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RESEARCH ARTICLE

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Improvement of soil fertility in historical ridge and furrow cultivation

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Abstract

Ridge and furrow cultivation is the most widely used agricultural technique in medieval and postmedieval Europe, but the fertilization of soils during their use is not yet fully understood. Pedological analyses of this cultivation technique provided information, which led to the assumption that some of the investigated sites in Northern and Central Germany were manured with livestock excrements during cultivation. The objective of this study is to determine whether and how the soils have been fertilized and which materials were applied for this purpose. We investigated soils at five sites using phosphate and steroid analyses (stanols and bile acids), black carbon analyses, and a micromorphology study. The results showed that livestock waste was likely used as fertilizer at four of the five studied sites at low intensities, with pigs and herbivores being the probable sources of the excrement. But also the application of human feces to the soil might be possible at least at one site. Often used agricultural methods such as plaggen cultivation and an intentional charcoal input to enhance soil fertility could not be clearly verified for our study sites.

KEYWORDS
ancient agriculture, biomarker analysis, manuring, ridge and furrow

1 | INTRODUCTION

Nutrients are an important prerequisite for plant growth and subsequent successful harvests (Hartshorn et al., 2006; McCauley et al., 2011; Shrivastav et al., 2020). To ensure the supply of nutrient elements like phosphorus, potassium, and nitrogen, the application of feces to the soil has been regarded as an effective tool since prehistory. For instance, in Roman times, several authors described methods of fecal-based fertilization practices (Cato, 2nd c. BC (Cato & Froesch, 2009), Columella, 1st c. AD (Columella, 2014), Plinius Secundus, 1st c. AD (Plinius, 2013), Varro 1st c. BC (Varro & Owen, 1800)). Some studies detected that even much earlier—in Neolithic times—livestock manure was used to increase crop yields (Bakels, 1997; Bogaard, 2012; Bogaard et al., 2013; Fokkens, 1982; Guttmann-Bond et al., 2016). In medieval times (European classification 500–1500 AD) and the early Modern Period (from 1500 onwards), cleverly devised agricultural techniques were testified and discussed in numerous historical traditions as described as early as the Carolingian period (e.g., *Capitulare de villis vel curtis imperii*, 8th c. AD; Schneider, 1968), in the high and late Medieval Period (e.g., de Crescentiis, 1471; Ermisch & Wuttke, 1910; Magnus, 13th c. AD) and in the Modern Period (e.g., Beckmann, 1770; Coler, 1645; Germershausen, 1783; Heresbach, 1603; Thumbshirn, 1616; Tull, 1731).

Manuring using livestock waste and also partly plaggen appears to be one of the most essential factors for intensifying crop production according to these medieval and postmedieval descriptions (Enders, 2016; Giani et al., 2014; Jones, 2012; Käubler, 1972; Linke, 1976; van Mourik et al., 2016; Niemeier, 1961). For plaggen cultivation, organically enriched soil sods were cut and "used for animal bedding in stables or together with farmyard manure for composting, and applied to the fields" (Blume & Leinweber, 2004). While manuring with plaggen is proven to have been a common agricultural technique in Northern Germany it is not entirely understood what cultivation techniques were actually implemented in other parts of Germany.

An investigation of the so-called ridge and furrow (RIFU) cultivation helped to bring light to the manuring practices, as this agricultural technique in Germany was likely used from the early Middle Ages into the Modern Period (Langewitz et al., 2020). The RIFU technique was widespread in Europe and occurred, for example, in Scandinavia, Switzerland, France, Greece, and Great Britain (Catsadorakis et al., 2021; Ewald, 1969; Hutter, 2020; Kerridge, 1951; Mead, 1954; Upex, 2004; Vejbæk, 1984, 2005; Widgren, 1997). Similar field types with ridges can be found in South and North America (McKey et al., 2010; Parsons & Bowen, 1966; Smith et al., 1968).

The RIFU systems in Central and Northern Germany that we investigated in our study are easy to identify due to their characteristic ridges with heights up to 1.2 m, widths up to 18 m, and lengths up to 300 m and more. The emergence of the ridges, framed by furrows, was predominantly associated with plowing activities in which the moldboard plow turned the topsoil material toward the field strip center, where a significant amount of material was accumulated, causing a ridge to develop gradually over time. But also other implements like shovels could be used to form the RIFUs by removing the soil from the furrows (Fowler, 2002; Langewitz et al., 2021; Woithe, 2003). The typical shape of the RIFUs entailed some positive effects for cultivation: The ridges created space for plant roots, protected them against waterlogging conditions in deeper soil, and the defined areas could even indicate ownership structures (Alcántara et al., 2017; Bernatz, 1875; Chomel, 1750; Coler, 1645; Kerridge, 1951; Linke, 1979).

In a previous study that investigated the pedological properties of RIFU sites, elevated soil phosphorus ("Olsen P") contents and significant $\delta^{15}N$ values were detected, which are indicators for manuring (Langewitz et al., 2021). For that reason, this study aimed at identifying if fertilizer was intentionally added to the RIFU cultivated fields, and if yes, which kind of manure was applied. We assessed the possible input of livestock waste, plaggen, or charcoal that may have improved the soils and therefore ensured and increased the harvest yields.

We selected five of the previously studied sites to identify possibly used techniques for soil improvement. To scrutinize the manuring with farm waste like livestock dung, we carried out a photometric determination of phosphorus (P). Even if P shows a greater resistance and is more immobile than C and N (Holliday & Gartner, 2007), it is not considered to be the most suitable indicator for manuring activities in the past. Next to "the depletion of added phosphorus by growing of crops [−], losses of soluble forms by leaching" (Evershed et al., 1997) also pose a problem. Therefore, analyses of stanols and bile acids were performed additionally (Bull et al., 2005). Stanols are formed in the intestinal tracts and transformed in the mammalian gut and under environmental conditions. Bile acids are formed in the liver and intestine (Bull et al., 2002). Their detection enhances the knowledge of fecal input in general and makes it possible to identify and distinguish feces from different animal species. Livestock of individual farmers was listed in inventory registers, which reveals a high degree of diversity among the species, but it remains to be clarified whether all species were used for manure production (Abel, 1967; Benecke, 1994; Bock, 2014).

Another tool to improve the soil is the application of charred organic matter, which was formed in fireplaces, hereinafter called black carbon (BC). BC added to the soil enhances the water holding capacity and increases nutrient retention (Wiedner et al., 2015). However, it is unclear if charred matter such as charcoal has been intentionally applied; for instance, in conjunction with dung to exploit the positive effects it has on the soil, or if it was deposited as a component of organic waste from the settlements. A supplementary micromorphological study supported the results from soil chemical analyses and found additional indicators for human impact on the soils by identifying materials, such as charcoals or manure residues.

2 | METHODS

2.1 | Study sites

The studied sites (Figure 1) are located in forest areas of the Northern Altmark (acronyms with A-) and the western and eastern foreland of the Harz Mountains (Leine Uplands and Harzgeröder Zone, acronyms with HA-). The sites were selected in different regions to be able to study the manuring activities of RIFU systems in different environmental settings.

During the Elster and Saale glaciations, the Altmark region was affected by glacial processes. Boulder clay and till originate from these periods, while aeolian dust and glacio-fluvial deposits were accumulated as part of periglacial processes during the Weichselian glaciation, when the Fennoscandian ice sheet did not reach the region. During the Holocene, aeolian sands were widely deposited (Bachmann et al., 2008; Rothe, 2019; Wagenbreth & Steiner, 1990). These parent materials formed the basis for the formation of Luvisols, (stagnic and dystric) Cambisols, and Podzols (Heunisch et al., 2017; Kainz, 1999; Kainz & Fleischer, 2006; Schröder et al., 1995). The south-western Harz foreland is part of the Central German block–faulted area (Hagedorn & Rother, 1992; Wagner, 2011). Sandstones and limestones were superimposed by aeolian dust, which led to the formation of Luvisols and Cambisols (Adler, 2000; NIBIS®, 2014). The eastern foothills of the Harz Mountains are characterized by sedimentary and basaltic rocks (Müller et al., 2012; Wagenbreth & Steiner, 1990). Also here, loess was deposited as thin layers and shallow soils like Cambisols and Luvisols developed (Kainz & Fleischer, 2006).

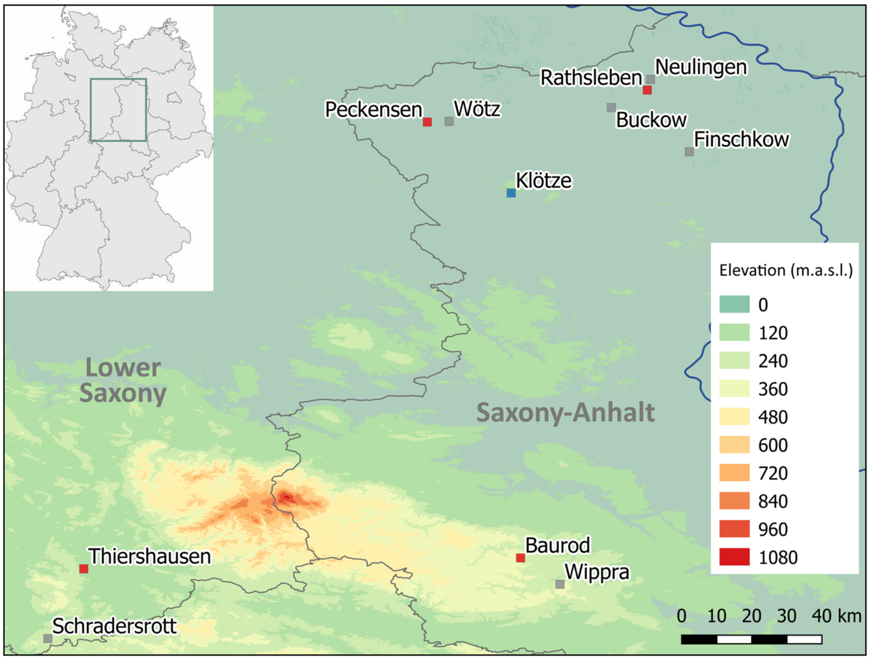

FIGURE 1 The map shows the investigated sites in Germany, as described in Langewitz et al. (2021). The sites marked by red or blue squares were selected for this study to examine indications for soil fertility improvement: Rathsleben (A-RAT), Klötze (A-KLÖ), Peckensen (A-PECK), Thiershausen (HA-THI), and Baurod (HA-BAU). Micromorphological studies were only conducted on the study site Klötze (blue square). [Color figure can be viewed at wileyonlinelibrary.com]

Soil types and vegetation of the study sites are mentioned in Table 1. At our study sites, low pH-values and total organic carbon (TOC) contents were measured (Table S3). For more details about the pedological properties of the studied sites, we refer to Langewitz et al. (2021).

The RIFUs of our sites showed straight-lined shapes with good conservation status. The ridges are up to 0.88 m high and 9–17 m wide. A dating approach to the fields enabled a chronological classification of single fields (Table 1). Our researched RIFU fields were dated from the Early Middle Ages to the Modern period whereby continuous use is not necessarily assumed (Langewitz et al., 2020).

2.2 | Fieldwork and sampling

An excavated cross-section was used to document the soil horizons of the RIFU systems (see Figure 2 and Table 2) according to the FAO (2006) and the soil color according to the Munsell Color Firm (2010). For each horizon, the bulk density was determined after weighing and drying in the laboratory (Table 2). An Apb horizon could be identified at all study sites. This horizon had a brown/gray coloration of different intensities and it is assumed that this horizon was tilled in the past. It is superimposed by recent humic topsoil with partly eluvial characteristics (Ah(E) horizon). The ridges (RIs) were sampled in 10 cm increments to obtain bulk samples. Undisturbed samples for micromorphological investigations were taken at the study site Klötze and at the site Buckow (Goldberg & Macphail, 2003; Goldberg et al., 2009). Since the Buckow site is not otherwise included in this study, the soil information is provided in Table S1.

In the previous study, it was observed that the furrow areas within the RIFU systems were mostly not part of the agricultural activities. At Thiershausen, the furrows of RIFU systems located on a slope were even heavily eroded. Therefore, the present study focused on the ridges of the sites.

For each study site, a reference site (Ref) that was not impacted by RIFU cultivation was selected in the same forest area. The reference soil profiles were sampled in the same way as those from the ridges to obtain comparable results. However, agricultural use or other human impacts in the past cannot be completely excluded from the reference sites.

2.3 | Laboratory work

2.3.1 | Phosphorus

Soil phosphorus measurements were based on the method described by Murphy and Riley (1962). A total of 50 ml of 0.5 M H_2SO_4 was added to unignited and ignited soil samples (ignition for 1 h at 550°C), respectively. After shaking (16 h) and centrifugation, the decanted clear samples were treated with a few drops of *p*-nitrophenol and 5 M NaOH until the color changed to yellow (Kuo, 1996). After the addition of a color reagent (2.5 M H_2SO_4, ammonium molybdate, potassium antimontartrate, 0.1 M ascorbic acid), the sample was shaken intensively and measured with a photometer (Hach Lange, DR 5000 UV/VIS). According to Kuo (1996) the ignited soil represents total phosphorus; inorganic phosphorus can be determined from the unignited soil, while organic phosphorus is the calculated difference from both measured fractions.

2.3.2 | Stanols and bile acids

Analysis of fecal stanols and bile acids was carried out according to Birk et al. (2012). Briefly, the total lipid extract was obtained by soxhlet

TABLE 1 Geographical positions, soil types, vegetation of RIFU and reference soils, estimated time of cultivation, and type of humus of the studied sites.

Study site	Coordinates	Soil type (USDA system)	Vegetation (RI)	Vegetation (Ref)	Estimated time of cultivation	Organic matter
Rathsleben	52°50′ 32″ N 11°32′ 22″ E	Dystric Cambisol (Inceptisols)	CF	CF	Late EMA-MP[a]	Moder
Peckensen	52°45′ 37″ N 10°58′ 32″ E	Stagnic Cambisol (Inceptisols)	DFMW	CF	EMA-?[a]	Mull/Moder
Klötze	52°34′ 43″ N 11°11′ 27″ E	Haplic Cambisol (Inceptisols)	CF	DFMW	EMA-MP[a]	Moder
Thiershausen	51°36′ 58″ N 10°05′ 42″ E	Haplic Luvisol (Alfisols)	DFMW	DFMW	EMA-?[a]	Moder
Baurod	51°38′ 38″ N 11°12′ 52″ E	Luvisol (Alfisols)	DFMW	DFMW	9th c. AD-?	Mull

Abbreviations: CF, coniferous forest; DFMW, deciduous forest and mixed woodland; EMA, Early Middle Ages; MP, Modern Period; RIFU, ridge and furrow.

[a]Langewitz et al. (2020).

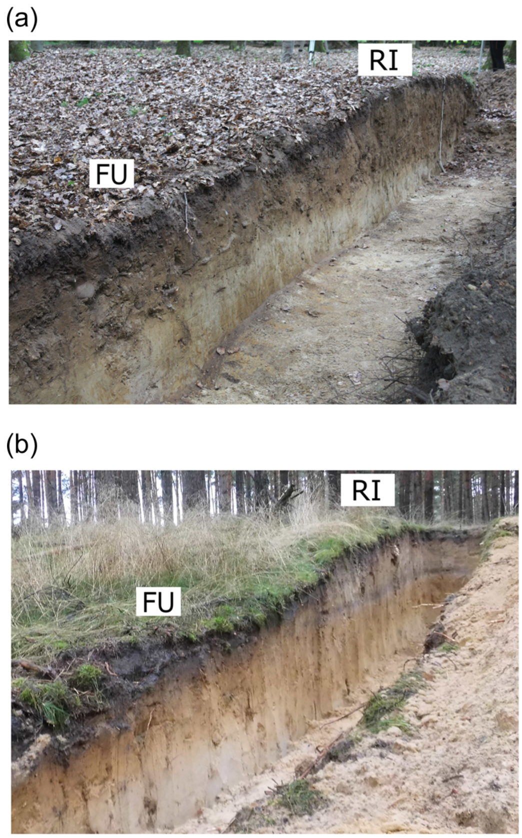

FIGURE 2 Excavated Altmark ridge (RI) and furrow (FU) systems of study site (a) Peckensen and study site (b) Rathsleben. [Color figure can be viewed at wileyonlinelibrary.com]

extraction of 10 g of soil with DCM (dichloromethane) and MeOH (2:1) for 36 h. After extraction, the first internal standard was added (100 µg of α-pregnanol for neutral lipid fraction and 100 µg of isodeoxycholic acid for acid–lipid fraction). Dried extracts were saponified at room temperature (for 14 h) according to Grimalt et al. (1990). Neutral and acidic fractions were separated by sequential liquid–liquid extraction. The acid–lipid fraction was methylated before both fractions were further cleaned up with solid-phase extraction and eluted (Birk et al., 2012; Isobe et al., 2002). Before the measurement, 25 µl of a second internal standard (α-cholestane) was added to samples and external standards. Derivatization was conducted with silylation reagents to quantify all substances by gas chromatography–mass spectrometry (Shimadzu GCMS-QP 2010).

2.3.3 | Black carbon

BC content was determined using the benzene polycarboxylic acid (BPCA) marker method according to Brodowski et al. (2005) and Glaser et al. (1998). The soil samples were first treated with trifluoroacetic acid to remove polyvalent cations and digested with HNO_3 (at 170°C for 8 h). To remove the remaining polyvalent cations, a cation exchange resin was used after adding the first internal standard (phthalic acid). Then the eluates were freeze-dried and a

TABLE 2 Geographical positions of the study sites and basic soil properties: Horizon depth, nomenclature, texture, color, and bulk density for ridges and references.

Study sites[a]	Soil depth (cm)	Horizon[b]	Texture[b]	Color[c]	Bulk density (g cm^{-3})	Soil depth (cm)	Horizon[b]	Texture[b]	Color[c]	Bulk density (g cm^{-3})
	Ridge					Reference				
Rathsleben	13	AhE	Sand	7.5YR 2/2	1.1	6	AhE	Sand	10YR 4/3	1
(A-RAT)	54	Apb	Sand	2.5YR 5/6	1.4	12	E	Sand	2.5YR 7/1	1.4
	65	IIAhb	Sand	2.5YR 4/3	1.4	33	Bw/Bs	Sand	2.5YR 6/6	1.4
	>75	IIBwb1	Sand	2.5YR 6/6	1.4	>33	C	Sand	2.5YR 7/4	1.5
	Ridge					Reference				
Peckensen	10	Ah	Loamy sand	10YR 4/3	1.4	5	AhE	Sand	7.5YR 3/4	1.2
(A-PECK)	36	Apb	Loamy sand	10YR 4/4	1.4	10	E	Sand	7.5YR 3/1	1.2
	60	Bw	Loamy sand	10YR 4/6	1.2	17	Bs	Sand	5YR 3/3	1.3
	70	EBg	Loamy sand	10YR 5/6	1.5	44	Bs/Bw	Sand	10YR 6/6/4/4	1.4
	>70	Bmg	Loamy sand	10YR 7/3	1.6	>44	Bw	Sand	10YR 5/6	1.5
	Ridge					Reference				
Klötze	7	Ah	Loamy sand	7.5YR 3/3	0.9	7	Ah	Sandy loam	7.5YR 1.7/1	0.7
(A-KLÖ)	23	Apb	Loamy sand	10YR 5/4	1.6	24	Bw1	Sandy loam	10YR 6/2	1.5
	34	IIApb/Ahb	Loamy sand	10YR 3/4	1.6	54	Bw2	Sandy loam	10YR 3/2	1.4
	>55	IIBwb1	Loamy sand	10YR 4/6	1.4	>54	Eg	Sandy loam	10YR 5/8	1.4
	Ridge					Reference				
Thiershausen	18	Ah	Silt loam	10YR 5/4	1	8	AhE	Silt loam	10YR 4/2	1.2
(HA-THI)	37	Apb	Silt	10YR 6/4	1.1	39	Bw	Silt	10YR 6/3	1.4
	51	E	Silt	10YR 7/4	1.6	46	E	Silt loam	10YR 5/4	1.4
	>70	Bw/C	Silt loam	7.5YR 5/4	1.7	>46	Bmg	Silt	10YR 5/6	1.6
	Ridge					Reference				
Baurod	8	Ah	Silt loam	10YR 3/2	0.9	11	Ah	Silt loam	7.5YR 4/2	1
(HA-BAU)	21	Apb	Silt loam	10YR 5/4	1.1	21	Bw	Silt loam	10YR 5/6	1.3
	43	Bw	Silt loam	10YR 5/8	1.2	>21	Bw/C	Silt loam	10YR 5/6	1.4
	>43	Bw/C	Silt loam	10YR 5/8	1.6					

[a]With acronyms.
[b]According to FAO (2006).
[c]According to Munsell Color Firm (2010).

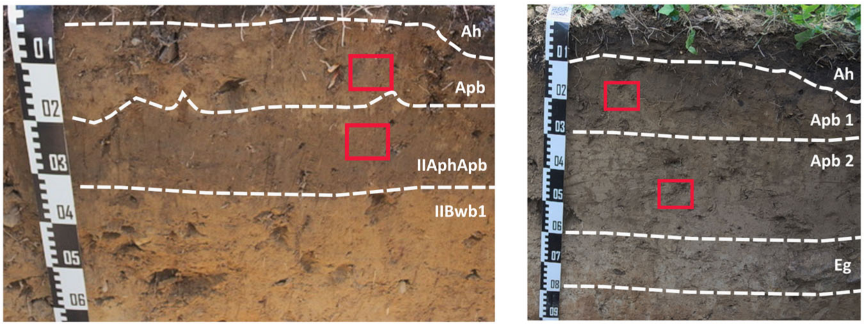

FIGURE 3 Sampling positions for micromorphological investigation in Klötze (A-KLÖ) and Buckow are highlighted by the red rectangles. At the site Klötze (left), an undisturbed sample was taken from the Apb horizon, which is assumed to be the tilled horizon and from the Aph/Apb horizon, a buried soil surface impacted by the anthropogenic soil tillage. At the study site Buckow (right), the two Apb horizons were sampled, respectively. [Color figure can be viewed at wileyonlinelibrary.com]

second internal standard (2,2′-biphenyldicarboxylic acid) was added. After freeze-drying, the samples were derivatized with silylation reagents. The derivatized oxidation products were analyzed on a gas chromatograph equipped with a flame ionization detector (Shimadzu GC-2010). The sum of individual BPCAs was converted to BC content by multiplication with 2.27 (conversion factor as suggested by Glaser et al., 1998).

2.3.4 | Micromorphology

The intact sample blocks (Figure 3) were dried at 40°C until they had reached a constant weight. The dried soil blocks were impregnated with polyester resin (1000 ml Oldopal P 80-21, 1.5 ml cyclohexanone peroxide as catalyst, 0.75 ml cobalt octate). After polymerization, the samples were prepared for sectioning according to Beckmann (1997). The thin sections were scanned and investigated with a polarization microscope (Zeiss Axioskop 40 coupled with a Zeiss AxioCam MRc). They were analyzed and described using standard micromorphological nomenclature (Bullock et al., 1985; Stoops, 2003).

3 | RESULTS

3.1 | Soil phosphorus

Contents of organic P (P_{org}), inorganic P (P_{inorg}), and total P (P_{tot}) were determined for all ridge and reference profiles (Figure 4). The soil profile of the ridge in A-RAT contained a remarkably high amount of P_{inorg} (about 500 mg kg^{-1}). In contrast, the contents of P_{org} are only elevated in 20–30 cm depth. The P_{tot} contents are about five times higher in the ridge profile when compared to the reference. A considerable increase was detected in the buried topsoil (Ahb-horizon) at 50–60 cm depth where the P_{inorg} contents reached more than 1000 mg kg^{-1}. In the A-PECK ridge profile, the contents of P_{org} and P_{inorg} were between 250 and 500 mg kg^{-1}, with a slight increase in the lower part of the profile. Contrastingly, P_{org} and P_{inorg} in the reference profile never reached 250 mg kg^{-1}, except for the depth of 10–20 cm (P_{inorg}: 693 mg kg^{-1}). In A-KLÖ, all P values were <500 mg kg^{-1}. In the ridge profile, the P_{org} contents appeared to be higher (20–30 cm: 226 mg kg^{-1}) than the P_{inorg} contents (20–30 cm: 142 mg kg^{-1}). However, the ridge profile revealed much higher P contents than the reference in which the P contents were considerably lower (0–84 mg kg^{-1}, except for 0–10 cm). In HA-THI, amounts of P in the ridge profile nearly equaled the P amounts in the reference. The values of P_{org} and P_{inorg} were generally low (<250 mg kg^{-1}) but increased with depth from 45 cm downwards and P_{org} contents were highest in 0–10 cm (ridge: 519 mg kg^{-1}, reference: 409 mg kg^{-1}). Also, the ridge and reference profiles of HA-BAU had similar tendencies. However, in both profiles, the P_{org} contents were high—mainly in the upper part of the ridge profile (>1000 mg kg^{-1}). In the lower part, especially P_{org} strongly increased again. No values are available from deeper soil depths at the reference site because of its shallow depth above the stony parent material.

3.2 | Fecal biomarker

3.2.1 | Stanols

Based on the determined stanols concentration, the following ratios were calculated: typical stanol ratios indicating herbivore feces (ratio I; Prost et al., 2017) and typical stanols ratios indicating human feces (ratio II; Bull et al., 1999) (Figure 5a). The stanol ratios were developed to describe the probabilities of fecal input into the studied soils. In the case of ratios lower than 0.3, a fecal input should be excluded. For ratios between 0.3 and 0.7, a fecal input can neither be reliably confirmed nor excluded. Ratios with values higher than 0.7 confirmed a fecal input (Prost et al., 2017). It should be noted that both stanol ratios detect the fecal input of omnivorous as well as herbivorous species—even if they are used to identify stanols of only one group of species.

Our results showed that according to the values for typical herbivore stanols (ratio I), an input of feces could be excluded in most

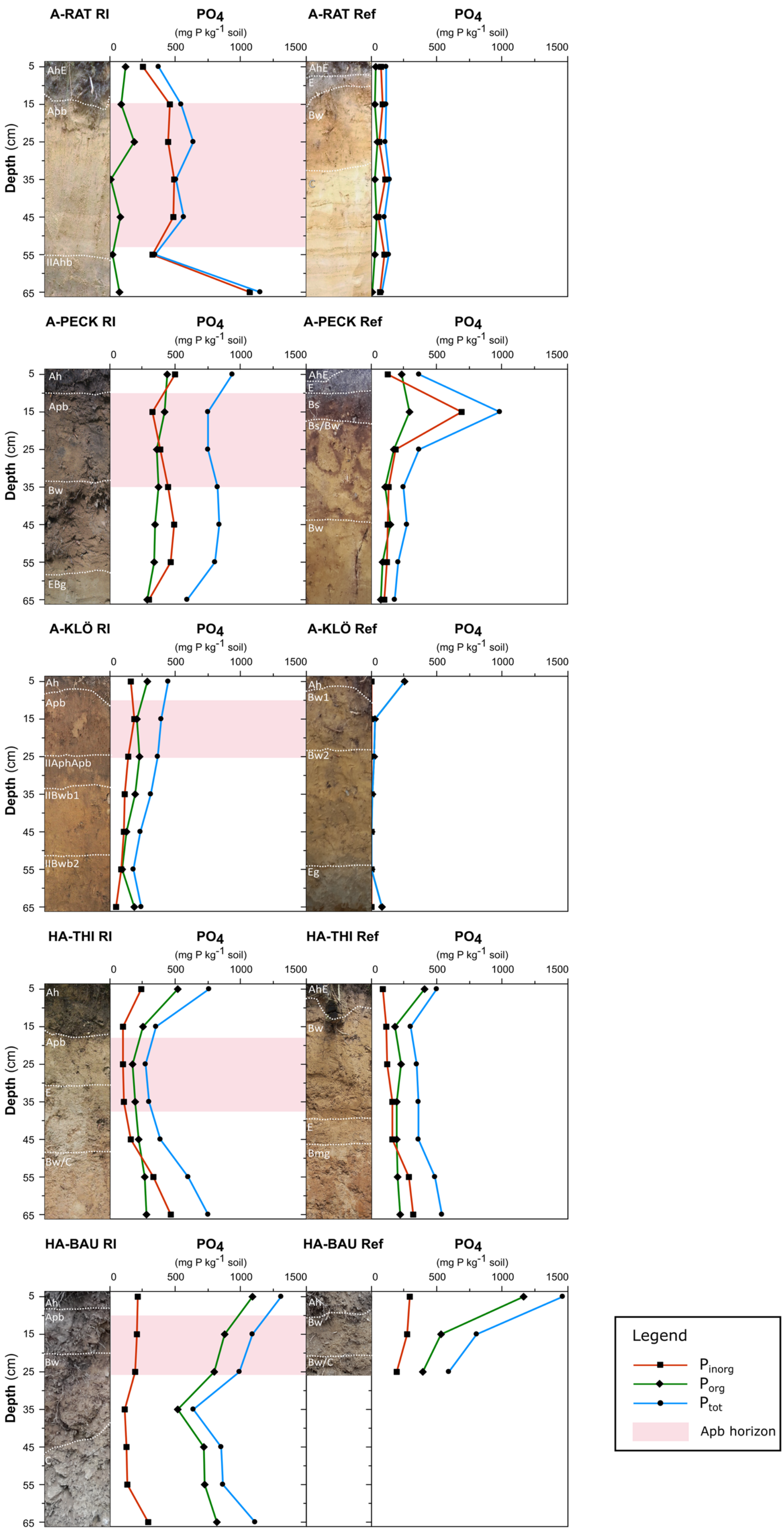

FIGURE 4 Phosphate contents of the ridge profiles (left) and of the reference profiles (right). The contents of P_{inorg} (red squares), P_{org} (green rhombi), and P_{tot} (blue circles) are plotted according to sampling depth. [Color figure can be viewed at wileyonlinelibrary.com]

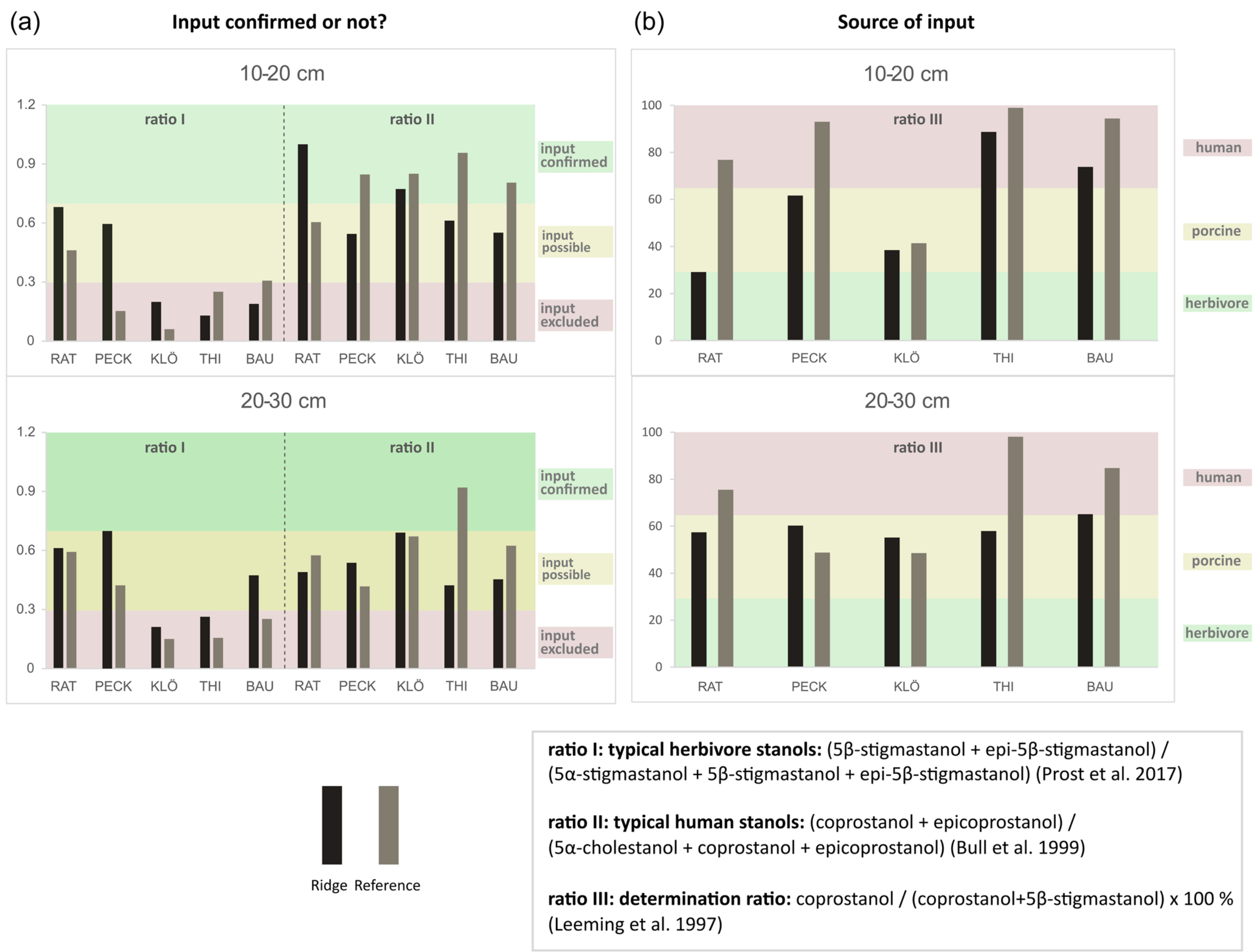

FIGURE 5 Measured stanol ratios for detection and identification of fecal input in ridge and furrow soils. [Color figure can be viewed at wileyonlinelibrary.com]

sites. Contrastingly, the reference sample of HA-BAU in 10–20 cm and the HA-BAU ridge sample in 20–30 cm showed higher values lying in the range where input is possible. Also, in A-RAT and A-PECK, the values were higher than 0.3 and hence a fecal input was possible, except for the reference sample of A-PECK in 10–20 cm.

The ratios that considered the input of typical human stanols (ratio II) revealed that for none of the analyzed samples should a fecal input be excluded, as all values were higher than 0.3. Most of the samples taken at a depth of 10–20 cm even exhibited elevated values higher than 0.7, confirming a fecal input in the reference profiles of A-PECK, A-KLÖ, HA-THI, and HA-BAU and in the ridge profiles of A-RAT and A-KLÖ. The other samples of this depth consequently showed values between 0.3 and 0.7. At a depth of 20–30 cm, all samples revealed values between 0.3 and 0.7, indicating a possible fecal input. The only exception was the reference profile of HA-THI where the ratio confirmed an input with values higher than 0.7.

The additional stanol ratio III that is shown in Figure 5b was calculated according to Leeming et al. (1997) to determine the source of the fecal input. The stanol ratio was developed to differentiate herbivores (<29%), pigs (29%–65%), and human feces (>65%). However, it should be noted that an assignment to animal species is only possible in combination with the bile acids (see Section 4.3). Furthermore, the analyzed samples contain a mixture of feces from different animals, which could lead to an alteration of the ratio. As shown in Figure 5, the ratios were variable for all soil profiles; however, none of the profiles indicated an input solely of herbivore feces. High ratios reflecting an input of human feces were measured in all profiles of the Harz region except for the ridge in HA-THI (20–30 cm). The Altmark profiles A-RAT, A-PECK, and A-KLÖ revealed ratios between 29% and 65% (pig feces) except for the reference profiles of A-RAT in both depths and the reference profile of A-PECK in 10–20 cm, which reflected again an input of human feces.

3.2.2 | Bile acids

The specific bile acids are steroid markers, which help to determine the origin of the fecal input due to their occurrence in vertebrate feces. To compare the measured bile acid compositions, isolithocholic acid, lithocholic acid (LCA), deoxycholic acid (DCA), chenodeoxycholic acid

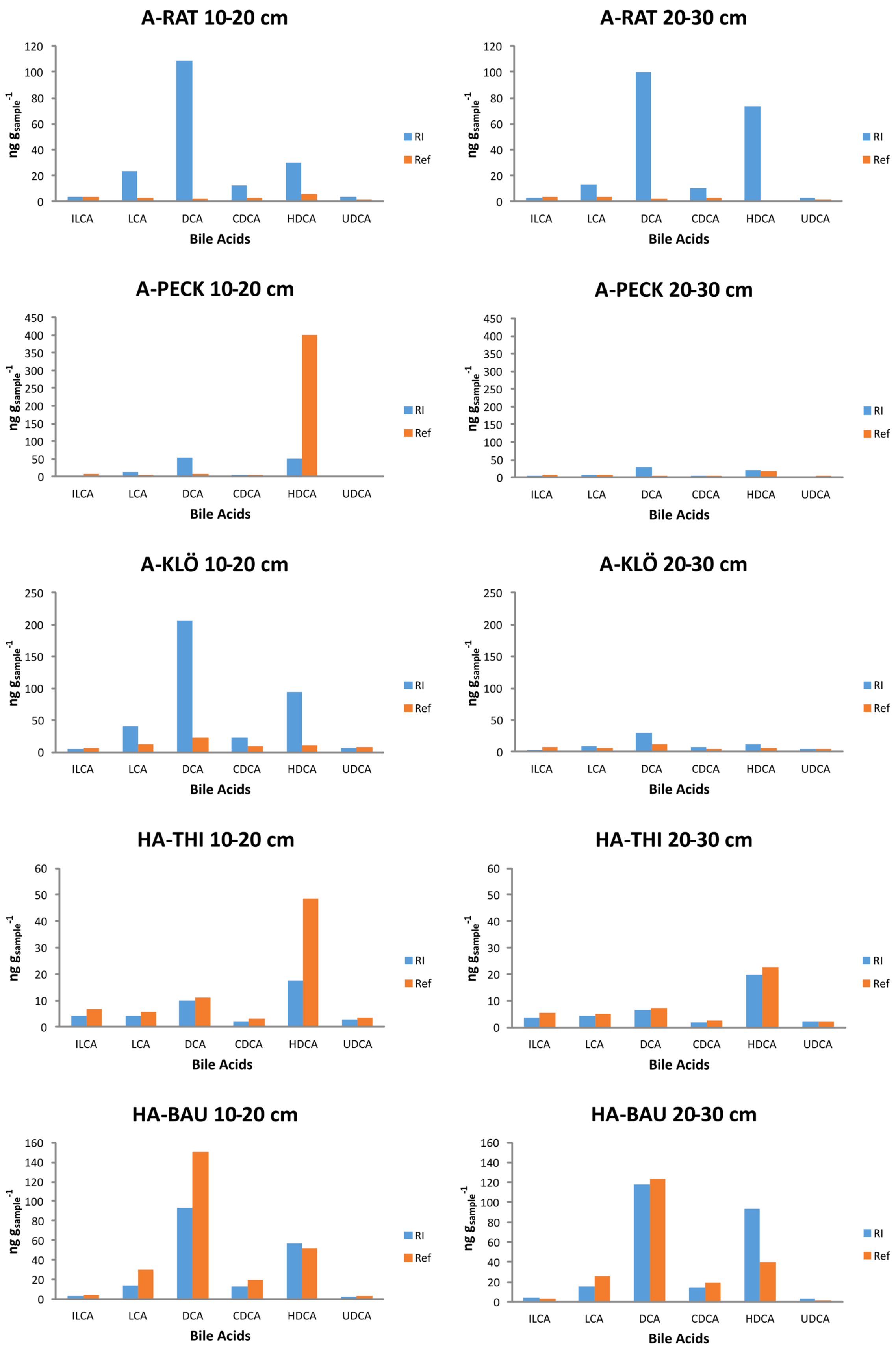

FIGURE 6 The bile acids isolithocholic acid (ILCA), lithocholic acid (LCA), deoxycholic acid (DCA), chenodeoxycholic acid (CDCA), hyodeoxycholic acid (HDCA), and ursodeoxycholic acid (UDCA) are set out for all study sites in the depth 10–20 and 20–30 cm. [Color figure can be viewed at wileyonlinelibrary.com]

(CDCA), hyodeoxycholic acid (HDCA), and ursodeoxycholic acid (UDCA) are shown in Figure 6. Amount, as well as the composition of bile acids, were highly variable among the study sites. In comparison to the reference site, bile acid contents were high in A-RAT with DCA contents of 108 ng g^{-1}. Furthermore LCA, CDCA, HDCA, and to a lesser extent also UDCA reached higher contents than the reference (2–6 times higher). In A-PECK, all values were quite low (<55 ng g^{-1}), with exception of the bile acid HDCA in the reference in a depth of 10–20 cm, which reached a high content >400 ng g^{-1}. However, the bile acid DCA of the ridge profile was about seven times higher than in the reference concerning both depths. In A-KLÖ, the contents of LCA, DCA, CDCA, and HDCA were several times higher in the ridge profile than in the reference, whereas DCA even reached values of >200 ng g^{-1}. The bile acid contents of HA-THI were low (<50 ng g^{-1}). The HDCA of the reference in 10–20 cm reached 49 ng g^{-1} and was almost three times higher than the contents of the ridge profile. On the contrary, the profiles of HA-BAU contained high values of bile acids, but with an irregular composition. While the reference contained 59 ng g^{-1} more DCA in 10–20 cm, HDCA is about 53 ng g^{-1} higher in the ridge profile in 20–30 cm.

3.3 | Micromorphology

Two micromorphological samples were taken at the Klötze study site, originating from the Apb horizon and the underlying Apb/Ahb horizon. Due to the very similar results of both thin sections, only one is described in the following representatively (see Figure 3, Klötze, Apb horizon).

The thin section showed a micromass without vughs or channels. An apedal microstructure was observed with varying intensity of brown color in the low magnification performed with the scanner (Figure 7a). Using a higher magnification, different contents of darker material with different degrees of compactness were revealed. The thin sections are mainly characterized by loosely arranged quartz grains (Figure 7d).

Iron oxides (Figure 7f) and organic material (Figure 7c,f,h) formed intergrain microaggregates, which have positive effects on the stability of the soil structure. In some cases, the aggregates adhere to the quartz grains, in others, they are loosely distributed. These aggregates indicate microbial activity and the supply of organic material. The uneven distribution of the organic material could be a result of soil tillage.

In the upper part of the thin section, sclerotia (persistent resting bodies formed by accumulations of fungal hyphae) and plant residues like roots were visible (Figure 7b,d) that are well-preserved. Some larger charcoal fragments occurred similar to the one shown in Figure 7g. Preservation of charcoal fragments varies, but most were highly weathered, amorphous, and inter-aggregated. Phytoliths—inorganic plant remnants consisting mainly of hydrated silica (Piperno, 2006)—were found in parts of the thin section, but their number was limited (Figure 7e).

The thin sections of both Apb horizons in Buckow showed similar results (Figure 8). However, less organic material and charcoal fragments were found than in Klötze. In addition, incorporated fragments of crusts are visible due to the parallel orientation of the fine particles and are preserved in the soils with loamy sand texture, indicating the tillage history of the soil (Pagliai & Stoops, 2010).

3.4 | Black carbon

In the examined ridge profiles of A-PECK, HA-THI, and HA-BAU, the BC contents (Figure 9, blue) were lower than in the corresponding reference profiles and rarely contained >1 g kg^{-1} BC. For instance, very low values were measured in A-PECK, whereas the highest value reached 0.07 g kg^{-1}. All profiles showed decreasing quantities with depth in the profiles with small increases in A-RAT (40–50 cm), A-KLÖ (10–20 cm), and HA-BAU (20–30 cm).

The reference profiles showed the highest values in the topsoil, which decreased with depth. Only in A-RAT (40–50 cm) and A-KLÖ (20–30 cm), slight elevations were observed.

The BC stocks (Figure 9, red) of the ridge and reference profiles were calculated under consideration of measured bulk density and sampling depth. The BC stocks of A-PECK, HA-THI, and HA-BAU were higher in the reference profiles reaching even up to 2.5 Mg ha^{-1} and decreasing rapidly with depth (not measured in HA-BAU). In the ridge profile of A-PECK, the stocks were very low throughout the whole profile (<0.5 Mg ha^{-1}), with a slight increase in depth. In the ridges of HA-THI and HA-BAU, the BC stocks increased to a depth of 25 cm, with a decrease in HA-THI with depth. The reference BC stocks of A-KLÖ reached almost 2 Mg ha^{-1} in the depth of 20–30 cm. The ridge profile showed variable contents with increasing tendencies and highest values in 30–40 cm, reaching 2.77 Mg ha^{-1}. Also, the contents of the A-RAT ridge profile resulted in high BC stocks with more than 3 Mg ha^{-1} but only in the depth of 40–50 cm. A second but smaller peak is registered in 10–20 cm with up to 0.61 Mg ha^{-1}. There are similar increases in the reference profile but to a lesser extent (1.7 Mg ha^{-1} in 30–40 cm).

4 | DISCUSSION

4.1 | Detection of fecal input for soil improvement of RIFU cultivation

The soil phosphorus analyses conducted for each study site revealed large differences between the sites. In HA-THI, the P amounts were generally low, comparable between the ridge and reference profile and highest in the lower soil profile part. This case seems to represent a natural occurrence of P in the soil or a buried surface, which is not visible anymore. At A-RAT, A-PECK, A-KLÖ, and HA-BAU sites, the Apb horizon of the ridges contained more P than the reference sites, which could be an indicator of past manuring in ancient agricultural fields. Comparable P amounts were detected in investigations of ancient agricultural fields like the *Celtic Fields*, which had raised P amounts in the tilled soil horizons with a sandy soil texture (Bruns et al., 2017). However, the references at HA-BAU and A-PECK also contained higher amounts of P. In the latter case (A-PECK), a remarkably high P content, but only in the depth of 10–20 cm, could

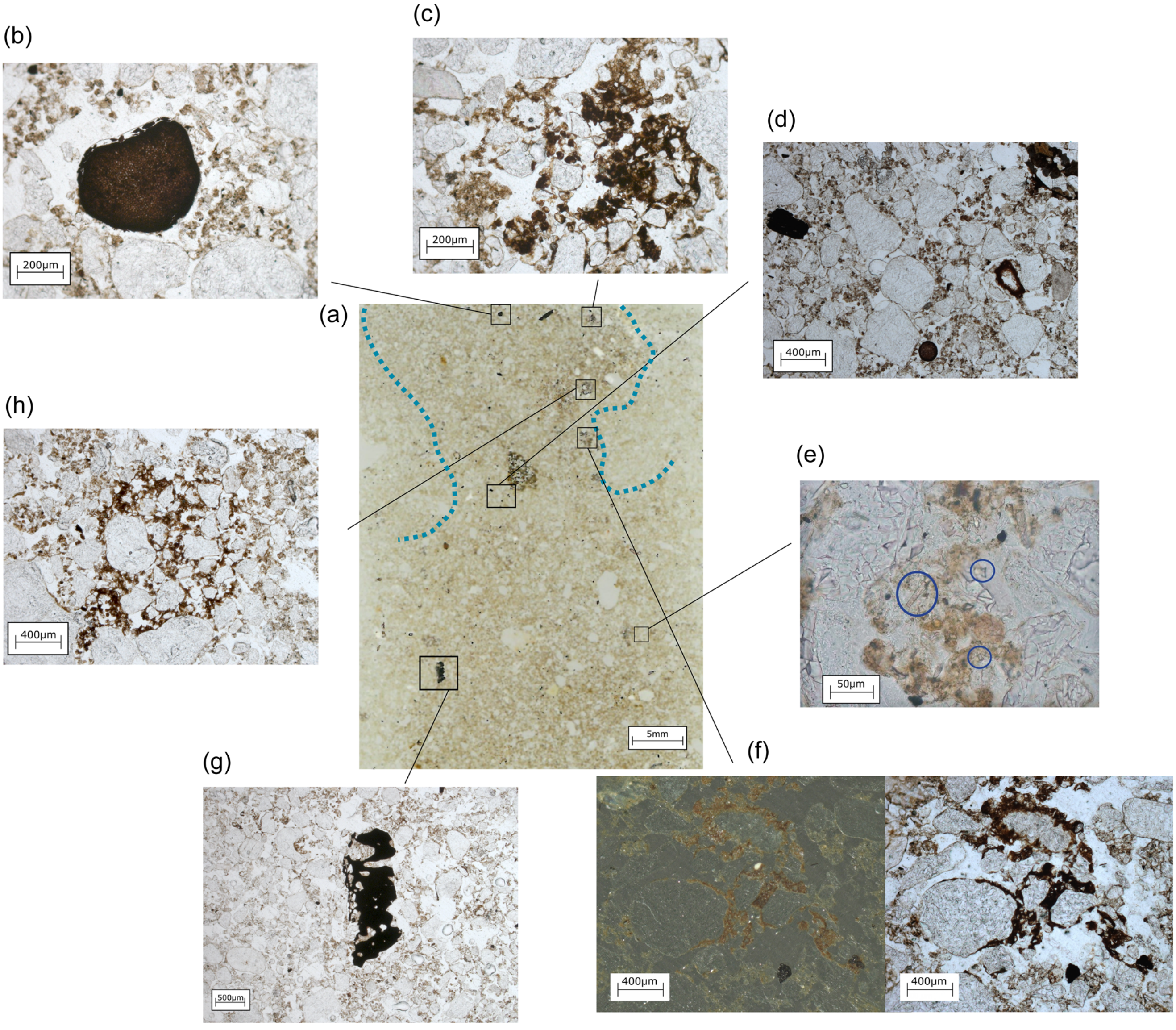

FIGURE 7 Thin section of the Apb horizon in Klötze (A-KLÖ). The image in the center (a) was scanned and shows the thin section with differences in the contents of organic material. In (b) sclerotia, (c) and (h) different degrees of organic-rich material, (d) plant residues, (e) phytoliths (blue circles), (g) a charcoal fragment are detectable with plane-polarized light, and (f) shows organic material with iron impregnation using an additionally oblique incident light (left). [Color figure can be viewed at wileyonlinelibrary.com]

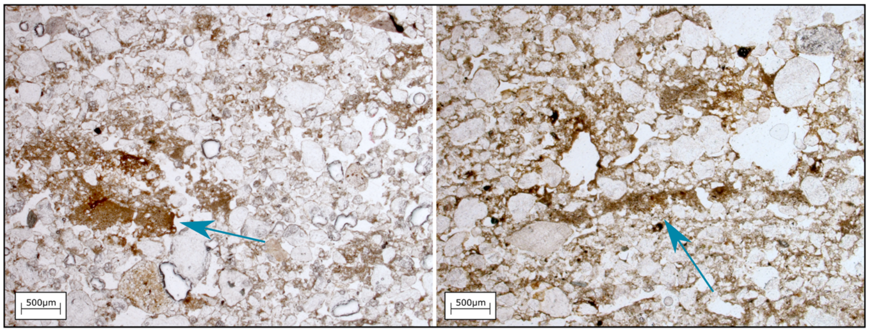

FIGURE 8 In the two Apb horizons (Apb 1, left and Apb 2, right) of the study site Buckow (A-BU), the thin sections show aggregates (blue arrows) indicating incorporated topsoil resulting from anthropogenic activities such as plowing. [Color figure can be viewed at wileyonlinelibrary.com]

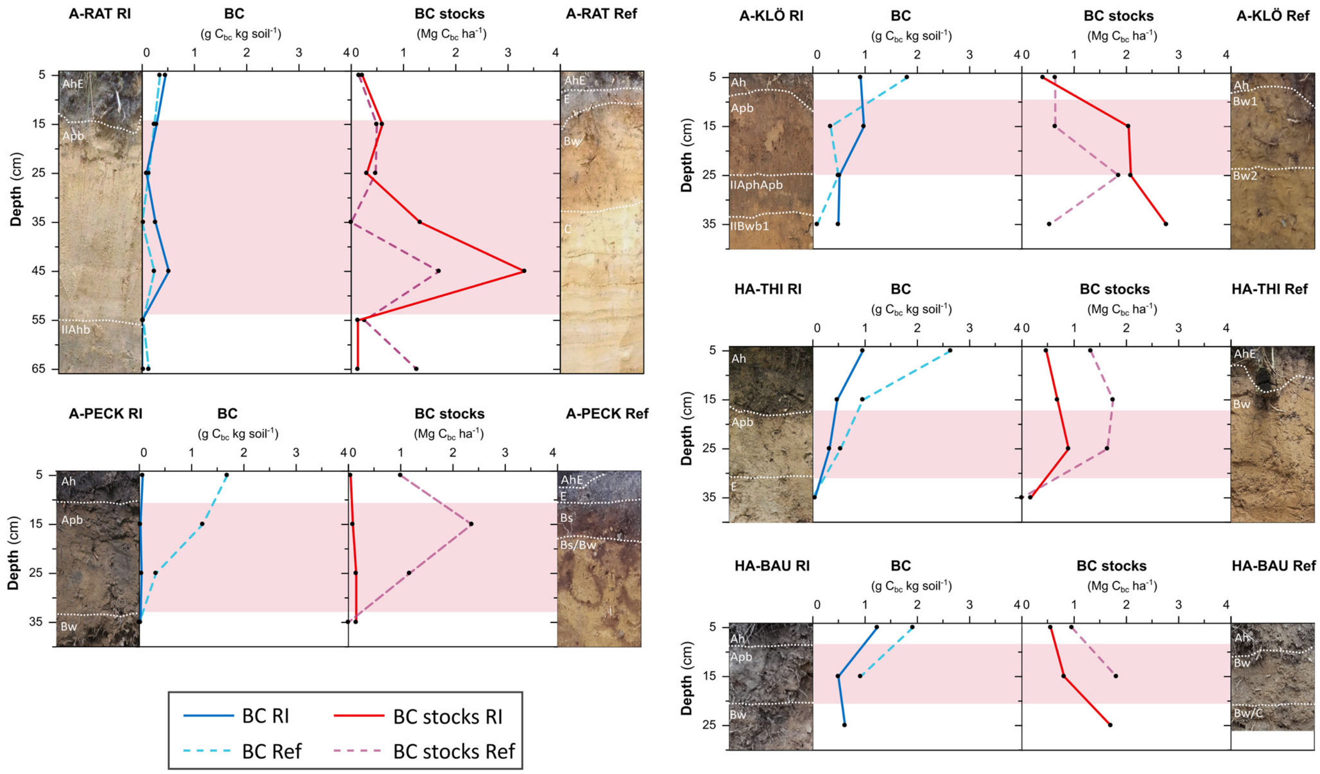

FIGURE 9 Charred organic carbon was determined using the molecular marker benzene polycarboxylic acid. Black carbon contents (left) and black carbon stocks (right) were determined in 10 cm increments. In the HA-BAU reference soil, it was only possible to analyze the samples until the depth of 20 cm. [Color figure can be viewed at wileyonlinelibrary.com]

indicate a recent input, where P binding was promoted by sesquioxides occurring in the Bs horizon due to an increased pH-value (Oonk et al., 2009; Wild, 1995). Elevated P contents were detected also in the HA-BAU reference profile, although lower than the contents in the ridge profile; it is noteworthy that in the ridge and reference profiles, P_{org} is considerably higher than the P_{inorg} contents. These results call into question whether this is due to intensive past manuring or local factors such as lower mineralization rates by soil biota.

Nutrient depletion by harvesting would reduce P contents at ridge sites significantly but also the usual dynamics of soil-forming processes lead to changes in elemental composition. This would lead to an incorrect interpretation of the results, which is why steroid contents have been measured additionally. The stanol ratio I by Prost et al. (2017)—considering 5β-stigmastanol, epi-5β-stigmastanol, and 5α-stigmastanol—indicated that an input occurred rather in A-RAT, A-PECK, and HA-BAU. However, the stanol ratio II by Bull et al. (1999) showed that a fecal input is possible for all samples of all sites as the ratio reached values >0.3.

Furthermore, the correlation of phosphate and bile acid contents strongly suggested soil amelioration by application of livestock waste at some sites. Bile acids are the best indicator because they are resistant to weathering and "absent in plants and invertebrates, which makes them more appropriate than stanols and stanones for characterizing the origin of fecal input" (Porru et al., 2021). At A-RAT and A-KLÖ sites, increased amounts of some bile acids—particularly DCA and HDCA, and to a lower extent LCA and CDCA—were detected in comparison to the reference profiles, although the values were comparably lower than in other steroid analyses (e.g., Prost et al., 2017; Zocatelli et al., 2017). It should be noted that the studied sites were located at off-site positions, thus, outside the settlements, and therefore lacking concentrated manure as in manure heaps or in the stable of residential areas. Therefore, the comparison with reference soils is important for interpretation. In A-PECK, the contents of bile acids LCA, DCA, and HDCA were only slightly increased (amounts less than 50 ng g^{-1}). Thus, a fecal input is not unambiguously verifiable but possible as it also was the case for some Neolithic fields of the research of Guttmann-Bond et al. (2016), which were used for arable and pastoral farming. The reference soil of A-PECK, however, contained an exceptionally high value of the bile acid HDCA in the depth of 10–20 cm. This value corresponds to the high P amount in this depth and indicates again a recent input of feces. In both profiles in HA-THI, the values of all bile acids are low (<50 ng g^{-1}), thus manuring activities are improbable, as was already suggested by the low phosphate contents, which were similar in the ridge and reference profiles. In HA-BAU, the amounts of bile acids LCA, DCA, CDCA, and HDCA are elevated for the ridge and the reference profile with even higher contents in the reference soil. In addition to the phosphorus contents, the bile acids indicate a fecal input. It is possible that the contents of P and the bile acids are naturally higher than at other sites. However, the high contents at HA-BAU cannot necessarily be explained by the finer grain size (silt loam), pH-values, or TOC contents (Table S3). The study site HA-THI had similar characteristics, but lower P or bile acid contents. Furthermore, the proximity to the abandoned medieval village Baurod, located less than 500 m away from the study area, could explain these contents. It can be assumed that livestock waste was disposed of on the arable fields and the surrounding areas of the village (Civis, 2015; Linderholm, 2007).

4.2 | Soil improvement strategies for RIFU cultivation

4.2.1 | Intensity of manuring with livestock waste

It is difficult to estimate the intensity of manuring based on our results. As already mentioned, the amounts of compounds that signify manuring are generally low (Tables S2 and S3). Although biomarkers are mainly well preserved for "hundreds to thousands of years" (Prost et al., 2017) in soils, our study sites do not have the favorable properties for their retention due to the often sandy texture and the scarcity of organic matter (Tables S3) to which the steroids adsorb. Furthermore, feces deposition was not concentrated as described above. These circumstances further complicated the reconstruction of the manuring intensity. However, larger P and steroid contents in A-RAT, A-PECK, A-KLÖ, and HA-BAU than in the reference soils indicated that feces may have been applied.

Despite the poor preservation of steroids in our soils, the results suggest manuring. In accordance with the manuring facilities and soil properties, suitable cereal species were selected by the local farmers. It is therefore not surprising that rye was one of the most widely cultivated cereals in the studied regions as numerous historical sources revealed. Tithe registers, recording the levies of the farmers, showed that rye accounted for the largest part of the tithes, often accounting for more than 65% of the total sowing (Abel, 1967; Bock, 2014; Enders, 2016; Scholkmann, 2009). The rye's demands on the soil, nutrient, and water supply are lower than those of other cereals and it can still produce good crop yields even on sandy and acidic soils (Behre, 1992; Land- und Forstwirtschaftliches Versuchszentrum Laimburg, 2013). Even though it can be assumed that the pH values have always been low, it is likely that they have decreased over time due to soil processes induced, for example, by coniferous forests as vegetation.

Considering the widespread occurrence of RIFUs in all forested areas of the Altmark region and the Harz Mountain foreland (especially in the western foreland of the Harz Mountains) it is a logical consequence that the dung received from livestock was insufficient to supply enough dung on the fields even if these were not used simultaneously (Enders, 2016; Jones, 2012). The availability of feces for manuring influenced the manuring intensity depending on the quantity of livestock, which was highly variable (Duby, 1977; Enders, 2016). The distance to the related farm must have influenced the amount of applied dung (Linke, 1976). A long transport distance required the power of draught animals and was time-consuming (Bogaard, 2012; Wilkinson, 1997), whereas a local removal of livestock waste near the villages was probable and assumed for the study site HA-BAU (Section 4.1). The procurement of excrements from the nearby cities, which produced large amounts of feces, was a common method to access manure but the dung was mostly provided for own domestic use, as for gardening in the cities. Furthermore, it was not accepted in all communities to export livestock waste (BLHA, 1802).

Crop rotation systems have been known since the High Middle Ages, with two- and three-field rotation being the most common (Enders, 2016). To restore soil nutrients, the fields were left fallow for a period of time. Scholkmann (2009) proposed manuring by using the field as pasture land during this fallow period, which would explain low P and steroid levels as detected at our study sites. For instance, when cattle, pigs, or sheep grazed on fields for consuming crop waste, their excrements were dispersed on the soil surface. However, whether the grazing and the associated fecal matter application took place during the fallow period or even after the fields had been abandoned cannot be distinguished with our methods.

Although there are known cases when fields were cultivated continuously and not left fallow ("*Brachsömmerung*"; Nau, 1791), this would be unlikely for the poor soils with sandy textures like in A-RAT, where fallow periods were an important part of the recovery of soil fertility.

Pottery scatters within agricultural fields are common and part of identifying arable zones (Jones, 2014; Wilkinson, 1990). The incorporation of waste into the manure caused sherd to scatter across the manured arable fields. In our study, single sherds were only found in the upper part of the soil profiles in A-KLÖ and HA-THI. The absence of a greater amount of ceramic fragments does not point to the conclusion that the fields were not manured (Poirier, 2016). There are several possible reasons for the absence of ceramic pieces; Schreg and Behrendt (2011), for example, concluded that ceramics could be part of the manuring process just since the late Middle Ages. Therefore the period of agriculture can determine the presence of sherds (Wilkinson, 1997). Waste separation in the villages, allowing feces and household waste to be disposed of separately, could be another explanation (Jones, 2012). But also Scholkmann's (2009) hypothesis that manuring happened while grazing during the fallow period is supported by the absence of ceramics. Moreover, ceramic fragments would be missing, if the dung was applied after stable bedding—as it was practiced with the plaggen cultivation.

4.2.2 | Plaggen use during RIFU cultivation

Examples of plaggen use in combination with RIFU cultivation are known in Germany (Antony et al., 1989; Kasielke et al., 2020). Additionally, historical sources from the 18th and 19th c. explicitly mention that plaggen cultivation was practiced at some of our studied sites in the Altmark region in the context of RIFU cultivation (Linke, 1976). Even if the study sites in the Altmark are mentioned, it is not known if these are the same sites we sampled.

Unambiguous identification of a contemporaneous plaggen cultivation on RIFU fields is impossible. Elevated P contents combined with a darker soil color could indicate the use of plaggen at the site Klötze since these are the usual indicators identifying plaggen soils (Blume & Leinweber, 2004). Therefore, micromorphological samples were taken there. The thin sections did not show a great amount of phytoliths, which would indicate plaggen application as remains of the plants in the cut sods (Hubbe et al., 2007). The few phytoliths in the thin sections are more likely remains of the incorporation of the in situ topsoil or topsoil from the furrows, which was blended during plowing or shoveling on the ridges. This result is also observed in the micromorphological samples from Buckow. Only a few phytoliths are found, but the soil tillage is well recognizable (likely due to the finer soil texture; Table S1).

Also, the use of plaggen was dependent on factors, such as the distance to the belonging farm and availability of manpower to transport and disperse the plaggen in the stables and on the fields (BLHA, 1668), as well as the availability of the plaggen itself. Quite often the cutting of sod was prohibited and disputes over these limited resources have been recorded in historical sources (BLHA, 1744). Finally, the benefits of the plaggen use may be questioned in the study areas (Enders, 2016). The *Kammerdirektor* Borgstede criticized the practice of plaggen cultivation during his journey through the Altmark region in the 18th c. He described this cultivation technique as an improvement of soils on nutrient-poor sands using just comparably nutrient-poor soil and therefore doubted as a significant enhancement (BLHA, 1792).

In summary, we question whether the resources, manpower, and proportionality of time and use were available to carry out a plaggen cultivation to a detectable extent during the times of RIFU cultivation.

4.2.3 | Charcoal input during RIFU cultivation

During the excavation campaign, identifiable charcoal specimens were found and determined in A-KLÖ (six pieces of Quercus, Betula, and nonspecifiable deciduous wood) and A-PECK (one piece Quercus) (Langewitz et al., 2020). Because of these findings, the amount of charcoal in the soil was analyzed as BC to investigate possible intentional input of charcoals. The BC contents of the ridge profiles are generally low but we could detect enrichment in the ridge profiles at the study sites A-RAT and A-KLÖ. The latter study site showed the highest BC stocks, also in comparison with the other soils (Figure 9). The thin section sampled in A-KLÖ revealed enrichment of charcoal particles and fragments (Figure 7). However, at the other studied sites, the BC contents and stocks of the reference profiles were considerably higher than in the ridge profiles.

It is not possible to identify the origin of the charcoal, and BC contents in soils do not have to be highly elevated even after fires (Eckmeier et al., 2007). Strong detectable BC enrichment requires a repetitive process lasting several years. Slash-and-burn clearances or natural fires that occurred many years ago cannot be completely ruled out and could affect the BC content of the ridge and reference profiles as our results indicated. However, long-lasting or repetitive fire activities probably did not happen and also livestock waste, which was mixed with fire remains, was not dispersed on the fields. Therefore, we suggest that charcoal was not applied intentionally for soil improvement because the BC contents were low and the ridge soils did not contain higher BC contents than the reference soil profiles.

4.3 | Identification of fecal input of RIFU cultivation

Livestock was important in a number of ways in the RIFU farming system. Cattle and sometimes horses provided draft power for dung and harvest transportation as well as for plowing. Furthermore, all farm animals could play an important role in supplying dung, and therefore fertilizer production. Archaeozoological investigations as well as historical inventories of livestock information attest to a heterogenous mix of livestock species in all medieval periods. Benecke (1994) found that since medieval times, the pig is the dominant domesticated animal, while with the beginning of the late medieval period, cattle became more important. However, specific historical inventories showed that among the farms different species of livestock were kept due to the varying sources of income (Abel, 1967; Bock, 2014; Enders, 2016). For instance, a farmer in Wegenitz (Altmark) possessed various species, of which horses and pigs accounted for the majority (LHASA, 1541-1744). On the contrary, in Kläden (Altmark), a tax register revealed mainly sheep as livestock of a farmer (LHASA, 1541-1751).

The stanol ratio III (Figure 5b) and the bile acid compositions reflect heterogeneity of livestock in the ridge profiles. To identify herbivore, porcine, and human feces with stanols, it is important to consider that the stanol ratio is the result of a mixture of feces derived from different animal species. If feces were included that lead to a higher ratio (omnivorous feces), the feces of herbivores cannot be clearly identified.

In the following, only the ridge profiles are considered for which manuring was interpreted (see Section 4.1: A-RAT, A-PECK, A-KLÖ, and HA-BAU). In these profiles, the quantities and compositions are not identical. The presence of the bile acid HDCA in all profiles indicates manuring with pig feces since this bile acid is exclusively specific to them (Zocatelli et al., 2017). In the reference profile of A-PECK, extremely high content exclusively of the bile acid HDCA in the upper part of the soil profile may be explained by a recent and natural fecal input of a herd of wild boars, as it is not possible to distinguish between domesticated pigs and wild boars.

According to the lower values of the determination stanol ratio and to higher DCA, LCA, and CDCA values in A-RAT, A-PECK, and A-KLÖ, the feces of herbivores, such as cattle, sheep, or horses could be a further dung component next to the feces of pig (Prost et al., 2017). Although pig excrements also contain the bile acids LCA and DCA, the higher values of DCA compared to HDCA and the presence of CDCA support the assumption that excrements of different animal species were applied. However, as none of the remaining bile acids is characteristic of only one animal species, a distinct classification is not possible.

In HA-BAU, high determination stanol ratios, which are even larger than 65%, are noteworthy in the reference and ridge profiles, although a mixture of the dung with herbivore feces would reduce these values. A higher ratio means elevated amounts of coprostanol, which is produced during omnivorous digestion and is called "a feasible marker for the input of human feces in archaeology soil samples" (Bemmann et al., 2014). Furthermore, higher amounts of the bile acids DCA and LCA were detected, which could be indicative of human or herbivore feces (cattle, sheep, and goat, Guttmann-Bond et al., 2016; Prost et al., 2017). Therefore, an input of human feces cannot be excluded in HA-BAU. Waste management, especially feces disposal, was an unaddressed subject in medieval sources (Schreg & Behrendt, 2011). It is therefore difficult to obtain written records on this issue. There are meticulous explanations of the benefits of different types of manure produced by different animal species only from later times, for instance, from Coler (1645) and Germershausen (1783), but the application of human feces is not mentioned in the sources. However, in the case of HA-BAU, our results and the proximity of the agricultural field to the village indicate the possibility of manuring with human feces.

5 | CONCLUSION

For the majority of studied sites, it is strongly supported that animal excrements were applied to the soil, even if the intensity is low. The weak signature of manuring cannot be explained by nutrient depletion and soil processes over time alone because more persistent marker compounds like steroids indicate low manuring intensities. Furthermore, sophisticated strategies with different tools like plaggen cultivation and the intentional input of charred material could not be clearly established for our study sites, as the micromorphological study also showed. The agricultural techniques for crop production included the widespread construction of RIFUs and not an intensive and ingenious soil improvement of a small number of sites. Regarding phosphorus, BC, and steroid analyses and the paucity of ceramics, it is possible that the feces was directly applied to the soil by the livestock grazing in the fields during the fallow periods. The bile acids revealed that for all study sites, which seemed to have been manured, pig feces were used, as well as herbivore feces and at least for one study site located in the immediate vicinity of a village, even human feces may have been applied.

The studied sites revealed a versatile picture of manuring activities and showed that logistical reasons like livestock keeping and the distances to their owners' homes were likely of great importance for the intensity of manuring. For a comprehensive understanding of manuring techniques during RIFU cultivation, further study sites with higher organic contents and finer soil texture are worth investigating as part of future work in which conservation conditions as biomarkers could be better.

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SUPPORTING INFORMATION

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

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