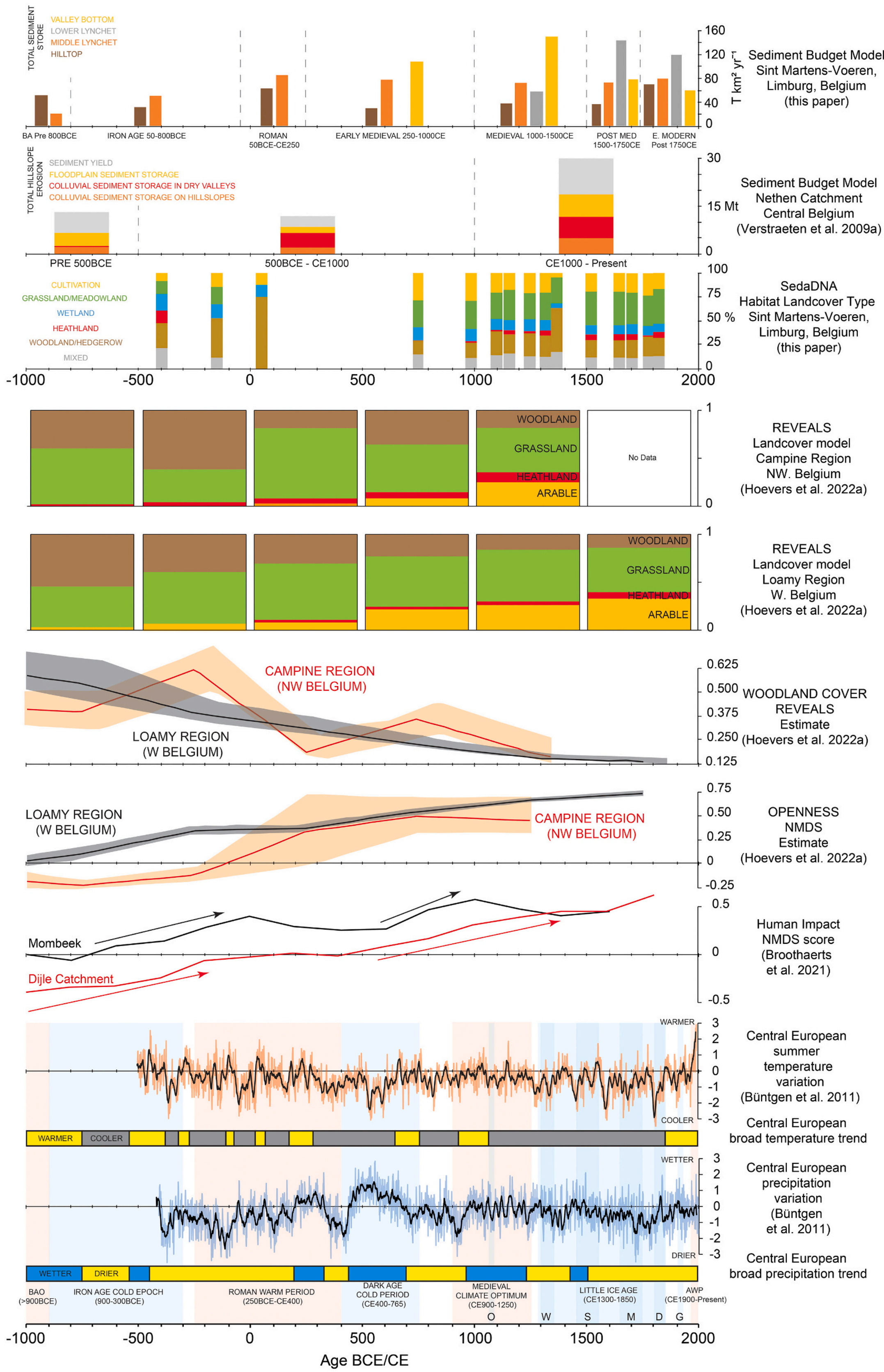

Fig. 13. Summary sedimentological budget modelling, habitat landcover type from sedaDNA for Sint Martens-Voeren and comparative environmental results from the Nethen, Dijle and Mombeek catchments with summer temperature and precipitation levels for central Europe.

Holocene erosion was calculated at 817 ± 66 Mt, of which 327 ± 34 Mt was deposited as colluvium [40 %], and corresponds with a net Holocene soil erosion rate of 10.8 ± 0.8 × 103 Mt ha^{-1} (Notebaert et al., 2009). Alongside total catchment sediment budgets, mean sediment export rates over the last 1000 years were also determined and revealed 75 % of colluvial sediment deposition took place in the last 1000–1200 years, between 0.8 and 1.3 Mt ha^{-1} yr^{-1}, an average erosion rate for agricultural land of 9.2 ± 2.2 Mt ha^{-1} yr^{-1} (Notebaert et al., 2009). Other studies that applied similar methodologies in the Belgian loess areas report erosion rates ranging from 2.8 to 17.6 Mt ha^{-1} yr^{-1} for the last 1000 years, whereas present-day rates of water erosion processes equal 2.6 and 16.7 Mt ha^{-1} yr^{-1} (Verstraeten et al., 2009a).

Further work on sedimentological drivers for deposition in the Dijle catchment demonstrated variable accretional patterns across individual sample locations but that at the catchment-wide scale, land use patterns were mainly responsible for variations in sedimentological system dynamics, with little to no evidence for the role of climate variations (Notebaert et al., 2011a, 2011b).

Palynological evidence between 50–1500 CE suggest an acceleration in human impact in the catchment through the historic period, although variations in results from different topographic locations also suggest variability in floodplain-hillside interconnectivity (Broothaerts et al., 2013, 2021). At Sclage, the steeper sample location, the greatest human impact was determined after c. 1430 CE which resulted in increased overland flow, soil erosion and colluviation (Notebaert et al., 2011b). This suggests that in some cases floodplains surrounded by steep slopes stored eroded sediments in dry valleys during periods of reduced anthropogenic activity until land use pressures went beyond a connectivity threshold (Houben et al., 2013; Broothaerts et al., 2014; Hoevers et al., 2024). In smaller catchments such as the Gete it has been suggested that the increased alluviation from the 7th to end of the 10th century CE (van Zon et al., 2025) was driven by a combined increase in anthropogenesis and shifting climatic variability during the Dark Age Cold Period and Medieval Climate Anomaly (Büntgen et al., 2011; Riechelmann and Gouw-Bouman, 2019), as well as an expansion in the hillslope-channel connectivity (Houben et al., 2013).

The extent of cropping erosion with specific cultivars and agrarian land use has been modelled in the contemporary German landscape (Auerswald et al., 2009), and the use of sedaDNA in this research presents us with the opportunity to relate particular phases of slope-sediment transfer to these. The presence of major cultivars (barley, oat, wheat) from the early medieval period is indicative with typical mean erosion [c. 0.1–103 t ha^{-1} yr^{-1}]. However the intensification of the cultivation of beet [c. 231–458 t ha^{-1} yr^{-1}] and the introduction of specialist cultivars including hops [c. 15–205 t ha^{-1} yr^{-1}] significantly increased in the medieval and post medieval periods, in conjunction with the development of the oxen-powered mouldboard plough resulting in a major increase in slope-sediment transfer and soil erosion (Dotterweich, 2008; Houben et al., 2013).

Agricultural intensification from the 13th century onwards is marked by the nature of cultivated crops and crop rotation. Three-course rotation on larger demesne farms was commonplace from the 12th century onwards, alongside the more piecemeal '*Flurzwang*' system across smaller Flemish villages and manors and comprising smaller sections of open fields sub-divided by anthropogenic and natural boundaries (Thoen, 1997).

As well as agrarian intensification, the medieval period was also marked by increased agricultural specialisation. From the 12th century the sandy soils of central Flanders would have supported the extensive commercial cultivation of oats to produce ale, which until the late 13th century was more important than beer made from barley (Thoen, 1997, 72). The use of hops in the brewing process occurred much later in Flanders than other areas, beginning in the 15th century (Van Uytven, 1973).

Reflections on the agricultural productivity of manorial farms and estates can also be determined from the palaeoeconomic evidence uncovered from archaeological excavations within major urban medieval centres. In Brussels, plant remains from medieval contexts show that rye, wheat, oats and barley are the most common cereal crops around c.1200, relating to the production and consumption of porridge, bread and beer (Speleers and van der Valk, 2017). Similar ecological patterns determined from the sedaDNA from Sint Martens-Voeren also reflect agricultural processes across the wider rural landscape of the Netherlands and France (Bakels, 2005), particularly buckwheat (Bakels, 2017), but the presence of beet, turnip, pea, walnut, apple, pear, grape, hop, hemp, hazel and hawthorn in both contexts suggest a wider range of cultivars being brought in from rural sites alongside those grown in urban gardens and orchards.

Urban evidence from the 13th to 15th centuries indicates an increase in economic diversity, with greater herbs and exotics (Speleers and van der Valk, 2017), although this is not identified in the sedaDNA from Sint Martens-Voeren. At both locations though the continued presence of rye, oats and barley over wheat reflects the onset of the three-field cultivation process and possibly the changing environmental conditions, alongside pulses, pea and lentil.

7. Conclusions

This paper has, for the first time, demonstrated that the loessic-dominated sediments of classic dry valley features are suitable for the extraction of sedaDNA for localised palaeoecological and palaeoagronomic reconstructions. When combined with OSL dating and sediment analysis, this provides an analytical basis for comparisons of the erosivity of soils and the erodibility of crop types in different land use areas through time.

The utilisation of OSL dating with chemostratigraphic modelling at Sint Martens-Voeren has significantly improved our understanding of the chronological development of lynchet development, slope-sediment transfer and dry-valley erosional processes linked to land use and climatic variability through time.

This has therefore provided the basis for comparisons with the significant corpus of research in larger fluvial catchments across Belgium and other loess dominated locations. The cultivation of loessic-dominated sediments across the dry-valley hilltop occurred from the Bronze Age (1900–700 BCE), with lynchet formation and increased agricultural activity on the steep valley sides occurring from later prehistory (Iron Age 700–50 BCE), akin to increased localised accretion rates during the Gallo-Roman period (Nyssen et al., 2014). The greatest extent of sedimentation, downslope erosion and land use activity though occurs from the early medieval period onwards across the lynchets and valley bottom. This arable activity accelerates in the medieval period, with the onset of the open field cultivation system, and is reflected by a major period of loessic reworking, erosion and colluviation across steeper, unterraced areas into the valley bottom, with greater sediment trapping across the lynchets. By the post-medieval period, sediment transfer and colluviation appear to have slowed despite a continuation of arable activity across the valley side possibly as a result of an increase in the enclosure of farmland with trees and hedges.

Despite similar ecological taxonomies at all the sample locations, there is also crucial evidence of a greater variability in palaeoagronomy through the sedaDNA evidence of cultivars which are linked to landscape position. The dominance of *Triticeae*, *Hordeum*, *Beta vulgaris, Fagopyrum,* and *Avena* across the hilltop and valley bottom suggest intensive arable cultivation and crop rotation across a large, open three-field agrarian system typical of the early and later medieval periods leading to extensive soil erosion and sediment transfer.

In contrast the steepest topographic areas occupied by the agricultural lynchets act as sediment stores due to their low bed gradient and the sedaDNA has demonstrated that the sheltered microclimates provided ideal conditions for the growing of garden/fodder crops (*Pisum*, *Lens*, *Raphanus*, *Cannabis sativa*) as well as specialist cultivars, including *Humulus lupus* (Hops), and tree/shrub cultivars (e.g. *Pyrus, Prunus,* *Maleae and Juglans*).

The lower lynchet and valley bottom sequences provide an excellent record of ecological diversity and historic land use, particularly over the last 1000 years. The higher relative abundance of *Saliceae*, *Alnus* and *Populus* as well as the appearance of *Juncus* and *Equisetum* suggests a greater proportion of wet woodland and wetter ground conditions in the valley bottom from the later medieval period (c. 1250 CE), the time at which the Voer valley becomes part of the 'Lands of Overmaas'. Crucially, the species diversity in the valley bottom may also be a reflection of sediment erosion and colluvial transfer from the rapidly degrading lower lynchet, a theory backed up by the presence of drier ground species present in both locations e.g. *Juglans*, cultivated across northwestern Europe from the Roman period, and driven by the intensive cultivation of crops many of which are known to be highly erosive (e.g. wheat, beet and hops).

In methodological terms this study shows how the combination of OSL dating and sedaDNA can identify both the response and the drivers in this coupled hillslope-floodplain headwater system with a precision that has hitherto been unattainable.

CRediT authorship contribution statement

Ben Pears: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Sam Hudson:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Andreas Lang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lisa Snape:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Chiara Bahl:** Methodology, Investigation, Formal analysis, Data curation. **Marie Føreid Merkel:** Software, Methodology, Investigation, Formal analysis, Data curation. **Inger Greve Alsos:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dan Fallu:** Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Kristof Van Oost:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Pengzhi Zhao:** Methodology, Investigation, Formal analysis, Data curation. **Kevin Walsh:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Antony Brown:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest, and have no additional published or submitted works which overlap with the current submitted research paper '*Late Holocene sedimentation and palaeoagronomy in a carbonate dry valley system using OSL, sedaDNA and geochemistry: Implications for understanding anthropogenic slope-sediment transfer in fluvial headwaters*' for consideration for inclusion in *Geomorphology*.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2025.110008.

Data availability

Data will be made available on request.

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