

Prehistoric alteration of soil in the Lower Rhine Basin, Northwest Germany—archaeological, ^{14}C and geochemical evidence

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Abstract

In Early Holocene, Chernozems were assumed to have covered the entire loess landscape of the Lower Rhine basin—today mirrored by the distribution of Luvic Phaeozems. These Luvic Phaeozems have characteristic dark brown (Bht) horizons accumulating clay and humus, inherited and translocated from their precursors Chernozem black humic A horizons. We examined Luvic Phaeozems along a 33-km-long and 2.0–2.5-m-deep gas pipeline trench in the Lower Rhine Basin, west of Cologne. Along this transect we discovered clusters of hundreds of regularly shaped pits. These pits were always connected to the Bht horizons of adjacent Luvic Phaeozems. The Luvic Phaeozem horizons and the pits were investigated by combining methods from (geo-) archaeology (geographical distribution within the landscape, shape of the pits, soil texture), geochemistry (content of carbon, nitrogen and black carbon), palaeobotany (species determination of charcoals) and AMS ^{14}C measurements.

We found that the Luvic Phaeozems occurred not only in the loess-covered landscape but also in the sandy Holocene floodplain, and their distribution could not be limited to certain slope positions or parent material. Carbon and nitrogen concentrations in the Luvic Phaeozem horizons and pits were larger than in the surrounding Luvisols, whereas the C/N ratios were small (<10). Material found in the Luvic Phaeozem pits was clearly different from material found in prehistoric settlements. The pits investigated here never contained artifacts, and carbon and nitrogen concentrations and C/N ratios were smaller. We found charcoal particles, and black carbon contributed up to 46% of the total organic carbon. The AMS ^{14}C ages of charcoals and black carbon indicated that fire occurred from Mesolithic (9500–5500 BC) to the Medieval Ages (500–1500 AD), and mainly in the Late-/End Neolithic period (4400–2200 BC). We conclude that (i) the Luvic Phaeozem pits and horizons are man-made, formed during several archaeological epochs between Mesolithic and Middle Ages, (ii) these pits must have been formed outside the actual prehistoric settlements (off-site) and may serve as a novel archaeological feature, (iii) the purpose of these pits at present is not clear and (iv) human activity has altered and ultimately formed the investigated soils of the Lower Rhine basin in prehistoric time.

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1. Introduction

By concept, Chernozems are “zonal” soils, formed under a dry continental climate and vegetation of the mid-

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latitude grasslands on calcareous loess or loess-like sediments (FAO/ISRIC/ISSS, 1998). The pedogenesis of Central European Chernozems (German classification: Schwarzerde/Tschernosem; AG Boden, 1994), especially in Northwest Germany has been studied by soil scientists, palynologists and archaeologists very intensively (Scheffer and Meyer, 1963; Catt, 1989; Ehwald et al., 1999). It is difficult to provide an overview of the discussion, not only because of the multitude of sometimes contradictory hypotheses, but also because different degradation stages of Chernozems have been studied (Ehwald et al., 1999). At the transition to the moister climates of the forest regions, decalcification and clay translocation led to the formation of Luvic Phaeozems with a characteristic dark argic B horizon rich in humus (German classification: Bht horizon). In humid regions, Luvisols were the final products of the soil development (Roessmann, 1968; Driessen et al., 2001).

In Central Europe, the entire spectrum of this soil development series can be found, from Haplic Chernozems in the Central German dry region to Luvic Phaeozems of the Mainz Basin, Soester and Warburger Boerde, Leine valley, Wetterau and Lower Rhine Basin (Mückenhausen, 1985).

In the Lower Rhine Basin, Kopp (1965) and Schalich (1981) considered Luvic Phaeozems as relicts of former Chernozems which have covered the loess landscape in Early Holocene. Today, these Luvic Phaeozems have characteristic dark brown Bht horizons, which were assumed to be inherited from their Chernozem precursors (Fig. 1a). Although soil maps of the Lower Rhine Basin region do not show Luvic Phaeozems in a separate category, they are included under the term Luvisol with the note: Chernozem relicts or humic

horizon (=Bht horizon) present at a depth of a few tens of cm (Kopp, 1965).

In the Lower Rhine Basin, west of Cologne, we followed a gas pipeline, and discovered clusters of hundreds of regularly shaped pits—presumably man-made. These pits were always connected to the Bht horizons of adjacent Luvic Phaeozems, provided that these horizons were not eroded (Fig. 1b). In the present study, we combined complementary methods from (geo-) archaeology (geographical distribution within the landscape, shape of the pits, soil texture), geochemistry (carbon, nitrogen, black carbon), palaeobotany (species determination of charcoals) and AMS ^{14}C measurements to address the following questions:

- Are these Luvic Phaeozem pits natural or man-made?
- Do these Luvic Phaeozems differ from prehistoric settlement soils?
- Are the Luvic Phaeozems and associated pits uniformly distributed in the landscape?
- Which implications do our results have for the pedogenesis (soil forming process and time) of Luvic Phaeozems (and their precursors Chernozems) in the Lower Rhine Basin?

2. Materials and methods

2.1. Study area and sample sites

In the Southern Lower Rhine Basin, west of Cologne, we followed pipeline excavations (Wingas AG Kassel). The trench was 2.0–2.5 m deep and 33 km long, ending at the coordinates $6^{\circ}45'39''\text{E}/51^{\circ}0'18''\text{N}$ and $6^{\circ}58'35''\text{E}/50^{\circ}50'35''\text{N}$ (Fig. 2). The entire length of the gas

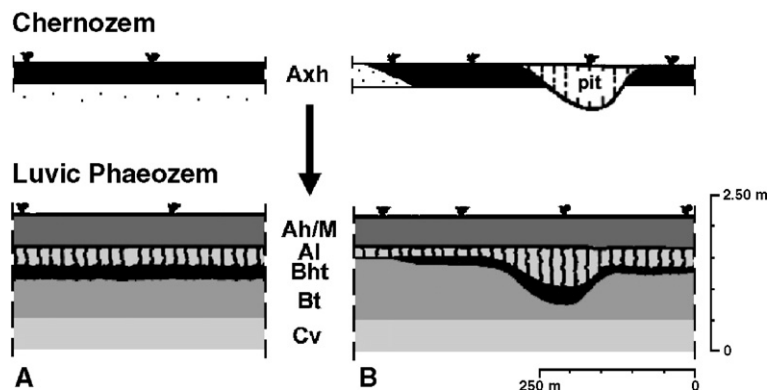


Fig. 1. Soil formation in the Lower Rhine Basin (schematic). (A) Degradation model from Chernozem to Phaeozem, (B) soil formation as observed in this study. Soil formation processes typically transport clay and humus from the topsoil (i.e. a former mollic (Axh) horizon and pit fillings) into the recent argic (Bht) horizons, which inherit the black colour following the former pit structures. Often a colluvial cover (M horizon) protects the underlying horizons against erosion.

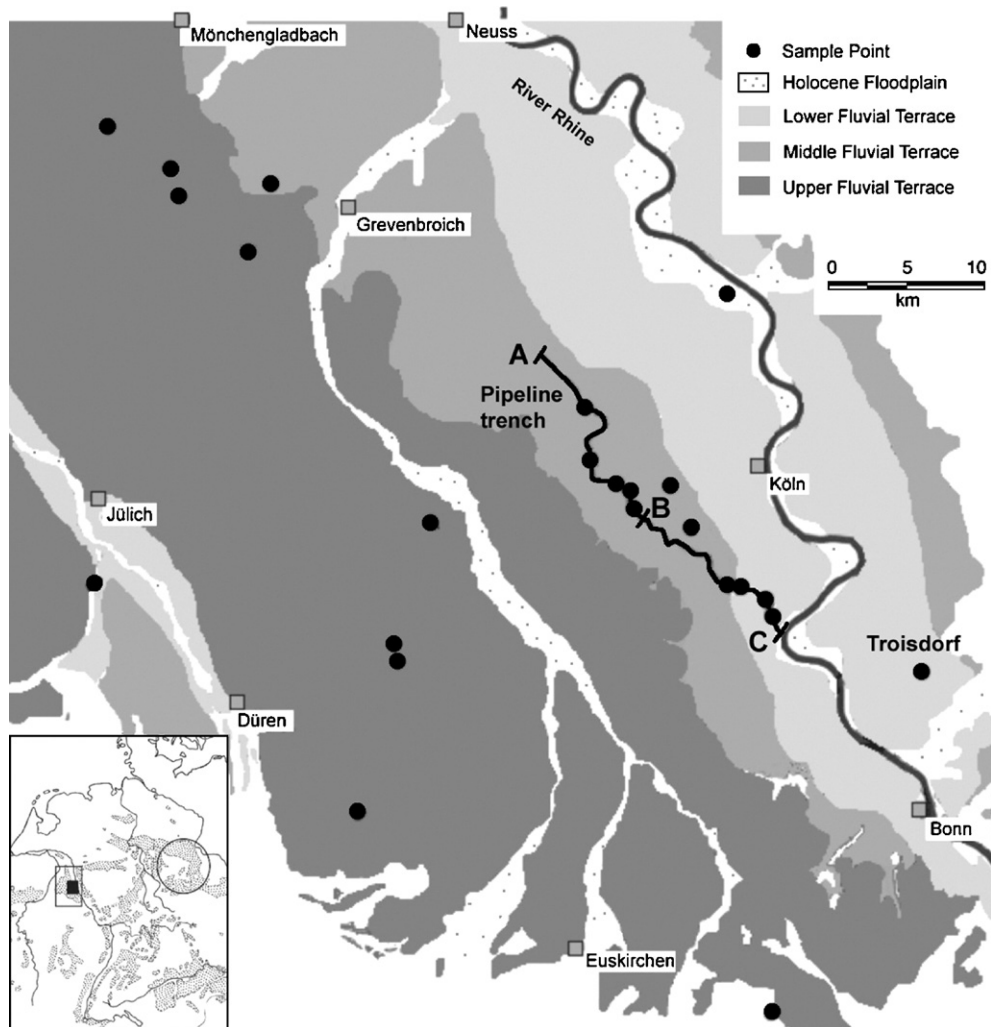


Fig. 2. Study area, including the main geomorphologic units, the pipeline trench (ends indicated with A and C) and locations of soil sampling, and additional sampling plots at archaeological excavations. The inset map shows the distribution of loess in Central Europe, highlighting the Lower Rhine Basin (rectangle), the study area (black square), and the Central German Chernozem region (circle).

pipeline trench was surveyed and 500 pits were discovered, documented and grouped into morphological classes (Fig. 3). The trench crossed the loess-covered higher and middle terraces, the loamy and sandy lower terrace and the Holocene sandy floodplain of the river Rhine. Additionally, we included observations from 15 archaeological large-scale (0.5 to 5 ha) excavations within the region.

Annual precipitation in the study area is 650–700 mm, increasing from the lee of the Eifel mountains (Euskirchen: 550–600 mm) to the West (Jülich 600–650 mm), North (Mönchengladbach 700–750 mm) and East (Cologne/Bonn 700–750 mm) (Minister für Umwelt Raumordnung und Landwirtschaft des Landes Nordrhein-Westfalen, 1989).

2.2. Sample collection and preparation

A total of 71 bulk samples (2 kg each) were taken from soil profiles in the trench and at the excavation sites: six samples from six Bht horizons, 38 samples from 29 black earth pit fillings and, additionally, 14 samples from black prehistoric settlement pit-fillings and five samples from prehistoric settlement floors. Eight samples were taken from the surrounding horizons without humus accumulation (WRB: argic and cambic horizons). After drying at 40 °C the soil aggregates were crushed and coarse material (>2 mm) was removed by dry sieving. Sub samples were ball-milled for carbon and nitrogen analysis.

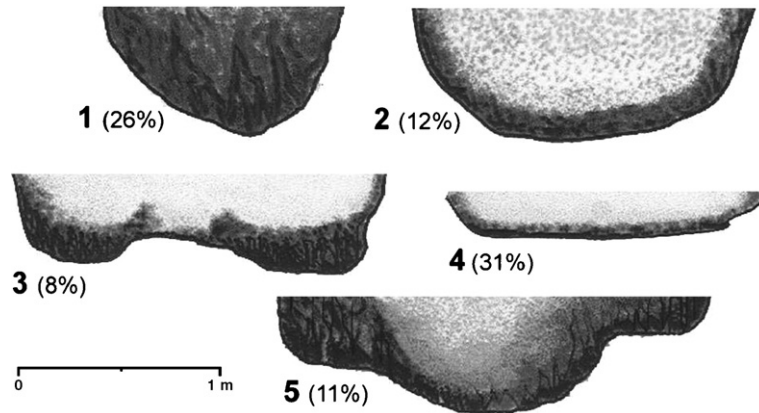


Fig. 3. The five observed types of Luvic Phaeozem pits and their proportions of all 500 observed pits, excluding poorly defined features such as ditches representing 12% of all observed features. (1) Deep v-shaped pits (maximum depth 1.4 m, diameter 0.8–1.0 m). (2) U-shaped pits (maximum depth 1 m, diameter \leq 1.6 m). (3) Pits with irregular hollows in the base (diameter \leq 2.8 m). (4) Shallow hollows, potentially heavily eroded type 2 pits. (5) Shallow pits with one hollow in the base (maximum depth 1.5 m, diameter \leq 2.8 m).

2.3. Soil analyses

The particle-size distribution was examined by wet sieving and gravitational sedimentation (pipette method) according to a standard method (Schlichting et al., 1995), and size classes were selected according to the German classification (AG Boden, 1994; Fig. 7).

Total carbon and nitrogen were determined in duplicates by dry combustion with an elemental analyzer (Elementar Vario EL). The values for total organic carbon corresponded to the total carbon content because the soil samples did not contain calcareous material.

2.4. Charcoal extraction and identification, black carbon quantification, AMS ^{14}C measurements

Macroscopic charcoal pieces were manually selected from bulk soil for radiocarbon dating and identification

of wood species (by U. Tegtmeier, Institute of Pre- and Protohistory, Archaeobotanical Laboratories, University of Cologne). Black carbon was measured at CSIRO laboratories, Adelaide, Australia in 11 samples taken from Luvic Phaeozem pits and Bht horizons. Analytical details are reported in Schmidt et al. (1999). Briefly, charred organic carbon was analysed after removal of less stable soil organic matter via high-energy UV photo-oxidation by ^{13}C nuclear magnetic resonance (NMR).

We dated nine charcoal samples and three black carbon samples taken from deeper parts of the Luvic Phaeozem Bht horizons and pits to estimate the approximate age of the soils. The material was washed with deionised water and subsequently dated by accelerator mass spectrometry (Universities of Kiel and Utrecht). The ^{14}C ages were calibrated using the program OxCal v3.5.

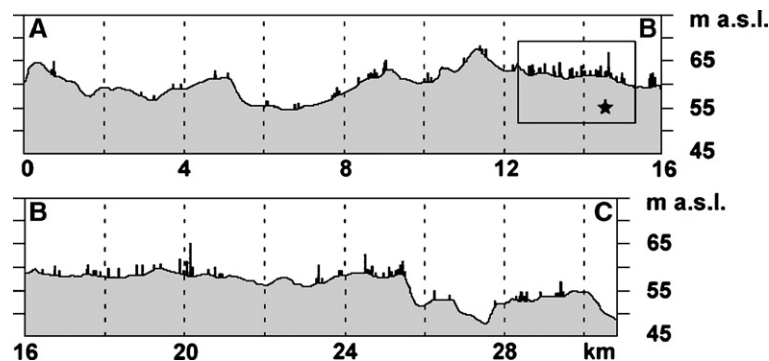


Fig. 4. Cross section showing the loess landscape with typical dry valleys and low hills. The length of the black vertical lines represents the numbers of Phaeozem pits per 50 m. Note the exaggerated relief; actual maximum relief is approximately 25 m. The scale lines on the frame correspond to 2 km. The asterisk marks a known Neolithic settlement area. The rectangle highlights the largest concentration of Luvic Phaeozem pits.

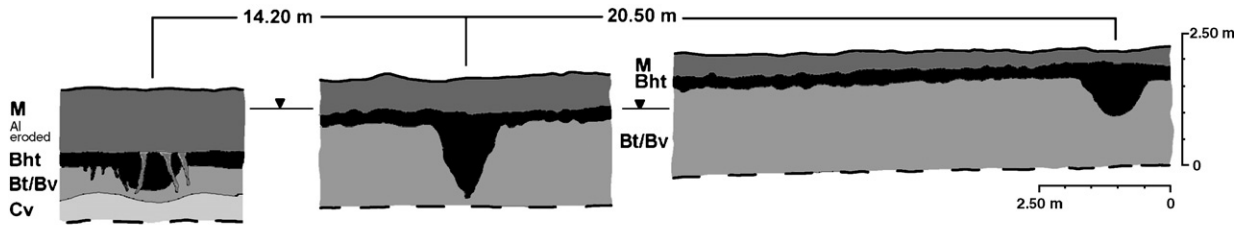


Fig. 5. Typical cross section (ca. 37 m long), as produced by the pipeline trench. The slope dips from right to left, with the thickness of the colluvial cover (M) increasing accordingly. The eluviated horizon (Al) was eroded and not present in this cross section. The Luvic Phaeozem argic horizon (Bht) with humus accumulation and pits are shown in black, followed by the argic horizon without humus accumulation (Bt) or cambic horizon (Bv), respectively, and loess as parent material (Cv). The first pit shows tubular traces of eluviation.

2.5. Geographical information analysis

The entire length (33 km) of the gas pipeline trench was surveyed and 500 pits were documented and classified. Results were expressed as number of pits per 50 m of trench, and were plotted to the relief of the trench (Fig. 4). Geographical information analysis was performed using MapInfo 6.0 software (MapInfo Company, Troy, New York).

3. Results

3.1. Characteristics of Luvic Phaeozems and pits within the pipeline trench and archaeological excavations

For the 240 pits found along the pipeline trench, and another 260 pits that have been documented in archaeological excavations in the Lower Rhine Basin between the years 1999 and 2004 (data not shown here), two observations became clear. First, the Luvic Phaeozem Bht horizons, where clay and humus accumulated, never occurred without pits, filled with material similar to that found in adjacent Bht horizons (Fig. 5). The Bht horizons always followed the floor line of the pits. Second, Luvic Phaeozem pits were always associated with humic Bht horizons of Luvic Phaeozems, but never with the reddish-brown argic horizons of adjacent Luvisols. Thus, the pits must be considered as integral parts of the Luvic Phaeozems. These pits have not been described in the literature so far, and we called them Luvic Phaeozem pits.

When covered with colluvial sediments, the Bht horizons were usually protected from erosion and formed amorphous patches. When the Bht horizons were missing due to erosion, the bottoms of the Luvic Phaeozem pits still were clearly visible in the trench (Fig. 6).

In the 500 described Luvic Phaeozem pits we never found archaeological artefacts, such as pottery or bones—typical for pit fillings found inside prehistoric

settlements (in archaeology known as on-site features). From the absence of artefacts and other settlement features, such as post-holes, we concluded that these pits occurred outside the actual settlements (in archaeology called off-site features). The Luvic Phaeozem pits occurred in several distinct shapes, which can be subdivided into five groups (Fig. 3).

Often pits occurred in characteristic clusters with individual pits 1–3 m apart. In the pits we found only few charcoal remains and some reworked gravels. The highest density and greatest number of these Luvic Phaeozem pits occurred close (<1 km) to an established Neolithic settlement (asterisk in Fig. 4).

3.2. Spatial distribution of Luvic Phaeozems and pits

Until now, researchers assumed that in the Rhine region the occurrence of Luvic Phaeozems was limited to loess as parent material and to depressions where a cover of colluvial sediment could protect them from further degradation (Kopp, 1965; Schalich, 1981). However, the results obtained along the pipeline trench showed that Luvic Phaeozems were not limited to loess

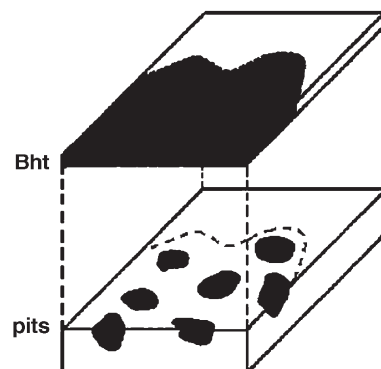


Fig. 6. Luvic Phaeozem (Bht) horizons mostly formed patches. In some cases natural erosion or anthropogenic activity removed the Bht horizon. Then, only the Luvic Phaeozem pits were still visible.

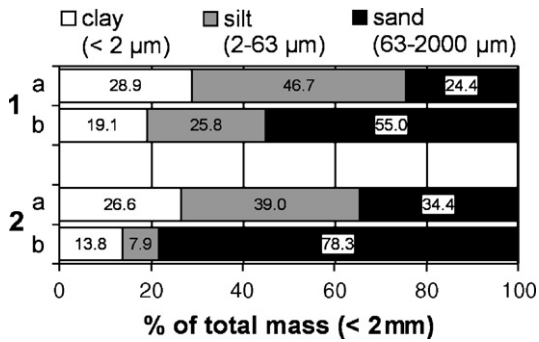


Fig. 7. Particle-size distribution from the location Troisdorf (see Fig. 2) on the lower terrace of the river Rhine. Textures of two pit fillings (a) are compared to the adjacent cambic horizons (b). Size classes according to AG Boden (1994).

as a substrate, but also occurred on loamy and sandy alluvial sediments on the lower terrace of the river Rhine and on the Holocene floodplain (Fig. 2). They appeared in different geomorphologic positions, i.e. in depressions, on slopes as well as on top of hills (Fig. 4). About 80% of the observed Luvic Phaeozems were covered by 20 to 180 cm thick colluvial sediments, but 20% were preserved uncovered. Thus, the preservation of Luvic Phaeozems did not depend on the presence of protecting colluvial cover of sediments, and the occurrence of Phaeozems was independent of substrate, microrelief, microclimate, exposition and slope angle.

3.3. Texture

Particle-size distributions of Luvic Phaeozem pit fillings found within the loess area were similar to the

surrounding soil material. Contrasting, pit fillings from the lower Rhine terrace (a in Fig. 7) contained more clay and sand than the surrounding soils (b in Fig. 7), as exemplified for the excavation site at Troisdorf (for site location see Fig. 2). Pits contained more clay (27/29 mass %) and less sand (34/24%) than the adjacent soils (14/19% clay and 78/55% sand). One pit contained a single stone that could not have been fluviially transported.

3.4. Total organic carbon and total nitrogen

The Luvic Phaeozem horizons and pit fillings (Fig. 8) had smaller concentrations for C (arithmetic means: 3.5 g C kg⁻¹ for pits and 4.4 g C kg⁻¹ for Bht-horizons) and N (arithmetic means: both 0.5 g Nt kg⁻¹) than the materials found within prehistoric settlements, either floors (arithmetic means: 7.6 g C kg⁻¹ and 0.6 g N kg⁻¹) or settlement pit fillings (arithmetic means: 5.0 g C kg⁻¹, 0.6 g N kg⁻¹). Resulting C/N ratios are small (arithmetic means: horizons 8, pits 7), although the Bht horizons and pit fillings were supposed to be relicts of humic horizons. Humic Bht horizons of Phaeozems usually have C/N ratios of 10–15 (Gunreben, 1992).

3.5. Identified species of charcoal pieces and black carbon concentration

The identified wood species of the charcoal pieces chosen for radiocarbon dating are shown in Table 1. We found the following species: *Quercus*, *Ulmus*, *Pomoidae* and other unidentified deciduous wood. Large proportions of the soil organic matter taken from the Luvic Phaeozem pits and Bht horizons consisted of

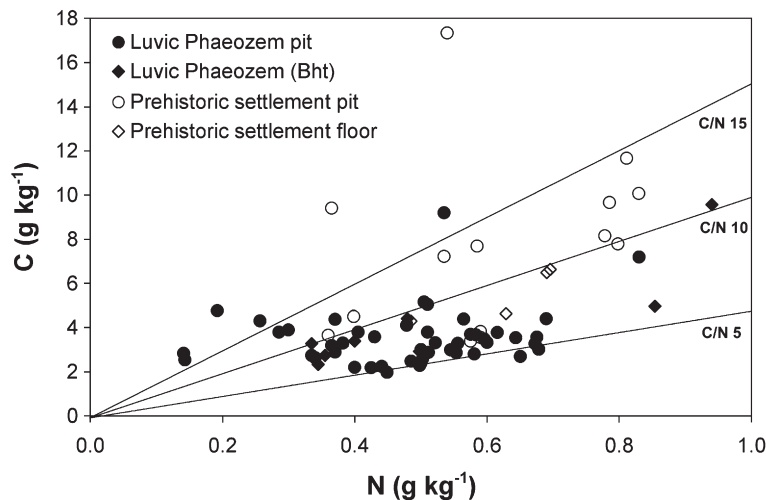


Fig. 8. Total carbon and nitrogen in Luvic Phaeozem horizons and pit fillings (off-site) (black) and in settlement soils (on-site) (white) in the Lower Rhine Basin. The diagonal lines mark C/N ratios 5, 10 and 15.

Table 1
Radiocarbon ages of Chernozems, Luvic Phaeozems and Luvic Phaeozem pits in Germany (calibrated ages calBC/AD; OxCal v3.5)

Ages, calBC/calAD	Material ^a	Identified wood species (charcoals)	Sampling site ^b	Region ^c	Horizon ^d	Data source lab. code
BC						
7530–7200	Charcoal	Deciduous	Köln–Rondorf (lt)	Lower Rhine Basin	LP pit	UtC 11209 ^e
7540–7140	Charcoal	n.d.	Köln–Nord (hfl)	Lower Rhine Basin	LP pit	UtC 11208 ^e
6230–6090	Black C		Köln–Rondorf (lt)	Lower Rhine Basin	LP pit	UtC 11406 SE 10 ^e
5210–5000	Charcoal	Ulmus	Mönchengladbach (ut)	Lower Rhine Basin	LP pit	UtC 11205 ^e
4490–4260	SOC		Söllingen D	CDR	AxhSwd	f
4460–4250	SOC		Lantershofen	Middle Rhine	Bht	f
4230–3990	SOC		Söllingen C	CDR	Axh	f
4220–3970	Charcoal	Pomoideae	Pulheim (mt)	Lower Rhine Basin	LP pit	KIA 10696 ^e
3890–3640	SOC		Eltville	Rheingau	Bht	f
3760–3640	Charcoal	Pomoideae	Kerpen (ut)	Lower Rhine Basin	LP pit	UtC 11203 ^e
3700–3380	SOM		Söllingen A	CDR	Axh	f
3500–3350	Charcoal	Quercus	Köln–Immendorf (lt)	Lower Rhine Basin	LP pit	KIA 10693 ^e
3370–3100	Black C		Seeben/Halle	CDR	Axh	g
2890–2670	Charcoal	Quercus	Kerpen (ut)	Lower Rhine Basin	BhtGor	UtC 11201 ^e
2880–2630	SOC		Inden	Lower Rhine Basin	Bht	f
2880–2620	SOC		Fellbach	Stuttgart	B(h)t	f
2880–2620	SOC		Soest II	Westphalia	fAxh/AM	f
2860–2470	SOC		Söllingen B	CDR	AxhSwd	f
2830–2350	SOC		Hildesheim A	CDR	SwdAxh	f
2830–2350	SOC		Soest II	Westphalia	fAxh/AM	f
2290–2140	Black C		Köln–Immendorf (lt)	Lower Rhine Basin	LP pit	UtC 11403 SE 69 ^e
2200–2030	Black C		Harsum/Hannover	CDR	Axh	g
2200–1970	SOC		Muddersheim	Lower Rhine Basin	fBhv	f
1880–1690	Black C		Pulheim (mt)	Lower Rhine Basin	LP pit	UtC 11404 SE 70 ^e
1525–1430	Black C		Diedenhof/München	South Bavaria	AxhBhv	g
1500–1320	Black C		Sossmar/Hannover	CDR	Axh	g
1500–1310	SOC		Hildesheim A	CDR	SwdAxh	f
1290–1120	Charcoal	Quercus	Pulheim (mt)	Lower Rhine Basin	LP pit	KIA 10697 ^e
810–540	SOC		Wallertheim	Rheinessen	fAxh	f
AD						
80–250	SOC		Fehmarn A	Baltic Sea	SwdAxh	f
560–770	SOC		Fehmarn B	Baltic Sea	SwdAxh	f
675–780	Charcoal	Deciduous	Garzweiler (ut)	Lower Rhine Basin	Bht	UtC 11207 ^e
720–940	Black C		Grossenbrode	Baltic Sea	Axh	g

Dates were plotted in Fig. 9.

^a SOC=Soil organic carbon, Black C=Black carbon.

^b hfl=Holocene floodplain, lt=lower terrace, mt=middle terrace (loess-covered), ut=upper terrace (loess-covered).

^c CDR=Central dry region of Germany (see Fig. 2).

^d AG Boden (1994); LP pit=Luvic Phaeozem pit.

^e This study.

^f Ages from Scharpenseel et al. (1996) were obtained from the deepest horizons (Bht or Axh) of the analysed soil profiles.

^g Schmidt et al. (2002).

Table 2

Black carbon concentrations (in g BC kg⁻¹ soil) and percentage of black carbon to total organic carbon (TOC) in all analysed bulk soil samples after UV-photooxidation

Lab no. SE	Description	TOC (g kg ⁻¹)	Black C (g kg ⁻¹)	Black C (% of TOC)
5	LP pit	4.4	1.7	40
10	LP pit	7.2	2.5	35
16	LP pit	8.2	2.8	34
18	Bht	3.6	1.1	30
25	LP pit	2.3	0.6	25
34	LP pit	2.7	0.5	19
42	Bht	5.9	1.7	29
53	LP pit	5.3	2.2	41
58	LP pit	2.8	0.7	25
59	LP pit	7.5	3.8	46
69	LP pit	3.0	1.0	33
70	LP pit	2.4	0.6	26

black carbon (Table 2), with values between 19% and 46% of total organic carbon (arithmetic mean: 33%).

3.6. Radiocarbon measurements

Charred organic matter is a single—although broadly defined—inert constituent of soils. Soil organic matter, however, comprises a continuum of many constituents, ranging from relatively inert charred particles to microbial biomass turning over in hours to days. Analysis of ¹⁴C of an individual charcoal particle may date an individual fire event, whereas measuring mixtures of mechanically separated charcoal particles or bulk soil organic matter may yield mean, apparent ages. Faunal remixing and rejuvenation through biomass input of the soil organic matter can make radiocarbon ages of soil humus difficult to interpret. A closer approximation to the actual soil age can be obtained using deeper and more

protected horizons of palaeosoils, buried wood or charcoal (Scharpenseel and Becker-Heidmann, 1992).

In the following, we show results of radiocarbon measurements, transformed into calibrated ages (OxCal v3.5) expressed as years BC or AD (Table 1, Fig. 9). We measured nine charcoal pieces (filled squares) picked manually, and three chemically separated black carbon fractions (filled circles). Those 12 results span a long time period from the Mesolithic (9500–5500 BC), Late/End-Neolithic (4400–2200 BC), Bronze Age (2200–750 BC) to the Middle Ages (500–1500 AD). One charcoal particle dated as Early Neolithic (Linear Pottery Culture; 5500–5000 BC).

Due to the limited number of samples we compared our results with already published results. Black carbon separated from subsurface (A_{xh}) horizons of German chernozemic soils (Schmidt et al., 2002) is displayed as triangles. Scharpenseel et al. (1996) measured radiocarbon concentrations in soil organic matter separated from deeper horizons of chernozemic soils in Germany (diamonds), as they found that in many chernozemic soils radiocarbon ages increased uniformly with depth (Scharpenseel et al., 1968). Despite differences in materials analysed (i.e. charcoal, black carbon, soil organic carbon), radiocarbon ages were complementary and covered a long time period, with a cluster in the Late/End-Neolithic period between 4400 and 2200 BC.

4. Discussion

4.1. Are these Luvic Phaeozem pits natural or man-made?

The shape and presence of Luvic Phaeozem pits were the most obvious evidence for anthropogenic influence.

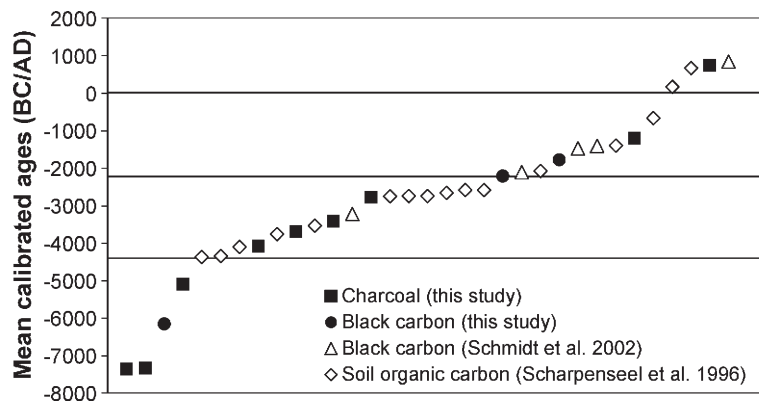


Fig. 9. Radiocarbon ages of charcoal and black carbon taken from Luvic Phaeozem horizons and pit fillings in the Lower Rhine Basin (black symbols), compared to radiocarbon data for black carbon and soil organic matter from different Chernozems and Phaeozems in Germany (white symbols). Details are listed in Table 1.

The Luvic Phaeozem pits on the lower Rhine terrace were filled with material that clearly differed from the surrounding soil, a phenomenon difficult to explain by natural processes. Furthermore, the stone found in one pit is a clear hint for anthropogenic influence. We subdivided the pits into five groups, depending on their shapes (Fig. 3). The pits often have been overlooked during archaeological excavations, or they remained undocumented because they were classified as natural features (weathering structures, tree holes, etc.). Falling trees typically tilt adjacent soil horizons in upright positions (Langohr, 1993), which was never reported in the 240 Luvic Phaeozem pits along the pipeline trench and more than 260 pits investigated between 1999 and 2004 in that region. Although some of these pits might have formed by falling trees or up-rooted tree stumps, the majority of the described pits showed such distinct shapes that we could not find another explanation than that these pits are man-made features.

Elemental analyses for carbon and nitrogen clearly revealed differences between the fillings of the Luvic Phaeozems pits and soil organic matter from adjacent Luvisols and other typical Phaeozems. C/N ratios for Phaeozem Bht horizons typically are in the range of 10 to 15 (Gunreben, 1992). Here, the C/N ratios were surprisingly small (5–10), indicative of bacterial biomass and heavily degraded organic matter containing nitrogen rich material, such as proteins. Soil organic carbon concentrations were low (3.5 g C kg⁻¹), but large fractions of this carbon (19–46%) consisted of black carbon, probably originating from biomass burning. When combined, the last two results show some apparent contradiction and need some further explanation. In the bulk organic matter every fifth to tenth carbon is attached to nitrogen (C/N ratios 5–10), whereas a large fraction of this bulk organic matter was detected as black carbon from charred biomass—typically assumed to be carbon rich (C/N ratios >50). However, the method used here is known to separate not only highly condensed aromatic compounds but also include only slightly thermally altered biomass, i.e. containing functional groups. As an example, charred organic matter produced in the laboratory from peat has more narrow C/N ratios (29), even decreasing with degree of thermal alteration (Almendros et al., 2003). In the char material, nitrogen was present in heteroaromatic structures such as pyrroles, indoles or pyridines with C/N ratios of less than 10. Also black carbon separated from soils using the same method we used here had C/N ratios (14–30) well below 50 (Knicker and Skjemstad, 2000). These observations may explain some of the nitrogen present

in the Luvic Phaeozems and pits, but we still cannot explain the small C/N ratios conclusively. It would be promising to find out in which chemical forms the nitrogen survived for millennia, which could help to elucidate the purpose of the pits.

4.2. Do Luvic Phaeozems differ from prehistoric settlement soils?

Black soils found in prehistoric settlement areas were often classified as former Chernozems, and therefore pedogenesis was dated by archaeological evidence. As a clarification, the dark humic soil material found in the Luvic Phaeozem pits should not be confused with the black filling material, e.g. in Neolithic pits and ditches within the actual settlements (on-site), often containing waste material (including excrements, food waste, bone, charred biomass, potsherds) mixed with soil material.

As an example, Baumann et al. (1964) investigated a Linear Pottery Culture settlement near Dresden and concluded that a black soil horizon had formed as an ‘indirect settlement layer’ because of anthropogenic input of organic material into the A horizon within the settlement area. The authors pointed out that the black material should not be equated with Chernozems outside the settlement area. The black soil layer in this Neolithic settlement showed differences from soil A horizons, including higher concentrations of nitrogen and phosphate, larger C/N ratios, different macroscopic features and humus composition. The amounts of humic acids were very high (58–72% humic acids in total carbon).

Geochemical analyses of pit fillings in a Middle to Late Neolithic settlement near Munich (Münchshöfen Kultur, 4600–4200 BC), provided further evidence that pit fillings within prehistoric settlements were not similar to natural soils (Schmid et al., 2001). The black settlement pit fillings differed from A horizons of Phaeozems, when polysaccharide and lignin were analyzed by CPMAS ¹³C NMR spectroscopy. It was concluded that the black pit fillings could not be interpreted as evidence for the occurrence of Chernozems in the vicinity of the settlement during Middle/Late Neolithic time. Further analyses showed that charred material formed 23–70% of the organic carbon in the pit fillings (Schmid et al., 2002). Again, these black soil remnants that archaeological excavations typically reveal inside prehistoric settlements (on-site) were man-made soils (WRB: Anthrosols) within settlements, and not Chernozems as defined by soil scientists.

4.3. Are the Luvic Phaeozems and associated pits uniformly distributed in the landscape?

As observable in the pipeline trench, Luvic Phaeozems always occurred closely associated with pits and the Bht horizons formed patches with a diameter of up to 100 m. We assume that the relicts preserved today still allow inferring the original distribution of the Bht horizons, although some erosion over time cannot be excluded. The results obtained from the linear trench show that Luvic Phaeozems and pits do not cover the entire landscape but are focused on certain areas. This two-dimensional observation along a transect was supported by large-scale archaeological excavations outside prehistoric settlements (Fig. 2). Once the topsoil was removed, these 0.5–5 ha large excavations showed a typical patchwork of dark coloured Bht horizons and/or pits surrounded by lighter coloured Luvisols.

From these observations we concluded that the Luvic Phaeozems and associated pits probably never covered the entire landscape, even in prehistoric times. If we accept that today's Luvic Phaeozems are relict Chernozems, then also the Chernozems must have formed a patchwork of dark coloured islands, as indicated in Figs. 1 and 5.

A similar patchwork of Chernozem islands has been found in a loess region south of Hannover (Hildesheimer Börde). Satellite images and soil maps showed that the apparently uniform, regional cover of Chernozems is in fact a patchwork of grey (Greyzems) and black soils (Chernozems). Neither relief, parent material nor climate could explain this small-scale distribution and a prehistoric human influence has been postulated (Schmidt et al., 1999, 2002; Gehrt et al., 2002).

4.4. Which implications do our results have for the pedogenesis (process and time) of Luvic Phaeozems (and their precursors Chernozems) in the Lower Rhine Basin?

4.4.1. Agriculture and fire activity as driving factors?

We hypothesise that prehistoric fire-based agriculture may have contributed large amounts of charred organic matter, which could have found its way onto and into the agricultural soils.

There was evidence for fire-based agriculture in the early history of Central Europe. During Pre-Boreal, the forests were dominated by firs, which easily could be ignited by natural causes. However, this is much less the case for the deciduous forests that prevailed during Boreal and Atlantic time. Tinner et al. (1999) estimated that the natural fire frequency in Holocene mixed

deciduous forests of the Southern Alps was approximately two fires per year with a total burnt area of 30 ha in a total area of 440 km². Studies at Lake Lobsigen showed that these values might be representative for Central Europe as well. Thus, under natural conditions a particular area may therefore burn on average about once every 1400 to 1500 years (W. Tinner, University of Bern, personal communication). These results agreed with estimates for mixed deciduous forest in Southern Switzerland suggesting a mean fire interval of 1800 years (Berli et al., 1994) and of more than 1000 years for similar forest types in Eastern North-America (Aber and Melillo, 1991).

Discussion continues on the distinction between natural and human-caused fires and their frequencies in the temperate deciduous broadleaf forests (Moore, 2000). There is increasing evidence—particularly from the archaeobotanical record—that Mesolithic hunters in Central Europe deliberately used fire as a management tool (Erny-Rodmann et al., 1997; Mason, 2000). For the Lower Rhine Basin loess landscape, re-interpretations of pollen profiles indicated periodic accumulations of charcoal during the Mesolithic period, which could result from fire management by Mesolithic hunters and gatherers (J. Meurers-Balke, University of Cologne, personal communication).

The three charcoal and black carbon ages dating to the Mesolithic originate from pits in the swamp area between the middle and the lower terraces of the river Rhine, which is consistent with the fact that this is a typical environment of Mesolithic hunters and gatherers.

More than half of the radiocarbon ages we compiled for chernozemic soils and from Luvic Phaeozem pits dated to the Late/End-Neolithic time (Fig. 9, Table 1). For this period, archaeobotanical studies (charcoal and/or pollen analyses) showed evidence for extensive and long-term fire-based agriculture both in Southwestern Germany (Rösch, 1993) and Northern Germany to Denmark (Iversen, 1941; Kalis and Meurers-Balke, 1998).

Man-made fires may have peaked during the Late/End-Neolithic but probably were not limited to that period, as shown by radiocarbon ages from the Bronze Age, Roman period and Middle Ages. There may be regional differences in soil formation: Three of the four ages in the last 2000 years derived from chernozemic soils on the island of Fehmarn in the Baltic Sea. Gehrt et al. (2002) calculated that 20% of the organic matter in the A_{sh} horizon of current Chernozems in Lower Saxony consists of charred organic matter. Assuming land use for a period of 1000 years, this would represent

an average annual input of 40 kg BC ha⁻¹. Conversion rates of biomass carbon to black carbon for temperate deciduous forests are still not available. Using data for savannah and temperate coniferous forest, Schmidt et al. (2002) estimated a total of one to seven fires to produce 1.7 g BC kg⁻¹ soil, or six to 32 fires to produce 7.6 g BC kg⁻¹ soil. Macrocharcoal is rare in the chernozemic soils of Lower Saxony and the Lower Rhine Basin, which may indicate that the black carbon did not originate from charred wood, but from charred herbaceous plants or grass, which easily fall into dust-sized pieces. Charred grass has much smaller C/N ratios (<8) than charred wood and could at least partly explain the small C/N ratios observed in the pits (Knicker et al., 1996).

Circumstantial evidence may come from previously published work. In Australia (Skjemstad et al., 1996) and South America (Glaser et al., 2001) it was shown that fire management practice could form black soils. In Australia, black soils formed in areas regularly burnt by aborigines, whereas adjacent, forested areas had grey soils. In Central Amazonia, fertile black soils (Terra Preta do indio) occurred as small islands (up to 20 ha) surrounded by infertile soils (Ferralsols). The organic carbon of these Terra Preta soils consisted of approximately 20% black carbon from biomass burning, suggesting that they formed as a result of fire-based agriculture. Also in North American chernozemic soils under native grassland black carbon from vegetation fires contributed up to 35% of total organic carbon (Skjemstad et al., 2002; Glaser and Amelung, 2003). Recent work has shown that the content of aromatic carbon, a carbon species which dominates the black carbon structure, correlated significantly with soil lightness (Spielvogel et al., 2004). However, the process of incorporation of black carbon in soils remains unknown, and therefore also the processes that lead to the blackening of soils and the accumulation of deep black horizons remain unclear.

Summarizing, we assume that the Lower Rhine Basin Luvic Phaeozem pits and the associated Luvic Phaeozems originate from human activity, probably including fire-based agriculture, and that man has formed them between the Mesolithic and Middle Ages, clustering in the Neolithic time. However, we never found archaeological artefacts, such as pottery or bones—typical for pit fillings found inside prehistoric settlements (on-site features). From that we conclude that the observed pits must have been formed outside the actual settlements (off-site features). At present the shape does not fit any known pattern of human activity (e.g. storage) and their purpose remains unknown.

4.4.2. Further implications

Our results could have several implications. First, soil formation through fire-based agriculture could explain at least partially how Central European Chernozems, apart from hydromorphic Chernozems, could have formed under a climate too wet and too warm to agree with the current understanding of Central European Chernozems as zonal steppe soil. If the results hold true also for other regions, it may become necessary to revise conventional wisdom of uniform, natural soil development for many Central European chernozemic soils. Different processes could have affected the formation of these black soils at different times. Some Chernozems may have been formed under typical climate and vegetation, whereas other black soils could have formed through prehistoric or historic agricultural practice. As an example, in the Lower Rhine Basin it seems to have been human activity, probably including fire as a tool, that formed chernozemic soils, with a high activity during Late/End-Neolithic.

Second, archaeologists should differentiate between black pit fillings mixed with soil material often found in archaeological settlements and relict black soils and pits outside settlements, even if both may result from human fire activity. Archaeologists may be able to use relict chernozemic soils as novel archaeological evidence, especially where little other archaeological evidence from off-site areas is available. The localized occurrence of chernozemic relicts with their associated pits might provide new evidence for the type of land use and the extent of prehistoric agricultural lands.

5. Conclusions

In the Lower Rhine Basin, west of Cologne, we discovered clusters of hundreds of regularly shaped pits—presumably man-made. We concluded the following points:

1. These Luvic Phaeozem pits must be of human origin, as indicated by the (i) shape of the pits, (ii) texture contrast between fillings and surrounding soil, (iii) unusually small C/N ratios (5–10), and (iv) residues from biomass burning. The purpose of the pits remained unclear.
2. One implication for archaeology is that the pits never contained visible artefacts, and thus must have been formed outside the actual prehistoric settlements (off-site) and should not be confused with waste-filled pits typically found inside prehistoric settlements (on-site). Thus, off-site pits may serve as a novel archaeological feature, overlooked so far.

3. Luvic Phaeozems and Luvic Phaeozem pits were always closely associated and not uniformly distributed in the landscape, as observations along the linear transect revealed. Luvic Phaeozems and pits were not limited to loess or to depressions with a protecting colluvial cover. The highest density of Luvic Phaeozems occurred close to a known Neolithic settlement.
4. If we accept that man formed these patches of Luvic Phaeozems and adjacent pits, and that these Luvic Phaeozems are relicts of ancient Chernozems then it was human activity which has altered and ultimately formed these Chernozems in prehistoric time. Man must have formed these Luvic Phaeozems pits during several archaeological epochs between Mesolithic and Middle Ages, although dates from the Late-/End Neolithic period were most common, as radiocarbon ages of charcoal and black carbon suggest.

Several questions remain unanswered, including the purpose of these pits, the type of organic matter which survived for millennia in the pits, a conclusive explanation for its small C/N ratios, and finally if this type of prehistoric activity occurred in other regions of Central Europe and has been overlooked so far.

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