Received: 29 April 2023 | Accepted: 10 June 2023

DOI: 10.1002/jpln.202300150

REVIEW

Contribution to the HiStory series in Plant Nutrition

Earliest archeological evidence of fertilization in Central Europe

Silviane Scharl[1] | Tanja Zerl[1] | Eileen Eckmeier[2] | Renate Gerlach[3]

[1]Institute of Prehistoric Archaeology, University of Cologne, Cologne, Germany

[2]Institute for Ecosystem Research, Kiel University, Kiel, Germany

[3]LVR-Amt fuer Bodendenkmalpflege im Rheinland, Bonn, Germany

Correspondence
Silviane Scharl, Institute of Prehistoric Archaeology, University of Cologne, Weyertal 125, 50931 Koeln, Germany.
Email: sscharl@uni-koeln.de

This article has been edited by Alexander Wissemeier.

Funding information
Deutsche Forschungsgemeinschaft

Abstract

The beginnings of food production—animal husbandry and crop cultivation—and of a sedentary way of life represent one of the most drastic changes in human history. Likewise, this is accompanied by an increasing human impact on nature, which is mainly caused by agricultural practices. Agriculture is related to the clearing of forests, tillage, maintenance of the cultivated land, and finally harvesting, which alters not only the vegetation cover but also soil fertility as there is a potential risk for a loss of nutrients. People already countered this loss of nutrients in the times of early agriculture through different techniques and practices. The article summarizes the earliest evidence of fertilization in the prehistory of Central Europe and presents the most important methods for their investigation. What significance fertilization had for early farming societies can presently not be estimated due to the small amount of data. We therefore advocate the development of a routine for sampling during archaeological excavations and for the analysis of various materials (sediment and plant remains) using various methods. For this, the awareness must be raised that anthropogenic sediments, such as pit fills, are important archives for research into the history of humankind.

KEYWORDS

Central Europe, Neolithic, manuring, middening, slash-and-burn cultivation, soil fertility

1 | INTRODUCTION

The beginnings of agriculture mark a major turning point in human history. While people for hundreds of thousands of years relied on foraging for food supply, that is, hunting of game, gathering of wild plants, and fishing, agriculture enabled them to produce their food themselves. Agriculture is based on the domestication of animals and crop plants. In agrarian societies, both represent the main source of food; though, 'main source of food' can be defined differently (e.g., summarized in Smith, 2001). Zvelebil (1996), for example, assumes a minimum reliance on domesticates of 50%. Harris (1996), for example, adds that not only do agrarian products represent the main or exclusive source of food, but that more human labour is invested in the cultivation and the maintenance of agricultural facilities than in, for example, hunting or gathering. The boundary between foraging and agrarian societies is not clear-cut, however. This is why Smith (2001) defined a transitional zone (not in an evolutionary sense) between both modes of subsistence strategies, the so-called low-level food production. This term describes a broad field of human–plant and human–animal interaction including domesticates. The latter play only a minor role, and less than 30%–50% of the annual caloric intake come from domesticates (Smith, 2001). Likewise, hunting and gathering continue to play a varying role in agrarian societies that can be explained by cultural and economic choices. The focus of this article will be on food-producing societies in the sense that at least 50% of the annual caloric intake come from domesticates, and, in this context, we will focus on early agrarian societies in Central Europe ca. 5500–2000 before the Common Era (BCE), that is, the Neolithic period.

Food production includes the cultivation of crops and the keeping of domestic animals. Globally, the domestication of plants and animals took place at different times in different regions of this world (e.g., Gronenborn & Scharl, 2015). The oldest data are currently from Southwest Asia, where cereals (emmer, einkorn, barley), pulses (lentils, peas, chickpea, bitter vetch), flax, and animals (cattle, pig, sheep, and goat) were domesticated ca. 10,500 years ago (e.g., Bar-Gal, 2022; Riehl et al., 2013; Willcox, 2013; Zeder, 2011, 2017). In the second half of the 7th millennium BCE, this new way of life started to expand to Europe. It arrived in Central Europe around 5500 BCE with a partly reduced package of crops (emmer, einkorn, new glume wheat [probably *Triticum timopheevii* s.l.; cf. Czajkowska et al., 2020], lentil, pea, flax; cf. Bogaard, 2011, 2023; Colledge et al., 2005; Kreuz et. al., 2005). Related to this is the beginning of a new way of life. People started to build massive houses, lived in settlements year-round, produced pottery and stock-piled food. Moreover, this is characterized by an increasing human impact on nature that is mainly caused by agricultural practices. Agriculture is related to deforestation, tillage, maintenance of the cultivated land, and finally harvesting, which alters not only the vegetation cover but also soil fertility as there is a constant loss of nutrients (caused by leaching due to rainfall but also by nutrient removal due to repeatedly growing cereals in the same place). This can be counteracted by manuring, N_2-fixing plants, and fallow systems (Rösch et al., 2017). While the role of N_2-fixing plants and fallow systems is more difficult to assess, the role of manuring is a much-debated question for early agrarian societies.

1.1 | Did soil fertility change already in the early Neolithic?

Early agriculture in Central Europe focused on fertile soils, Loess derivatives, and climatically favourable regions. The latter can be described by a low annual precipitation (<500 mm year^{-1}) and high summer temperatures (Rösch et al., 2017). Compared to later forms of agriculture, it is characterized by uniformity rather than diversity (Schier, 2009). Due to the preference for the best soils and climatically favourable areas, fertilization has been considered unnecessary as means of improving soil fertility for a long time (summarized in Bogaard, 2004). This has changed during the last 20 years due to new research in this field showing that certain forms of fertilization were already used at an early stage of agriculture. This can be explained in terms of a change of soil fertility after the onset of agriculture. Soil management and crop cultivation led to large changes in soil quality due to the interruption of the natural or original mechanisms and biogeochemical cycles that would maintain organic or mineral or nutrient contents under 'steady-state' conditions (Amundson et al., 2015). Crop growth, soil erosion, and harvest removed organic matter from the cropped areas, and therefore an important source for plant-available nutrients was missing.

2 | METHODS TO DETECT PREHISTORIC FERTILIZING IN SOILS

To establish the knowledge on how soils were used and fertilized in prehistory, it is essential to investigate protected and well-dated remnants of former topsoil, for example, pit fillings or fossil soil horizons under colluvial sediments, and corresponding control sites. The determination of age is usually done using ^{14}C or optically stimulated luminescence (OSL) dating methods. Another requirement is to apply a combination of different methods. Various geochemical methods can be applied to measure the contents of relevant nutrients, especially when they are not mobile and stabilized by binding mechanisms, but the results are not strictly unambiguous (e.g., Salisbury et al., 2022). Less common are studies that consider additions of mineral material as soil amelioration material, and this is also even more difficult to detect (Druzhinina et al., 2022).

If soil amelioration was necessary already from the beginning of agriculture onwards, i.e. as soon as the first farmers started to cultivate crops on fertile loess-derived soils, is not known yet; there is, however, consensus on the fact that fertilization as an agricultural technique was established during the Neolithic period (Bakels, 1997; Bogaard, 2012, 2013; Fokkens, 1982). What is less clear is which material was used to fertilize, if only manure or also mineral material or if the effect of N_2-fixing crops was used intentionally.

A first approach to detect possible soil additions in agricultural contexts is to measure micronutrient contents using multi-element inductively coupled plasma mass spectroscopy or optical emission spectroscopy (ICP-MS or ICP-OES), after applying an extraction procedure (Middleton & Price, 1996). Measuring archeologically relevant phosphorus (P) contents is often questioned and debated, and the most relevant approach is to apply a P fractionation method that reflects different P-stabilizing processes in soils (Weihrauch, 2018). The effects of crops that can fix N_2, for example, legumes, can be detected by measuring the ratio of nitrogen (N) isotopes because preferentially lighter ^{14}N accumulates during the process (Virginia & Delwiche, 1982). Another approach is to measure specific compounds and their isotopic signature, such as amino acids, which are typical for specific crops (Simpson et al., 1999).

In contrast, soil can be enriched with ^{15}N as a result of the application of animal manure or by the spreading of material from midden heaps/domestic waste (= middening, cf. Bogaard, 2012), as was shown for prehistoric sites in Europe and Southwest Asia (e.g., Bogaard et al., 2013; Styring, Charles, et al., 2017; Vaiglova et al., 2020). The application of manure as a fertilizing agent can be detected with phosphorous measurements and so-called biomarker analysis. The ratio and contents of specific steroids (5β-stanols, 5β-stigmastanols and bile acids) are especially promising, since it is possible to differentiate between faeces of omnivores and herbivores, or even of humans, ruminants, and porcines (Birk et al., 2012; Bull et al., 2002). Another method of soil melioration is to burn plant biomass to release nutrients and remove weeds, which can be detected by charcoal or black carbon analysis (Eckmeier et al., 2007, 2008).

For European loess areas, an attempt to detect prehistoric fertilization with the combination of these methods was made by Lauer et al. (2014) on soils from sites dated to the Younger Neolithic to Iron Age in loess areas of Central and Western Germany (Rhineland and Saxony-Anhalt). In comparison to recent top- and subsoils, the study showed that the ancient soil was comparably fertile and not depleted of micronutrients or P. Also, N content was high, and $\delta^{15}N$ values indicated the use of manure, as well as higher amounts of bile acids. If this was done intentionally could not be proven.

The analysis of soil thin-sections, or micromorphology, allows for the detailed visual inspection of soil material and is a very suitable method for the detection of manure application (Macphail et al., 1990). The detection of faeces in soils, which is an integral part of manure, by identification of coprolites, phytoliths, and faecal spherulites is a common method in geoarchaeological micromorphology, as shown by recent reviews (Elliott & Matthews, 2023; Shillito et al., 2020).

So far, these methods are neither used systematically nor on a larger scale to detect early evidence of fertilization, that is, in archeological contexts. Case studies in the context of early agrarian societies, however, have provided plausible evidence that agricultural techniques for improving soil quality have already been used since the beginning of the Neolithic.

3 | EARLIEST ARCHEOLOGICAL EVIDENCE OF FERTILIZATION IN CENTRAL EUROPE

3.1 | Indication of manuring in Neolithic settlements of Central Europe

Early agriculture is not a homogenous phenomenon but a dynamic one in the sense that agricultural techniques and practices change over time and are characterized by regional variability. For the early and middle Neolithic, that is, ca. 5400–4500 BCE, various possibilities of how fields might have looked like are debated (for discussion and with further literature see, e.g., Bakels, 2009; Kreuz, 2012; Lüning, 2000; van der Veen, 2005; Wendt et al., 2015). Frequently asked questions are about their size, the intensity of their cultivation, and whether fallows were included. Regarding the field size, one finds—besides extensive discussion about the assumed caloric requirement per person and the yield per hectare to be produced for it—such different assumptions as 0.5 ha required cultivation area per person on the one hand (Kreuz, 2012) and max. 0.2 ha or less on the other (Bogaard, 2004). However, the smaller the cultivated area is calculated, the more intensive the cultivation regime must have been in order to achieve the necessary high yield and to maintain it over a longer period of time. With this as a premise, Bogaard (2004, 2015) postulates for the early Neolithic on fertile loess soils an 'intensive garden cultivation'—that is, a labour-intensive management (careful tillage, dibbling or row-sowing, hand-weeding or hoeing, manuring to maintain a high fertility level and watering) on fixed plots near the settlement (Bogaard, 2004). This hypothesis is supported by functional ecological analyses of crop-associated weed flora based on the measurement of 'functional

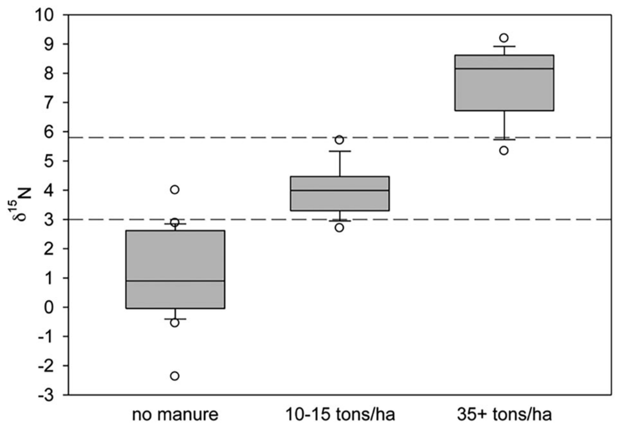

FIGURE 1 Range of $\delta^{15}N$ values in contemporary cereal samples (wheat and barley) grown under different fertilization rates in long-term agricultural trials at Rothamsted (UK), Askov (Denmark), and Bad Lauchstädt (Germany). The dashed horizontal lines represent the thresholds for low (i.e., remnants of previous land use history only), medium, and high manuring rates (from Bogaard et al., 2013).

attributes' (i.e., 'physical or behavioural characteristics of plants that predict their potential success under different ecological conditions'; Bogaard, 2015) used in the FIBS approach (Functional Interpretation of Botanical Surveys; cf. Hodgson et al., 1999) in conjunction with weed survey studies obtained through ethnographic observations, agricultural experiments as well as modern phytosociological datasets from Central Europe (e.g., Bogaard, 2002; Bogaard et al., 2016; Charles et al., 1997, 2002; Jones et al., 1999, 2000). Resulting from these analyses, the Early Neolithic weed assemblages from Central Europe reflect highly disturbed soil conditions and high soil productivity (possibly increased or maintained by manuring), which can be attributed to labour-intensive cultivation, as well as autumn sowing (Bogaard, 2004).

However, with functional weed ecology alone, it is not possible to identify fertilization as a cause of high soil productivity. For this purpose, analysis of stable N isotope ratios ($\delta^{15}N$) in plants is helpful. This is because $\delta^{15}N$ values in plants largely reflect the $\delta^{15}N$ value of the soil in which they grow, and this, in turn, is related to the $\delta^{15}N$ value of N inputs—for example, from manure (see above; and Styring, Rösch, et al., 2017 with further literature). Studies on modern crops from agricultural experiments have shown that manuring can increase $\delta^{15}N$ levels in cereals by up to 10‰ (Figure 1), with the intensity of application influencing the degree of effect (Bogaard et al., 2007, 2016; Fraser et al., 2011; Kendall et al., 2007). The applicability of stable N isotope ($\delta^{15}N$) analysis to archaeobotanical plant remains was thoroughly tested by experimental work on the influence of charring, burial, and pre-treatment on isotope values in cereals and pulses, which led to the development of methodological requirements for sample selection (degree of charring, sample size) and preparation (pre-treatment for cleaning) (Charles et al., 2015; Fraser, Bogaard, Charles, et al., 2013; Nitsch et al., 2015; Styring et al., 2013; Vaiglova et al., 2014).

To address the question of possible manuring in the context of the 'intensive garden cultivation' reconstructed for the Neolithic in Central Europe based on functional weed ecology analysis (as described above), stable N isotope analyses (δ^{15}N) were also carried out on charred cereals (and a few pulses) from Neolithic contexts in south-western Germany (Bogaard et al., 2013; Fraser, Bogaard, Schäfer, et al., 2013; Styring et al., 2016; Styring, Rösch, et al., 2017). One of the oldest settlements studied is the Linear Pottery Culture site of Vaihingen-Enz (Kr. Ludwigsburg), which was occupied from about 5500 to 5070 BCE (Bogaard, 2012). The analyzed charred cereals and pulses from Vaihingen show significantly elevated N isotope values (δ^{15}N) compared to the estimated values of (unmanaged) cereals (Styring, Rösch, et al., 2017). Similar results were also obtained from isotope studies at Viesenhäusener Hof, Stuttgart (5500–4000 BCE), Hornstaad-Hörnle IA (3918–3902 BCE), and Sipplingen-Osthafen (4000–2800 BCE), both Lake Constance (Styring, Rösch, et al., 2017). Most of the measured isotope values in the studied settlements lie in the range of medium manuring rates (>3‰; cf. Figure 1), some even in the range of high manuring rates (from ca. 6‰; cf. Figure 1). This high δ^{15}N values are most likely explained by regular application of ^{15}N-enriched manure or organic material on the cultivation areas (Styring, Rösch, et al., 2017), which is why they can be interpreted as evidence for manuring as part of the intensive farming regime in the Neolithic of Central Europe.

3.2 | Slash-and-burn cultivation as a means of improving soil quality

While manuring and 'middening' (see above; cf. Bogaard, 2012) as a means of improving soil quality is already discussed for the earliest agrarian societies, slash-and-burn cultivation as a further technique to improve soil quality is discussed for later Neolithic phases, particularly for the late 5th, 4th, and 3rd millennium BCE. Slash-and-burn cultivation describes an extensive form of agriculture. Our knowledge on this technique is based on long-term experiments, on data from geoarchaeological and palynological analysis. In a multi-year project in Forchtenberg/South Germany, for example, possible ways of slash-and-burn cultivation were tested experimentally, using data on historical slash-and-burn cultivation (Ehrmann et al., 2009; Rösch et al., 2017; Schier, 2009). In this framework, parcels of forest were cleaned during winter and burned during autumn or the following spring by using dry branches and twigs (the weak wood from the plots) as fuel. However, the gathered wood from one plot was not sufficient to burn the whole plot (Ehrmann et al., 2014). The branches and twigs were then piled up into burning wood rolls that were pulled over the ground (Figure 2). Afterwards, the crops were sown by dibbling (i.e., using a wooden stick to make individual holes) (Ehrmann et al., 2009, 2009, 2014; Rösch et al., 2017). As the Forchtenberg experiment shows, this cultivation method is particularly advantageous on soils of medium to poor quality, since it provides very high yields during the first and partly also the second year after burning. This is independent of the cereal species grown. Though, autumn-sown crops provided higher yields than spring-sown crops (Kolbe & Wellenberg, 2002; Rösch et al., 2017). During the Forchtenberg-experiment, from the third year onwards, the yields decreased rapidly, which is why a fallow of 10–15 years is considered necessary for the regeneration of the

FIGURE 2 Forchtenberg Project/Southwest Germany. A burning wood role is pulled over the ground (photo: Birgit Kury; project funded by the Landesamt für Denkmalpflege Baden-Württemberg).

soil (formation of humus) and the wood (Ehrmann et al., 2009, 2014). However, during this time, the natural succession on the plot provides further advantages for humans and animals as it can be used as pasture and provides various collectable plants such as wild strawberry, Chinese lantern, later on raspberry and blackberry, then hazelnuts and wild apple, and finally wood (Schulz et al., 2014). Moreover, it might have attracted wild game that could be hunted (e.g., Sørensen, 2014).

As interdisciplinary research in the context of the Forchtenberg experiment shows, this agricultural technique provided several advantages. The most obvious were the suppression of weeds and the mineralization of the organic part of the top soil since burning led to an increase in potassium, N, and P as macronutrients (Ehrmann et al., 2009, 2014). Moreover, burning increased the pH value (about 2 pH units) in the top soil since the low pH values in forest soils were usually too low for growing cereals such as wheat and barley (Ehrmann et al., 2014; Rösch et al., 2017). Next to this, the reduced albedo (i.e., the fraction of the incident sunlight that the surface reflects; Coakley, 2003) increases temperatures near the soil, which is particularly favourable for the growth of cereals during spring time. There are, however, also disadvantages of this agricultural technique: first and foremost, the high land consumption (Ehrmann et al., 2014; Rösch et al., 2017). On the one hand, the wood (branches and twigs) from one plot is not enough for burning. As Rösch et al. (2017) state, 'to burn a certain area requires the fourfold area for the supply of small wood' (Ehrmann et al., 2009; Rösch et al., 2017). Next to this, the decrease of yields after the first year(s) after burning makes the constant shifting of fields necessary. Whether this also necessitates a certain degree of residential mobility remains unclear so far. In the archeological record, we do see an increasing residential mobility from the late 5th millennium BCE onwards. A direct connection with a growing significance of slash-and-burn cultivation, however, remains speculative. This is also due to the fact that the role/significance of this new agricultural technique is still debated. For some regions (e.g., the Alps), on-site data rather hint at intensive forms of cultivation during this time period. This is based on weed spectra from Swiss lakeshore dwellings that mainly (90%) consist

FIGURE 3 Pit with 'black soil', Rhineland/Germany (photo: Renate Gerlach, LVR Amt für Bodendenkmalpflege im Rheinland).

of annual species. This kind of weed flora can only develop in the context of permanent cultivation, while fallows produce perennial weed species (Jacomet et al., 2016). The latter is difficult to prove; however, since slash-and-burn cultivation destroys weeds successfully, which is why we would not expect to find larger amounts of weeds in the settlements when this agricultural technique was practiced. In turn, indicators for slash-and-burn cultivation usually come from off-site data. So far, two major sources indicate an increasing significance of slash-and-burn cultivation during the late 5th, 4th, and 3rd millennium BCE: geoarchaeological data and pollen analysis (e.g., summarized in Schier, 2009). Geoarchaeological indicators from the Rhineland refer to so-called 'black soils' that have been repeatedly discovered in prehistoric pits (Figure 3). For a long time, it was assumed that these were soils comparable to the black earths (chernozem) in the Eurasian steppes that developed under very specific climatic conditions (very high evaporation that outweighs/exceeds precipitation totals, plus cold dry winters that inhibit microbial decomposition of the humus layer). Nowadays, however, an anthropogenic origin is being discussed. Micromorphological and organochemical analyses show that the black colour of the substrate can be explained with the presence of so-called pyrogenic carbon. This is produced by incomplete burning or carbonization of vegetation and is also known as black carbon. Absolute data of these fossil black carbon deposits show a conspicuous accumulation in the period between 4400 and 2000 BCE (Gerlach et al., 2006). This correlates with a clear increase of micro-charcoal, of pollen from heliophilous species (e.g., *Betula*), and indicators for burnt plots (spurs of *Pteridium*) in pollen diagrams of southwestern and northern Germany in the 4th millennium BCE (Figure 4; Dörfler, 2001; Rösch, 1987, 1990; Wiethold, 1998; summarized in Schier, 2009; see also Scharl, 2021). In South Scandinavia, Andersen (1993) analyzed pollen spectra that had

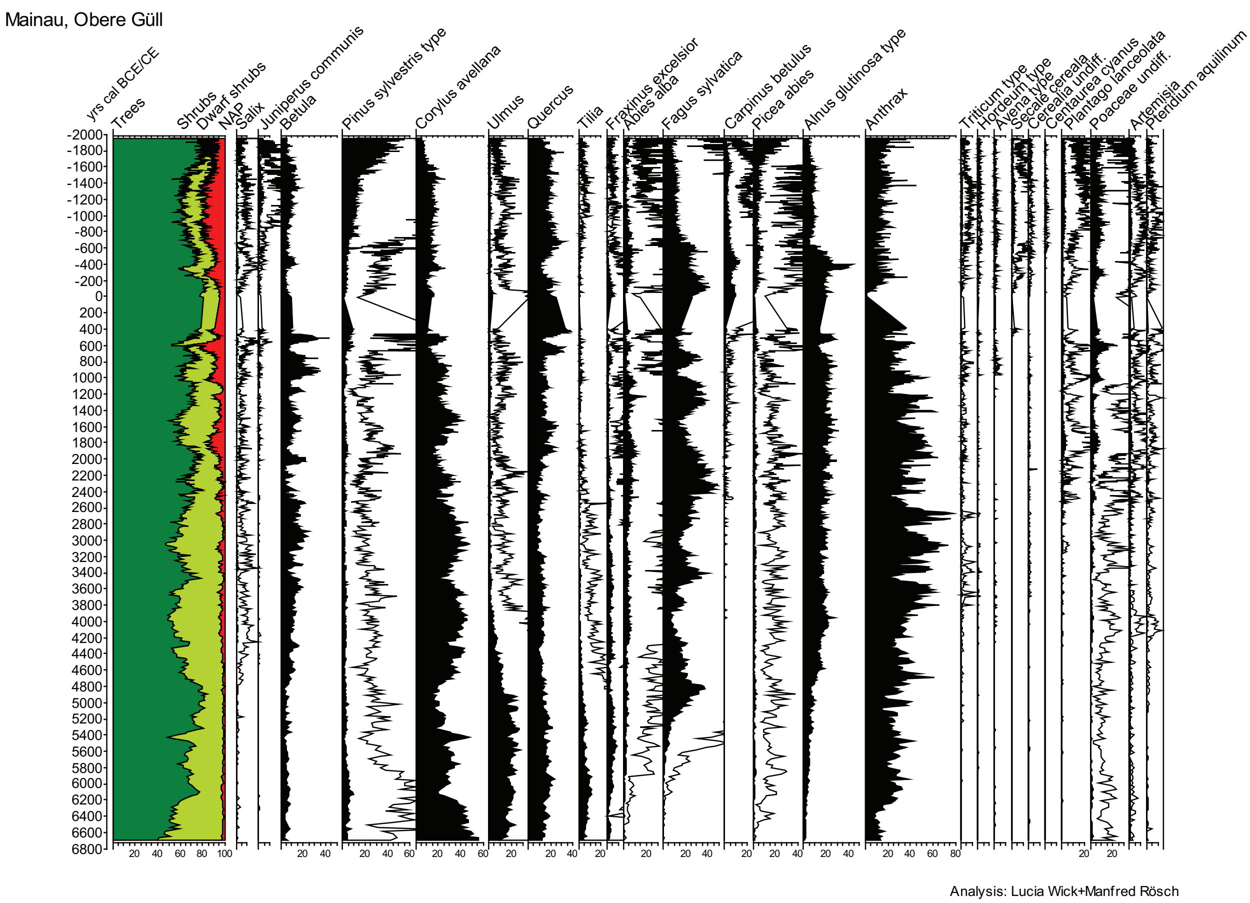

FIGURE 4 Pollen diagramm, Mainau 'Obere Güll', Lake Constance/Southwest Germany (from Rösch & Wick, 2017).

been sampled below burial mounds of the 4th millennium BCE. The author documented secondary birch forests with increased values of *Artemisia* and *Pteridium* and birch pollen, which were distorted by heat as indicators for the use of fire.

All this hints at an increasing significance of slash-and-burn cultivation during the late 5th, 4th, and 3rd millennium BCE (critically Jacomet et al., 2016). From an economic and cultural perspective, this might be explained with two developments. First, during the 4th and 3rd millennium BCE, we see an expansion of agrarian societies into areas with less suitable soils for agriculture, as, for example, into northern Central Europe and South Scandinavia or the Alpine foothills with its glacial soils (Scharl et al., 2021; Schier, 2009, 2017). Second, Rösch et al. (2017) discuss a decline in soil quality and yields in the Loess areas after more than one millennium of agriculture. This might have promoted the significance of slash-and-burn agriculture. Whether a climatic deterioration (dryer and cooler conditions) at the beginning of the subboreal period (ca. 3800 BCE) promoted this agricultural technique remains hypothetical (Kalis, 2010). However, one could add that an increasing significance of slash-and-burn cultivation, which is related to deforestation and the creation of potential pastures, also might have been related to an increasing significance of animal husbandry, especially of cattle, during this time ('pastoral turn' according to Schier, 2020). From a supraregional point of view, it should be emphasized that it is not a question of either slash-and-burn cultivation or intensive forms of cultivation. Rather, during the second half of the 5th millennium BCE, agricultural practice and techniques started to diversify which allowed for mixed strategies on a local and regional scale (Scharl, 2019).

4 | CONCLUSIONS AND OUTLOOK

Various archeological case studies show that fertilization already played a role in early agriculture. Methodological approaches to study fertilization in prehistoric contexts have evolved significantly in recent years. Their application to archeological contexts, on the other hand, is neither very systematic nor large-scale. Therefore, the significance and extent of different forms of fertilization in prehistoric contexts cannot be reliably assessed. One reason is the lack of awareness that anthropogenic sediments are important archives for the study of prehistoric life including agricultural practice. Added to this is the lack of knowledge about possible analysis methods among archaeologists. Therefore, an important task for the future is to develop a routine of sampling on archeological excavations (including a strategy for sample storage) that will be integrated into daily practice to end up systematically examining not only archeological finds but also sediments.

ACKNOWLEDGEMENTS

We would like to thank *Prof. Dr. Amy Bogaard*, University of Oxford, *Otto Ehrmann* and *Prof. Dr. Manfred Rösch*, University of Heidelberg for providing Figures 1, 2 and 4. In addition, we would like to thank the *Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)* for funding our *project No. 468729311 'Diversification and change—Analysing settlement patterns and agricultural practice during the 5th mil. BCE in Central Europe'* which is an important basis for our interdisciplinary collaboration in the field of early agriculture.

Open access funding enabled and organized by Projekt DEAL.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

REFERENCES

Amundson, R., Berhe, A. A., Hopmans, J. W., Olson, C., Sztein, A. E., & Sparks, D. L. (2015). Soil and human security in the 21st century. *Science*, *348*(6235), 1261071. https://doi.org/10.1126/science.126107

Andersen, S. T. (1993). Early-and middle-Neolithic agriculture in Denmark: Pollen spectra from soils in burial mounds of the Funnel Beaker Culture. *Journal of European Archaeology*, *1*(1), 153–180.

Bakels, C. C. (1997). The beginnings of manuring in western Europe. *Antiquity*, *71*(272), 442–445.

Bakels, C. C. (2009). *The Western European loess belt, agrarian history, 5300 BC–AD 1000*. Springer.

Bar-Gal, G. K. (2022). Animal domestication in the Near East. In S. Abbo, A. Gopher, & G. K. Bar-Gal (Eds.), *Plant domestication and the origins of agriculture in the ancient Near East* (pp. 199–228). Cambridge University Press.

Birk, J. J., Dippold, M., Wiesenberg, G. L., & Glaser, B. (2012). Combined quantification of faecal sterols, stanols, stanones and bile acids in soils and terrestrial sediments by gas chromatography–mass spectrometry. *Journal of Chromatography A*, *1242*, 1–10.

Bogaard, A. (2002). Questioning the relevance of shifting cultivation to Neolithic farming in the loess belt of Europe: Evidence from the Hambach Forest experiment. *Vegetation History and Archaeobotany*, *11*, 155–168.

Bogaard, A. (2004). *Neolithic farming in Central Europe: An archaeobotanical study of crop husbandy precticess*. Routledge.

Bogaard, A. (2011). Plant use and crop husbandry in an early Neolithic village: Vaihingen an der Enz, Baden-Württemberg. *Frankfurter Archäologische Schriften*, *16*. Habelt.

Bogaard, A. (2012). Middening and manuring in Neolithic Europe: Issues of plausibility, intensity and archaeological method. In R. Jones (Ed.), *Manure matters. Historical, archaeological and ethnographic perspectives* (pp. 25–40). Ashgate Publishing.

Bogaard, A. (2015). Lessons from modeling Neolithic farming practice: Methods of elimination. In R. Chapman & A. Wylie (Eds.), *Material evidence: Learning from archaeological practice* (pp. 243–254). Routledge.

Bogaard, A. (2023). From Anatolia to Swabia: The long journey of a rediscovered crop, Timopheev's wheat. In C. Pankau, H. Baitinger, & A. Stobbe (Eds.), *Ein Schwabe in der Welt. Festschrift für Rüdiger Krause zu seinem 65. Geburtstag* (pp. 69–79). Frankfurter Archäologische Schriften, 46. Habelt.

Bogaard, A., Heaton, T. H., Poulton, P., & Merbach, I. (2007). The impact of manuring on nitrogen isotope ratios in cereals: Archaeological implications for reconstruction of diet and crop management practices. *Journal of Archaeological Science*, *34*(3), 335–343.

Bogaard, A., Fraser, R., Heaton, T. H. E., Wallace, M., Vaiglova, P., Charles, M., Jones, G., Evershed, R. P., Styring, A. K., Andersen, N. H., Arbogast, R.-M., Bartosiewicz, L., Gardeisen, A., Kanstrup, M., Maier, U., Marinova, E., Ninov, L., Schäfer, M., & Stephan, E. (2013). Crop manuring and intensive land management by Europe's first farmers. *Proceedings of the National Academy of Sciences*, *110*(31), 12589–12594.

Bogaard, A., Hodgson, J., Nitsch, E., Jones, G., Styring, A., Diffey, C., Pouncett, J., Herbig, C., Charles, M., Ertuğ, F., Tugay, O., Filipovic, D., & Fraser, R. (2016). Combining functional weed ecology and crop stable isotope ratios to identify cultivation intensity: A comparison of cereal production regimes in Haute Provence, France and Asturias, Spain. *Vegetation History and Archaeobotany*, *25*, 57–73.

Bull, I. D., Lockheart, M. J., Elhmmali, M. M., Roberts, D. J., & Evershed, R. P. (2002). The origin of faeces by means of biomarker detection. *Environment International*, *27*(8), 647–654..

Charles, M., Jones, G., & Hodgson, J. G. (1997). FIBS in archaeobotany: Functional interpretation of weed floras in relation to husbandry practices. *Journal of Archaeological Science*, *24*(12), 1151–1161.

Charles, M., Bogaard, A., Jones, G., Hodgson, J., & Halstead, P. (2002). Towards the archaeobotanical identification of intensive cereal cultivation: Present-day ecological investigation in the mountains of Asturias, northwest Spain. *Vegetation History and Archaeobotany*, *11*, 133–142.

Charles, M., Forster, E., Wallace, M., & Jones, G. (2015). “Nor ever lightning char thy grain” 1: Establishing archaeologically relevant charring conditions and their effect on glume wheat grain morphology. *STAR: Science & Technology of Archaeological Research*, *1*(1), 1–6.

Coakley, J. A. (2003). Reflectance and albedo, surface. In J. R. Holton & J. A. Curry (Eds.), *Encyclopedia of the atmosphere* (pp. 1914–1923). Academic Press.

Colledge, S., Conolly, J., & Shennan, S. (2005). The evolution of Neolithic farming from SW Asian origins to NW European limits. *European Journal of Archaeology*, *8*(2), 137–156.

Czajkowska, B. I., Bogaard, A., Charles, M., Jones, G., Kohler-Schneider, M., Mueller-Bieniek, A., & Brown, T. A. (2020). Ancient DNA typing indicates that the “new” glume wheat of early Eurasian agriculture is a cultivated member of the Triticum timopheevii group. *Journal of Archaeological Science*, *123*, 105258. https://doi.org/10.1016/j.jas.2020.105258

Dörfler, W. (2001). Von der Parklandschaft zum Landschaftspark. Rekonstruktion der neolithischen Landschaft anhand von Pollenanalysen aus Schleswig-Holstein. In R. Kelm (Ed.), *Zurück zur Steinzeitlandschaft. Archäobiologische und ökologische Forschung zur jungsteinzeitlichen Kulturlandschaft und ihrer Nutzung in Nordwestdeutschland* (pp. 39–55). Albersdorfer Forschungen zur Archäologie und Umweltgeschichte, 2. Boyens & Co.

Druzhinina, O., Gedminienė, L., & van den Berghe, K. (2022). Geochemical study of the iron age settlement occupational layer and the early Roman time agricultural layer at Voorthuizen, the Netherlands. *Minerals*, *12*(3), 373. https://doi.org/10.3390/min12030373

Eckmeier, E., Gerlach, R., Skjemstad, J. O., Ehrmann, O., & Schmidt, M. W. I. (2007). Minor changes in soil organic carbon and charcoal concentrations detected in a temperate deciduous forest a year after an experimental slash-and-burn. *Biogeosciences*, *4*(3), 377–383.

Eckmeier, E., Gerlach, R., Tegtmeier, U., & Schmidt, M. W. I. (2008). Charred organic matter and phosphorus in black soils in the Lower Rhine Basin (Northwest Germany) indicate prehistoric agricultural burning. In G. Fiorentino & D. Magri (Eds.), *Charcoals from the past: Cultural and palaeoenvironmental implications* (pp. 93–103). British Archaeological Reports International Series, 1807. BAR Publishing.

Ehrmann, O., Rösch, M., & Schier, W. (2009). Experimentelle Rekonstruktion eines jungneolithischen Wald-Feldbaus mit Feuereinsatz—ein multidisziplinäres Forschungsprojekt zur Wirtschaftsarchäologie und Landschaftsökologie. *Prähistorische Zeitschrift*, *84*(1), 44–72.

Ehrmann, O., Biester, H., Bogenrieder, A., & Rösch, M. (2014). Fifteen years of the Forchtenberg experiment—Results and implications for the understanding of Neolithic land use. *Vegetation History and Archaeobotany*, *23*, 5–18.

Elliott, S., & Matthews, W. (2023). Dung detective! A multi-scalar, multi-method approach to identification and analysis of ancient faecal material. *Quaternary International*, https://doi.org/10.1016/j.quaint.2023.02.005

Fokkens, H. (1982). Late neolithic occupation near Bornwird provincie of Friesland. *Palaeohistoria*, *24*, 91–113.

Fraser, R. A., Bogaard, A., Heaton, T., Charles, M., Jones, G., Christensen, B. T., Halstead, P., Merbach, I., Poulton, P. R., Sparkes, D., & Styring, A. K. (2011). Manuring and stable nitrogen isotope ratios in cereals and pulses: Towards a new archaeobotanical approach to the inference of land use and dietary practices. *Journal of Archaeological Science*, *38*(10), 2790–2804.

Fraser, R. A., Bogaard, A., Charles, M., Styring, A. K., Wallace, M., Jones, G., Ditchfield, P., & Heaton, T. H. E. (2013). Assessing natural variation and the effects of charring, burial and pre-treatment on the stable carbon and nitrogen isotope values of archaeobotanical cereals and pulses. *Journal of Archaeological Science*, *40*(12), 4754–4766.

Fraser, R. A., Bogaard, A., Schäfer, M., Arbogast, R., & Heaton, T. H. (2013). Integrating botanical, faunal and human stable carbon and nitrogen isotope values to reconstruct land use and palaeodiet at LBK Vaihingen an der Enz, Baden-Württemberg. *World Archaeology*, *45*(3), 492–517.

Gerlach, R., Baumewerd-Schmidt, H., van den Borg, K., Eckmeier, E., & Schmidt, M. W. I. (2006). Prehistoric alteration of soil in the Lower Rhine Basin, Northwest Germany—Archaeological, ^{14}C and geochemical evidence. *Geoderma*, *136*(1–2), 38–50.

Gronenborn, D., & Scharl, S. (2015). Das Neolithikum als globales Phänomen. In J. Kunow, T. Otten, M. Rind, & M. Trier (Eds.), *Revolution Jungsteinzeit. Archäologische Landesausstellung NRW* (pp. 59–71). Wissenschaftliche Buchgesellschaft.

Harris, D. (1996). Domesticatory relations of people, plants and animals. In R. Ellen & K. Fukui (Eds.), *Redefining nature: Ecology, culture and domestication* (pp. 437–463). Routledge.

Hodgson, J. G., Wilson, P. J., Hunt, R., Grime, J. P., & Thompson, K. (1999). Allocating C-S-R plant functional types: A soft approach to a hard problem. *Oikos*, *85*, 282–296.

Jacomet, S., Ebersbach, R., Akeret, Ö., Antolin, F., Baum, T., Bogaard, A., Brombacher, C., Bleicher, N. K., Heitz-Weniger, A., Hüster-Plogmann, H., Gross, E., Kühn, M., Rentzel, P., Steiner, B., Wick, L., & Schibler, J. (2016). On-site data cast doubts on the hypothesis of shifting cultivation in the late Neolithic (c. 4300–2400 cal. BC): Landscape management as an alternative paradigm. *Holocene*, *26*(11), 1858–1874.

Jones, G., Bogaard, A., Halstead, P., Charles, M., & Smith, H. (1999). Identifying the intensity of crop husbandry practices on the basis of weed floras1. *Annual of the British School at Athens*, *94*, 167–189.

Jones, G., Bogaard, A., Charles, M., & Hodgson, J. G. (2000). Distinguishing the effects of agricultural practices relating to fertility and disturbance: A functional ecological approach in archaeobotany. *Journal of Archaeological Science*, *27*(11), 1073–1084.

Kalis, A. (2010). Umwelt, Klima und Landnutzung im Jungneolithikum. In Badisches Landesmuseum Karlsruhe (Ed.), *Jungsteinzeit im Umbruch. Die Michelsberger Kultur und Mitteleuropa vor 6000 Jahren* (pp. 37–43). Primus.

Kendall, C., Elliott, E. M., & Wankel, S. D. (2007). Tracing anthropogenic inputs of nitrogen to ecosystems. In R. Michener & K. Lajtha (Eds.), *Stable isotopes in ecology and environmental science* (pp. 375–449). Blackwell.

Kolbe, H., & Wellenberg, K. (2002). Anbauvergleich zwischen Winter- und Sommerweizen, Dinkel und Durum im ökologischen Landbau. [Planting trial comparing winter wheat, summer wheat, spelt and durum in organic agriculture]. *SÖL-Berater-Rundbrief*, *2*, 13–19.

Kreuz, A. (2012). Die Vertreibung aus dem Paradies? Archäobiologische Ergebnisse zum Frühneolithikum im westlichen Mitteleuropa. *Berichte der Römisch-Germanischen Kommission*, *91*, 23–196.

Kreuz, A., Marinova, E., Schäfer, E., & Wiethold, J. (2005). A comparison of early Neolithic crop and weed assemblages from the Linearbandkeramik and the Bulgarian Neolithic cultures: Differences and similarities. *Vegetation History and Archaeobotany*, *14*, 237–258.

Lauer, F., Prost, K., Gerlach, R., Pätzold, S., Wolf, M., Urmersbach, S., Lehndorff, E., Eckmeier, E., & Amelung, W. (2014). Organic fertilization and sufficient nutrient status in prehistoric agriculture?—Indications from multi-proxy analyses of archaeological topsoil relicts. *PLoS One*, *9*(9), e106244. https://doi.org/10.1371/journal.pone.0106244

Lüning, J. (2000). *Steinzeitliche Bauern in Deutschland*. Universitätsforschungen zur Prähistorischen Archäologie, 58. Habelt.

Macphail, R. I., Courty, M. A., & Gebhardt, A. (1990). Soil micromorphological evidence of early agriculture in north-west Europe. *World Archaeology*, *22*(1), 53–69.

Middleton, W. D., & Price, D. T. (1996). Identification of activity areas by multi-element characterization of sediments from modern and archaeological house floors using inductively coupled plasma-atomic emission spectroscopy. *Journal of Archaeological Science*, *23*(5), 673–687.

Nitsch, E. K., Charles, M., & Bogaard, A. (2015). Calculating a statistically robust δ^{13}C and δ^{15}N offset for charred cereal and pulse seeds. *STAR: Science & Technology of Archaeological Research*, *1*(1), 1–8.

Riehl, S., Zeidi, M., & Conard, N. J. (2013). Emergence of agriculture in the foothills of the Zagros Mountains of Iran. *Science*, *341*(6141), 65–67.

Rösch, M. (1987). Zur Umwelt und Wirtschaft des Jungneolithikums am Bodensee. Botanische Untersuchungen in Bodman-Blissenhalde. *Archäologische Nachrichten aus Baden*, *38/39*, 42–53.

Rösch, M. (1990). Veränderungen von Wirtschaft und Umwelt während Neolithikum und Bronzezeit am Bodensee. *Bericht der Römisch-Germanischen Kommission*, *71*(1), 161–186.

Rösch, M., Biester, H., Bogenrieder, A., Eckmeier, E., Ehrmann, O., Gerlach, R., Hall, M., Hartkopf-Fröder, C., Herrmann, L., Kury, B., Lechterbeck, J., Schier, W., & Schulz, E. (2017). Late Neolithic agriculture in temperate Europe—A long-term experimental approach. *Land*, *6*(1), 11. https://doi.org/10.3390/land6010011

Rösch, M., & Wick, L. (2017). Contributions to the European pollen database 41. *Western Lake Constance (Germany): Überlinger See, Mainau, Grana*, *58*(1), 78–80. https://doi.org/10.1080/00173134.2018.1509123

Salisbury, R. B., Bull, I. D., Cereda, S., Draganits, E., Dulias, K., Kowarik, K., Meyer, M., Zavala, E. I., & Rebay-Salisbury, K. (2022). Making the most of soils in archaeology. A review. *Archaeologia Austriaca*, *106*, 319–334.

Scharl, S. (2019). *Innovationstransfer in prähistorischen Gesellschaften – Eine vergleichende Studie zu ausgewählten Fallbeispielen des 6. bis 4. Jahrtausends vor Christus in Mittel- und Südosteuropa unter besonderer Berücksichtigung temporärer Grenzräume. Kölner Studien zur Prähistorischen Archäologie*, *10*. Leidorf.

Scharl, S. (2021). *Jungsteinzeit. Wie die Menschen sesshaft wurden*. Kohlhammer.

Scharl, S., Amelung, W., Bömke, B., Gerlach, R., Lauer, F., Lehmkuhl, F., Lehndorff, E., Maier, A., Schmidt, I., Szya, S., & Zimmermann, A. (2021). Population dynamics, mobility and human-environment interaction from the Palaeolithic to the Neolithic—A view from Central Europe to the world. In T. Litt, J. Richter, & F. Schäbitz (Eds.), *The journey of modern humans from Africa to Europe—Culture–environmental interaction and mobility* (pp. 153–204). Schweizerbart.

Schier, W. (2009). Extensiver Brandfeldbau und die Ausbreitung der neolithischen Wirtschaftsweise in Mitteleuropa und Südskandinavien am Ende des 5. Jahrtausends v. Chr. *Prähistorische Zeitschrift*, *84*(1), 15–43.

Schier, W. (2017). Die Tertiäre Neolithisierung—Fakt oder Fiktion? In J. Lechterbeck & E. Fischer (Eds.), Kontrapunkte. Festschrift für Manfred Rösch (pp. 129–145). Habelt.

Schier, W. (2020). The Toipoi research group textile revolution: Archaeological background and multi-proxy approach. In W. Schier & S. Pollock (Eds.), *The competition of fibres. Early textile production in Western Asia, South-East and Central Europe (10,000–500 BC)* (pp. 59–71). Ancient Textile Series, 36. Oxbow Books.

Schulz, E., Vannina, U., & Hall, M. (2014). The double mosaic-regeneration of vegetation and soil after clearing, burning, and cultivation: Lessons from the Forchtenberg experiment. *Vegetation History and Archaeobotany*, *23*, 19–36.

Shillito, L. M., Blong, J. C., Green, E. J., & van Asperen, E. N. (2020). The what, how and why of archaeological coprolite analysis. *Earth-Science Reviews*, *207*, 103196. https://doi.org/10.1016/j.earscirev.2020.103196

Simpson, I. A., Bol, R., Bull, I. D., Evershed, R. P., Petzke, K. J., & Dockrill, S. J. (1999). Interpreting early land management through compound specific stable isotope analyses of archaeological soils. *Rapid Communications in Mass Spectrometry*, *13*(13), 1315–1319.

Smith, B. D. (2001). Low-level food production. *Journal of Archaeological Research*, *9*, 1–43.

Styring, A. K., Manning, H., Fraser, R. A., Wallace, M., Jones, G., Charles, M., Heaton, T. H. E., Bogaard, A., & Evershed, R. P. (2013). The effect of charring and burial on the biochemical composition of cereal grains: Investigating the integrity of archaeological plant material. *Journal of Archaeological Science*, *40*(12), 4767–4779.

Styring, A. K., Maier, U., Stephan, E., Schlichtherle, H., & Bogaard, A. (2016). Cultivation of choice: New insights into farming practices at Neolithic lakeshore sites. *Antiquity*, *90*(349), 95–110.

Styring, A. K., Charles, M., Fantone, F., Hald, M. M., McMahon, A., Meadow, R. H., Nicholls, G. K., Patel, A. K., Pitre, M. C., Smith, A., Sołtysiak, A., Stein, G., Weber, J. A., Weiss, H., & Bogaard, A. (2017). Isotope evidence for agricultural extensification reveals how the world's first cities were fed. *Nature Plants*, *3*(6), 1–11.

Styring, A. K., Rösch, M., Stephan, E., Stika, H.-P., Fischer, E., Sillmann, M., & Bogaard, A. (2017). Centralisation and long-term change in farming regimes: Comparing agricultural practices in Neolithic and Iron Age south-west Germany. *Proceedings of the Prehistoric Society*, *83*, 357–381.

Sørensen, L. (2014). *From hunter to farmer in Northern Europe. Migration and adaptation during the Neolithic and Bronze Age*. Acta Archaeologica, 85. Wiley.

Vaiglova, P., Snoeck, C., Nitsch, E., Bogaard, A., & Lee-Thorp, J. A. (2014). Investigating the most appropriate laboratory pre-treatment method on archaeological charred grain/seed remains for stable isotope analysis (δ^{13}C and δ^{15}N). *Rapid Communications in Mass Spectrometry*, *28*, 2497–2510.

Vaiglova, P., Gardeisen, A., Buckley, M., Cavanagh, W., Renard, J., Lee-Thorp, J., & Bogaard, A. (2020). Further insight into Neolithic agricultural management at Kouphovouno, southern Greece: Expanding the isotopic approach. *Archaeological and Anthropological Sciences*, *12*, 1–17.

Van der Veen, M. (2005). Gardens and fields: The intensity and scale of food production. *World Archaeology*, *37*(2), 157–163.

Virginia, R. A., & Delwiche, C. C. (1982). Natural 15 N abundance of presumed N_2-fixing and non-N_2-fixing plants from selected ecosystems. *Oecologia*, *54*, 317–325.

Weihrauch, C. (2018). *Phosphor-Dynamiken in Böden, Grundlagen, Konzepte und Untersuchungen zur räumlichen Verteilung des Nährstoffs*. Springer.

Wendt, K. P., Hilpert, J., & Zimmermann, A. (2015). Landschaftsarchäologie IV—Ein Modell zur Rekonstruktion von Landwirtschaftssystemen am Beispiel der Linearbandkeramik und der späten vorindustriellen Neuzeit. *Berichte der Römisch-Germanischen Kommission*, *96*, 9–218.

Wiethold, J. (1998). *Studien zur jüngeren postglazialen Vegetations- und Siedlungsgeschichte im östlichen Schleswig- Holstein*. Universitätsforschungen zur Prähistorischen Archäologie, 45. Habelt.

Willcox, G. (2013). The roots of cultivation in southwestern Asia. *Science*, *341*(6141), 39–40.

Zeder, M. A. (2011). The origins of agriculture in the Near East. *Current Anthropology*, *52*(S4), S221–S235.

Zeder, M. A. (2017). Out of the fertile crescent: The dispersal of domestic livestock through Europe and Africa. In N. Boivin, R. Crassard, & M. Petraglia (Eds.), *Human dispersal and species movement. From prehistory to the present* (pp. 261–303). Cambridge University Press.

Zvelebil, M. (1996). Agricultural frontier and the transition to farming in the circum-Baltic area. In D. Harris (Ed.), *The origins and spread of agriculture and pastoralism in Eurasia* (pp. 323–345). UCL Press.

How to cite this article: Scharl, S., Zerl, T., Eckmeier, E., & Gerlach, R. (2023). Earliest archeological evidence of fertilization in Central Europe. *Journal of Plant Nutrition and Soil Science*, *186*, 375–382. https://doi.org/10.1002/jpln.202300150