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Dynamics of early agriculture – multivariate analysis of changes in crop cultivation and farming practices in the Rhineland (Germany) between the 6th and early 4th millennium BCE

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ABSTRACT

First evidence for food production in continental Europe dates to the late 7th (Southeast Europe) and the 6th mill. BCE (Central and Western Europe). Early farming practices, however, were not static and underwent considerable changes and developments in the centuries and millennia following their arrival. Regionally varying processes of standardisation and diversification can be observed. To gain a deeper understanding of these processes on a regional scale, which also allows for a review and discussion of possible causes, we collected data on archaeobotanical macro remains from 72 sites in the Rhineland (Germany), dating from the later 6th to the early 4th mill. BCE. The Rhineland was selected due to its rich record in archaeobotanical material. As a multivariate analysis shows, a statistically significant correlation can be demonstrated between chronological development on the one hand and the crop spectrum on the other hand. Moreover, the diachronic patterns reveals a diversification of the cereal spectrum. Similarly, settlement patterns also changed, and sites were located on a greater variety of soils. As a change in environmental factors can be ruled out, we discuss risk management strategies and growing experience with agriculture as possible causes for the observed transformation. Moreover, this methodological approach makes it possible to include sites that yielded only a small number of samples which were previously considered unrepresentative. Using multivariate statistics, we can demonstrate that the sample size has no statistically significant influence on the results of our analysis.

1. Introduction

The advent of agriculture in Europe constitutes a fundamental change in prehistoric everyday life. However, Neolithic agriculture is not a static phenomenon but is subject to continuous change. A supra-regional, diachronic perspective reveals regionally varying – non-linear, non-evolutionary – processes of standardisation and diversification that are interpreted as adaptations to varying environmental, economic, cultural and social factors (e.g. Kreuz et al., 2005; Conolly et al., 2008; Marinova and Valamoti, 2014; Antolín et al., 2015; Ivanova et al., 2018; Gastraa et al., 2019; Bouby et al., 2020; de Vareilles et al., 2022; Sabanov et al., 2024). In order to gain a deeper understanding of these complex dynamics and the context in which they take place, and to be able to discuss possible causes, we investigate early agriculture from a regional and diachronic perspective. We focus on crop cultivation and land use in a well-studied region (Rhineland, Western Germany) of the Central European Neolithic between the late 6th and the early 4th mill. BCE. Here, opencast lignite mining has resulted in the documentation of almost complete archaeological settlement areas, providing high-quality data. With additional data from the wider region, this offers a representative picture of the settlement and economic structure during the period under investigation. As agricultural systems are built around the range of crops under cultivation, our diachronic analysis allows us to draw conclusions about adaptation and cultural choices and the nature of the underlying farming systems (de Vareilles et al., 2022).

The earliest agricultural regime in Central Europe, known from Linear Pottery Culture (hereafter LBK) contexts of the late 6th and early 5th mill. BCE, is mainly centred on fertile soils developed from loess (e.g. Lüning, 2000; Kreuz et al., 2005; Petrasch, 2020). It can be characterised as small-scale horticulture in the immediate proximity of settlements,

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which focused on the cultivation of glume wheats (emmer, einkorn), pulses (pea, lentil) and oil plants (flax, opium poppy) (Bogaard, 2004; Kreuz et al., 2005; Salavert, 2011). Timopheev's wheat, formally known as 'new glume wheat' (Czajkowska et al., 2020; Roushannafas et al., 2021), was also cultivated to a certain extent (summarised in Bogaard, 2023). Free-threshing (naked) wheat and (naked) barley, on the other hand, are rare and usually documented in low numbers (e.g. Knörzer, 1997, 1998; Colledge and Conolly, 2007; Salavert, 2011; Herbig et al., 2013; Toulemonde et al., 2021), which is why they are generally interpreted as weeds (Bakels, 1984; Kreuz, 2012, 83). Whether manuring took place has been discussed repeatedly (e.g. Bogaard, 2012; Bogaard et al., 2013; Fraser et al., 2013; Styring et al., 2017; Gillis et al., 2020; summarised in Scharl et al., 2023). From sites with very good preservation due to waterlogged conditions, such as wells, we also know that a broad range of wild plants were used (e.g. Kalis et al., 2016). Livestock farming of cattle, pig, sheep and goat also played an important role (Benecke, 1994). Recent research shows that apart from meat, milk was already used/consumed in these early farming societies (Casanova et al., 2021; Evershed et al., 2022). In contrast, the archaeological record of the Young Neolithic (or Late Neolithic, not following the German terminology) from about 4300 BCE reflects profound changes of agricultural techniques and practices, as well as forest composition, as indicated by high values of lime and hazel in pollen diagrams (e.g. Gerlach and Meurers-Balke, 2015; Stobbe and Gumnior, 2021). An expansion to areas outside the Central European loess belt, such as to the north European plain and the Alpine foreland, is documented (e.g. Stöckli, 2016; Scharl et al., 2021). This means an expansion into areas with a cooler and more humid climate and with soils less favourable for crop cultivation. Settlements are rather short-lived, with a different spatial organisation and smaller houses (e.g. Seidel, 2017, 2022). Alongside this development we see a widening of the crop spectrum: in addition to glume wheats, naked barley and naked wheat (both the hexaploid *Triticum aestivum* and the tetraploid *Triticum durum/turgidum*) are now an important part of the cereal range (Bakels, 2003; Colledge and Conolly, 2007; Herbig, 2009; Kirleis and Fischer, 2014; Kreuz et al., 2014). Moreover, whether slash-and-burn cultivation and livestock farming (mainly cattle) increase in importance is a topic of discussion (Ehrmann et al., 2009; Schier, 2009, 2020; Rösch et al., 2014, 2017; critical discussions in Baum et al., 2016; Jacomet et al., 2016). Furthermore, the use of ploughs/ards as a new agricultural technique is documented by plough marks for the 4th mill. BCE in Denmark and northern Germany (e.g. Kirleis and Fischer, 2014, Fig. 7), although earlier evidence (early 5th mill. BCE) comes from Anciens Arsenaux, Switzerland (van Willigen et al., 2024).

The developments described above reveal a diachronic transformation of agriculture, land use patterns and settlement structure on a supra-regional level in Central Europe. To gain a deeper understanding of these processes, we chose a regional scale, which also allows for a discussion of potential triggers. For this, we collected data on crop cultivation, land use and settlement patterns in the Rhineland between

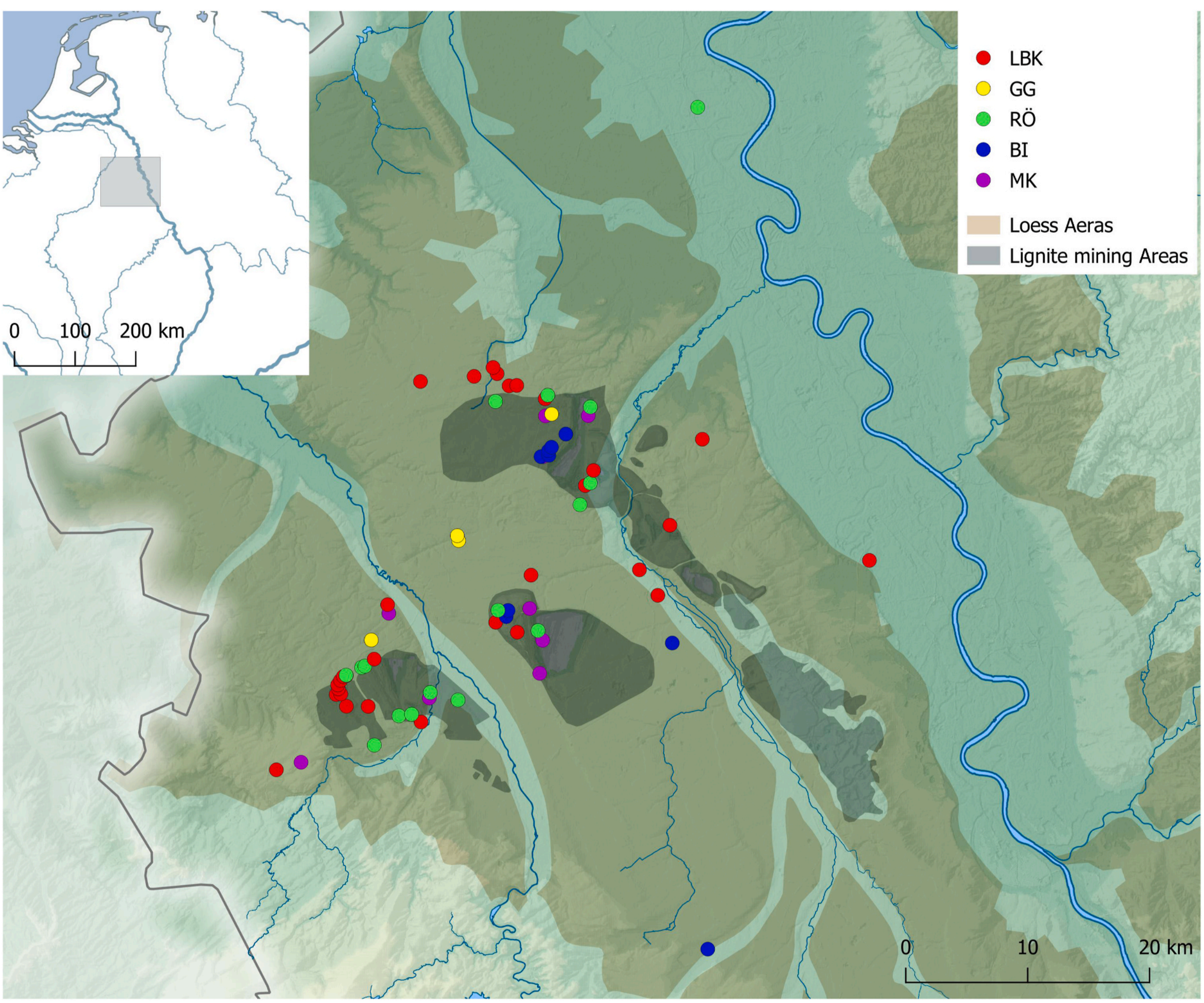

Fig. 1. Location of the study region in western Germany (Rhineland with opencast mines) and distribution of sites analysed for this study. Abbreviations: LBK Linear Pottery Culture, GG Großgartach, RÖ Rössen, BI Bischheim, MK Michelsberg. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Cologne, Aachen and Erkelenz (Fig. 1), covering a sequence from the late 6th to the early 4th mill. BCE. This region comprises about 2000 km^2 of fertile loess-derived soils, which have been settled since the Early Neolithic (hereafter ENL), from about 5300 BCE. The subsequent Neolithic groups of the 5th and 4th mill. BCE are also well-documented here (see Fig. 2), providing a comprehensive insight into the developments during the Middle Neolithic (hereafter MNL) and Young Neolithic (hereafter YNL). We hypothesise that changes in agricultural practices correlate with changes in settlement and land use patterns, such as the location of settlement sites.

2. Material and methods

2.1. Archaeological background

In order to take a closer look at the transformation of crop cultivation during the first two millennia after the introduction of agriculture in our study area (Rhineland), archaeobotanical data from ENL (LBK, c. 5300–5000/4900 BCE), MNL (Großgartach [GG], c. 4725–4580 and Rössen [RÖ], c. 4580–4450 BCE) and YNL (Bischheim [BI], c. 4450–4300/4200 BCE and Michelsberg [MK], c. 4350–3500 BCE) sites were collected (absolute dating according to Denaire et al., 2017; Seidel, 2022). The required accurate chronological classification was either taken from existing archaeological investigations or conducted as part of our project (DFG-project no. 468729311). In addition, we performed radiocarbon dating on short-lived plant material (mainly cereal grains) from selected sites (supplementary material, Table A1). In the Rhineland, a temporal gap of about two centuries is documented between the end of the LBK and the beginning of the early MNL (Großgartach) (Fig. 2), associated with the arrival of a new group of settlers (Denaire et al., 2017). However, this resettlement of the Rhineland was carried by people whose cultural and social roots lay in LBK traditions, e.g. visible in material culture (pottery, lithics) and architecture. All subsequent archaeological units show a temporal overlap or transition, which is interpreted as a continuous demographic development. As the typo-chronological analyses suggest, the Planig-Friedberg phase can be regarded as a subphase of Großgartach (e.g. Spatz, 1996; Eisenhauer, 2002). It is therefore included under Großgartach in the following sections.

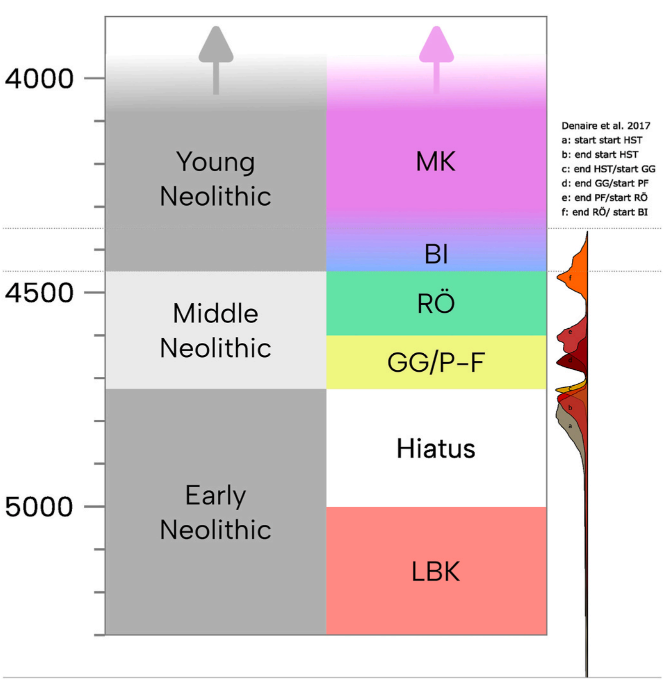

Fig. 2. Chronology of the archaeological groups mentioned in the text. On the right summary of the date estimates for phase boundaries after Denaire et al., (2017). Abbreviations: LBK Linear Pottery Culture, HST Hinkelstein, GG/P-F Großgartach/Planig-Friedberg, RÖ Rössen, BI Bischheim, MK Michelsberg. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2. Archaeobotanical data

2.2.1. Acquisition and archaeobotanical work

The archaeobotanical material included in the analysis was primarily recovered during rescue excavations, with most of them carried out in the context of the opencast lignite mining taking place in the study area. All samples originated from sunken features and were not collected systematically. The varying scale of the excavations had a significant impact on the number of archaeobotanical samples, which ranged from 1 to 232 per site. In addition, the sample sizes from older excavations are often quite small (sometimes <1 l, cf. supplementary material, Table A4–A8). These factors make the data set heterogeneous in terms of volume.

All samples were processed by hand-flotation using sieves with a minimum mesh size of 0.5 mm or 0.315 mm. Due to the taphonomic conditions, these samples contain only charred plant remains. The uncharred material from three ENL wells (Knörzer, 1998; Zerl and Herbig, 2012; Kalis et al., 2016) was not considered due to different preservation conditions.

Several of the sites had already been investigated by Karl-Heinz Knörzer between the 1960s and 1990s. The results of his studies (mainly for LBK sites) have not been fully published, but we had unrestricted access to the documentation and archaeobotanical remains, as his entire archive (finds and data) is managed by the Archaeobotanical Laboratory at the University of Cologne. Since the 2000s, additional material (mainly from the YNL) has been examined by T. Zerl and the Laboratory for Archaeobotany in Cologne. In recent years, further archaeobotanical work has been carried out (by T. Zerl) as part of the study presented here, with a focus on MNL sites. All researchers and the publication status of the archaeobotanical material are listed in the supplementary material, Table A1.

The integration of Knörzer's analyses into the new data set did not pose any major difficulties, as the merged archaeobotanical data are fairly homogeneous in their composition due to coming from the same landscapes. In addition, the preparation, cleaning and validation of Knörzer's data (e.g. potential conversion of sample weight in kg to volume in l; adaptation of determinations to current identification criteria; changes to taxonomic classification; other species groupings) is standard practice in the Cologne Laboratory and has already been successfully carried out for comparable data sets (for details, see Zerl, 2019). One problem, however, is Timopheev's wheat (*Triticum timopheevii* s.l.). Since this glume wheat was first described in 2000 (Jones et al., 2000), it does not appear in earlier identifications. Nevertheless, Timopheev's wheat can be expected to some extent in sites examined by Knörzer, given his comments on spikelets atypical for emmer and einkorn, as well as illustrations (most likely of chaff of Timopheev's wheat) for the LBK sites Mönchengladbach-Wanlo and Bedburg-Garsdorf (cf. WANLO and GARS in supplementary material, Table A1) (Knörzer, 1974, 1980; see also Bogaard, 2023). Due to the time required, though, no subsequent determination of *Triticum timopheevii* s.l. was made for Knörzer's material.

2.2.2. Representativeness

For our analysis we were able to collect archaeobotanical data from 72 sites (or settlement phases) (Fig. 1; supplementary material, Table A1). Due to the focus of previous investigations and a generally higher number of excavated sites, the LBK is the most frequently documented archaeological group with a total of 32 sites. 22 sites (four Großgartach and 18 Rössen) belong to the MNL, and a total of 18 sites (nine each from Bischheim and Michelsberg) belong to the YNL. The sites provided combined a total of 1378 samples with a volume of more than 3115 l of sediment (Table 1). The number of samples from each archaeological group corresponds closely to the number of sites investigated, with almost 50 % coming from the LBK.

An important factor in assessing the representativeness of the data set is the average concentration of macro remains per litre of sediment (n/l) for all sites within a phase (Table 1). As expected for dry mineral soil conditions, the average concentrations are rather low, with 50 % of the settlements showing 10–100 n/l, and 30 % even less than 10 n/l (Fig. 3; supplementary material, Table A1). The minority of sites show significantly higher concentrations (>100 n/l, or even >1000 n/l), suggesting that some charred mass finds (deposited all at once) are also documented. Nevertheless, the generally low concentration of macro remains indicate that the archaeobotanical material was mostly deposited gradually over the course of several activities or by chance (Jones, 1991), and that the archaeobotanical data represent a cross-section of the plant remains regularly present at the sites ('settlement noise', sensu Bakels, 1991).

The generally low average concentrations of macro remains together with the high number of threshing remains (especially of glume wheat, see section 3.1.), indicate that the archaeobotanical material consists mainly of crop processing by-products, which occurred regularly in the investigated settlements (van der Veen and Jones, 2006; Bogaard, 2011; Kreuz, 2012).

2.3. Environmental data

In addition, environmental factors were collected for all sites to facilitate a diachronic comparison of settlement patterns and land use, and to relate these to crop cultivation. Data from Germany's National Meteorological Service (Deutscher Wetterdienst) and the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe) were used for this purpose. We are aware that there is also data on prehistoric time periods (e.g. PaleoClim). However, as this is modelled rather than measured data, and therefore has less spatial resolution, we have preferred the modern records, also because we are interested in relative differences.

For the superordinate soil landscapes, we used data from Mückenhausen (1949), Geologisches Landesamt NRW 2005, Geologischer Dienst NRW 2016, Lehmkuhl et al., (2023) and GEOportal.NRW (soil types of the individual sites are listed in supplementary material, Table A1). A redundancy analysis was used for the initial evaluation (for the method see section 2.4.2.).

2.4. Statistical analysis

2.4.1. Data preparation

In order to analyse the developments in crop cultivation in more detail, the following transformations have been applied to the raw data set. (The raw data are included as supplementary material, Table A4–A8. For an overview of the data used for the different calculations see supplementary material, Table A2. All multivariate calculations and transformations with R can be reproduced using supplementary material, Table A3 and R Code).

(1) All ambiguous determinations of cereals were removed, except for grains of free-threshing wheat. In the case of pulses and oil plants, however, the ambiguous determinations were retained to avoid further reduction of poorly documented taxa.
(2) To slightly mitigate the predominance of glume wheat chaff and to account for the poorer preservation chances of rachis fragments of free-threshing cereals (Boardman and Jones, 1990), two glume bases were converted to a spikelet unit.
(3) As some assemblages (sites) had very different sample volumes, the counts of macro remains of the assemblages were converted into concentrations (n/l) on a sample basis to improve comparability.
(4) In accordance with standard methodology, only representative assemblages were used for the descriptive statistics. For this purpose, a minimum number of six samples per assemblage was specified. This minimum was based primarily on a comparison between sample count and species diversity (crops and weeds) for the spectra (supplementary material, Fig. A1), which showed that assemblages with five or fewer samples had the lowest informative value (representativeness); similar studies have also chosen this threshold value (e.g. de Vareilles et al., 2022).
(5) For the analysis based on multivariate statistics, the crop data from all assemblages were included in order to exploit the total information available (in contrast to descriptive statistic). For the diversity analysis, only the cereal remains were considered, as the preservation and/or detection of pulses and oil plants is rather random due to taphonomic reasons and would therefore distort the results. In addition, the taxa-points of pulses and oil plants in the redundancy analysis (see section 3.1.) are close to the origin of the coordinate system, which proves that they have hardly any influence on the distribution. Due to the large differences in the data volume/average concentrations (minimum: 0.07/ maximum: 90232.1 n/l), initial calculations of the diversity analysis did not show a clear result. Therefore, the data was logarithmised and multiplied by 100 beforehand (to avoid negative numerical values).

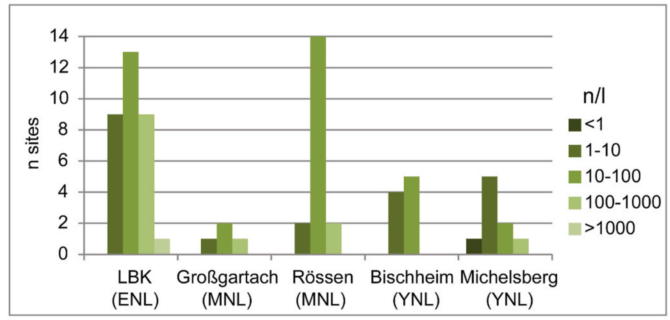

Fig. 3. Total number of sites per cultural group with different ranges of average concentrations (n/l) of macro remains. For abbreviations see Table 1.

Table 1
Overview of the available data (number of samples and features analysed, sediment volume) as well as average concentration calculated on basis of total counts of macro remains and total volume of all samples from a cultural group (n/l). Abbreviations: LBK Linear Pottery culture, ENL Early Neolithic, MNL Middle Neolithic, YNL Young Neolithic.

Phase	sites	samples	features	volume (l)	average concentration (n/l)
LBK (ENL)	32	626	399	1148.7	266.04
Großgartach (MNL)	4	128	23	105.2	215.33
Rössen (MNL)	18	317	150	885.2	77.96
Bischheim (YNL)	9	71	46	376.7	24.35
Michelsberg (YNL)	9	236	106	600.3	18.84
total	**72**	**1378**	**724**	**3116.1**	

(6) For the analysis of the archaeobotanical data in relation to environmental factors, in particular the soils, again only the cereal remains were taken into account, as these have been shown to be chronologically most relevant in the redundancy analysis (see section 3.1.). In addition, all data were summarised at species level, i.e. the values for grains and chaff were added together. In the case of the free-threshing wheat species, all data were summarised regardless of their ploidy level. Therefore, the categories '*Triticum monococcum*', '*Triticum dicoccum*', '*Triticum timoveevii* s.l.', '*Triticum aestivum/durum/turgidum*' and '*Hordeum vulgare nudum*' were analysed.

2.4.2. Applied analytical methods

As a first step we used descriptive statistics to compare the proportions of crops at all representative sites in order to gain an initial insight into the changes in agriculture from the late 6th to the early 4th mill. BCE (Fig. 4). This approach (using only representative assemblages with >5 samples) resulted in a reduction of the data set to 39 assemblages.

To prevent a possible distortion due to overrepresentation of glume wheats, the proportions of cereal grains and chaff are presented as discrete data sets and the diaspores of pulses and oil plants are plotted together with the cereal grains. The sites listed in grey in Fig. 4 yielded less than six samples with clearly determined crop remains at species level. Since this problem is especially prevalent in the poorly documented YNL sites, it was decided to integrate these assemblages here.

In a second step we applied multivariate analysis to test different correlations for significance using the crop quantities (average concentrations n/l). For the ordination we chose transformation-based redundancy analysis (hereafter tbRDA). TbRDA as a multivariate analysis provides the possibility to link the correlation of the initial data (spectrum and number of macro remains) with other variables (cultural classification/dating, sample size and environmental data) in a model. Since the (canonical) correspondence analysis (CCA) is very sensitive to rare species and outliers (Roth, 2022), tbRDA was preferred. If abundance data are used to calculate an RDA, as is the case here, it is possible, depending on the composition of species abundances, that two samples in which no species are the same may be represented as more similar than those that are identical in their species composition. This is known as the 'Orlóci paradox' (Orlóci, 1978; Ricotta, 2021). Therefore, the data must be transformed before the actual RDA calculation; the so-called Hellinger transformation is used here (Legendre and Legendre, 2012). The analytical method is therefore referred to as 'transformation-based RDA', hence tbRDA. The tbRDA makes it possible to statistically test this model for significance (ANOVA-like permutation test) (Legendre et al., 2011; Roth, 2022).

As a third step, a Renyi diversity profile was calculated. For this purpose, the remains of cereals (chaff and grains) were added up for each species and time stage (see section 2.4.2, point 6). In a Renyi diversity profile, the vertical axis represents the diversity index, the horizontal axis the parameter alpha. Alpha = 0 provides information on species richness, alpha = infinity on the proportion of the most abundant species. The Shannon diversity index can be read off at the value alpha = 1; alpha = 2 represents the logarithm of the reciprocal Simpson diversity index (Kindt and Coe, 2005). If one characteristic curve lies completely above another, the crop spectra of this community/group can be regarded as more diverse (Tóthmérész, 1995).

All multivariate calculations were carried out using the free statistical programming language R (Posit Team, 2024; R Core Team, 2024). The processing of the multivariate analyses and visualisations were conducted using the R-package vegan (Oksanen et al., 2020). All important statistical parameters are provided in the figures.

3. Results

3.1. The range of cultivated plants in the analysed sites

The complete archaeobotanical data set contained approx. 245,000 charred macro remains of 149 taxa, with ten cultivars accounting for over 75 % (n = 186,919) of all finds. Cereal remains totalled 185,140, most of which (71.5 %) were chaff (Table 2).

All cereal species known for the Central European Neolithic (see above) were documented in the Rhenish samples: the glume wheats einkorn (*Triticum monococcum*), emmer (*Triticum dicoccum*) and Timopheev's wheat (*Triticum timopheevii* s.l.), as well as the free-threshing cereals naked wheat (*Triticum aestivum/durum/turgidum*) – rachis fragments of the hexaploid (*Triticum aestivum*) and tetraploid (*Triticum durum/turgidum*) species could be distinguished – and barley, which, if well preserved, could be identified as six-row naked barley (*Hordeum vulgare* var. *nudum*).

The pulses lentil (*Lens culinaris*) and pea (*Pisum sativum*) are also present, as are the oil plants flax (*Linum usitatissimum*) and opium poppy (*Papaver somniferum*). However, remains of the last two groups are sporadic and mostly occur in small numbers, making up only 0.95 % of the crop spectrum. This is not unusual, as their chances of getting charred and/or surviving carbonisation are low (Butler et al., 1999; Fuller and Harvey, 2006; Märkle and Rösch, 2008). In the case of oleaginous plants, however, samples from waterlogged deposits (wells, bog and lakeshore settlements) indicate widespread cultivation in the Neolithic (e.g. Jacomet et al., 2015, 1989; Zerl and Herbig, 2012; Herbig et al., 2013; Antolín et al., 2015; Jesus et al., 2021). The same can be assumed for pulses.

3.2. Analysis of representative crop spectra (descriptive statistics)

The proportions of crop remains shown in Fig. 4 reveal clear differences between the Neolithic groups. As we already know, the glume wheats emmer and einkorn were cultivated in the LBK, probably in the form of mixed cultivation or 'maslin' (Kreuz, 2007; Bogaard, 2011). The absence of Timopheev's wheat in the LBK assemblages is most likely explained by the pre-2000 timing of the archaeobotanical analysis (cf. section 2.2.1.). However, very few remains have been found in the MNL and YNL assemblages analysed in recent years, so it can be assumed that this wheat was not very important in the Rhineland and occurred only to a limited extent. At first glance, the proportions of emmer and einkorn appear to be balanced if one summarises the slightly higher proportion of emmer grains and the higher proportion of einkorn chaff. However, one ear of emmer produces more grains than einkorn. Therefore, a higher number of emmer grains does not necessarily reflect more cultivated plants. In contrast, einkorn dominates the threshing residues. Since these values were calculated for both einkorn and emmer based on ear units (spikelets), they are more comparable. In addition to the glume wheats, pulses (lentil and pea) and oil plants (flax and opium poppy) are also found quite regularly and sometimes in higher quantities. The high proportions of flax are particularly notable, partly due to so-called 'mass finds' (e.g. in LA 2, cf. Knörzer, 1967).

At the beginning of the MNL (Großgartach), the range of cereals was extended to encompass naked barley and naked wheat. In addition, some threshing remains of Timopheev's wheat were found in HW2 (not recognisable in Fig. 4b), which was grown together with emmer and einkorn in a mix (Bogaard, 2023; Filipović et al., 2024). Considering only the evidence of chaff (Fig. 4b), emmer and einkorn dominate at all sites. However, this dominance of glume wheats is influenced by several factors: not only is there a greater chance that their chaff will be preserved during charring, but it also depends on the location of threshing. In the case of glume wheats, it can be assumed that they were stored in their glumes and that threshing took place regularly within the settlements, resulting in the predominance of glume wheat chaff in assemblages, while free-threshing cereals, on the other hand, may have been

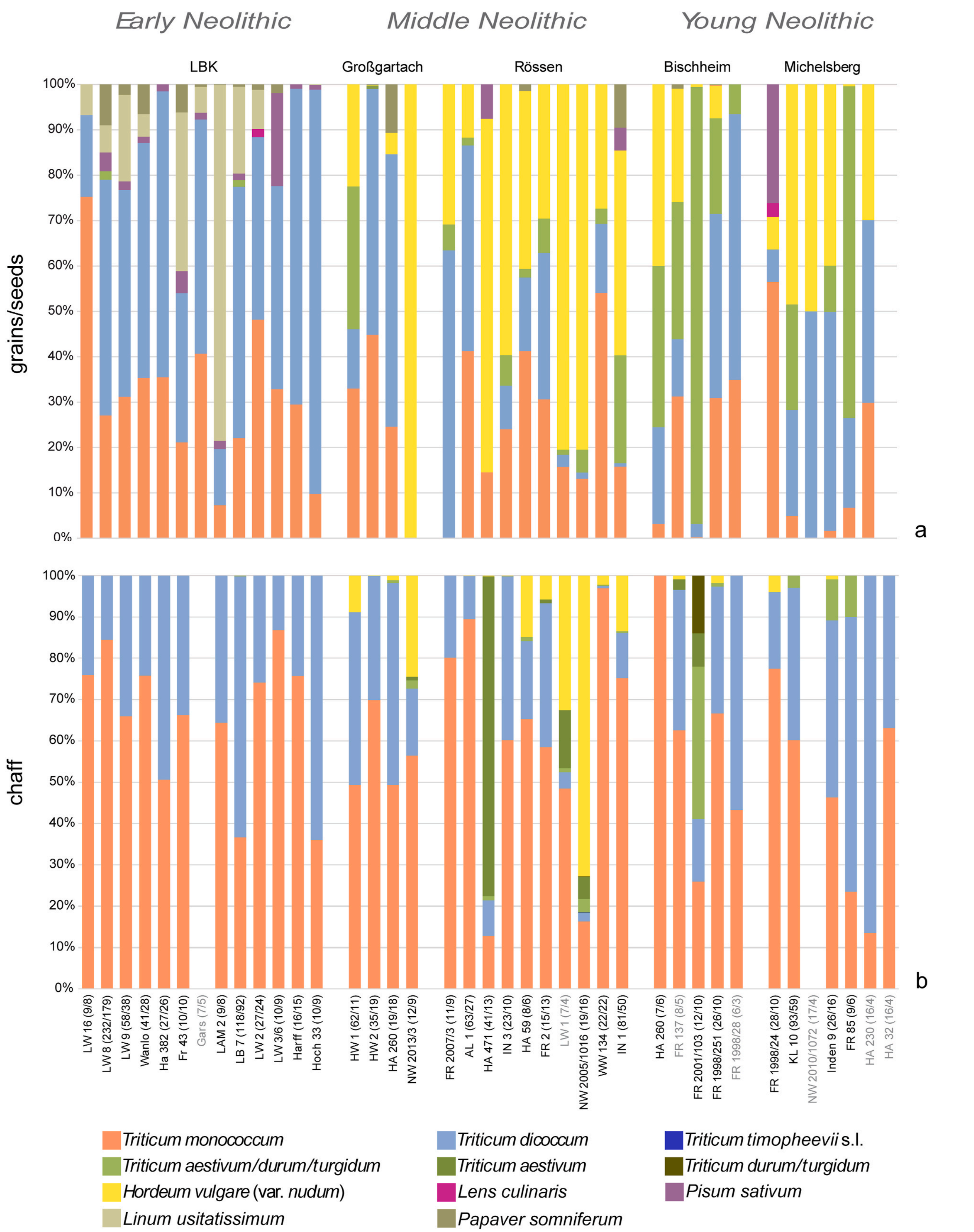

Fig. 4. Percentage of the identified crops in the representative assemblages (>5 samples). The quantities of grains/seeds (a) and chaff (b) are shown separately in order to estimate the respective over- or underrepresentation of threshing remains of glume wheat or of free-threshing cereals (naked wheat/barley) in relation to cereal grains. The assemblages marked in grey have fewer than six samples with crop remains identified to species level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Overview of the available data (number of taxa, total counts of macro remains and of crops remains) for all cultural groups. For abbreviations see Table 1.

Phase	taxa	macro remains	crop remains	cereal grains	cereal chaff	pulses	oil plants
LBK (ENL)	87	89,585	55,061	12,922	40,410	98	1631
Großgartach (MNL)	47	31,234	29,563	17,242	12,298	1	22
Rössen (MNL)	102	111,941	92,906	15,204	77,687	10	5
Bischheimer (YNL)	59	7181	6028	3187	2832	6	3
Michelsberg (YNL)	61	5049	3361	2847	511	3	
total		**244,990**	**186,919**	**51,402**	**133,738**	**118**	**1661**

processed in bulk usually outside the settlements (Hillman, 1981; van der Veen and Jones, 2006; Kreuz, 2012; Roushannafas et al., 2023). The proportions of cereal grains are consistent with these assumptions, as naked barley and naked wheat grains are documented in higher proportions than their threshing remains (in NW 2013/10 the only clearly determinable cereal grains belong to barley; Fig. 4a). Of pulses and oil plants, only opium poppy has been identified (HW 2, HA 260; also not visible in Fig. 4a), which is a clear difference to the LBK.

In the subsequent Rössen assemblages, the proportions of free-threshing cereals compared to emmer and einkorn are quite high, with naked barley even dominating the spectra of cereal grains. Naked wheat is documented as well, but only in smaller proportions (Fig. 4a). An exception is HA 471, showing high proportions of rachis fragments of hexaploid naked wheat (*Triticum aestivum*) (Fig. 4b); however, as these residues were found in only one pit, this could also represent a one-off event. Some possible threshing remains of both Timopheev's wheat and tetraploid naked wheat (*Triticum durum/turgidum*) are documented at the late Rössen site NW 2005/1016. In our study region, tetraploid naked wheat was previously only known from Bischheim (cf. FR 2001/103, Fig. 4b; Aurora and Zerl, 2004), but threshing residues of *Triticum durum/turgidum* were found in an equally late Rössen context in Dortmund-Oespel, located approx. 80 km north-east of Cologne (Becker and Pasternak, 2003). Threshing remains of barley and naked wheat are quite numerous at the Rössen sites, suggesting that the threshing of these cereals could also have taken place within the settlements. In the case of pulses and oil plants, only sparse evidence was found: in addition to opium poppy, pea is also identified in some spectra.

In the Bischheim phase/culture the proportion of cereal grains shows a clear increase of naked wheat in favour of naked barley (Fig. 4a). Aside from this, emmer and einkorn are still documented. Unsurprisingly, the glume wheats dominate among the threshing residues, but – as already mentioned – in FR 2001/103 rachis fragments of *Triticum durum/turgidum* are present alongside those of *Triticum aestivum* (Fig. 4b). Corresponding to the lower proportion of grains, threshing remains of barley are also scarce, which is a clear difference to the Rössen sites. However, the low numbers of pulses and oil plants are comparable to Rössen. Although lentil, pea and opium poppy are documented, their numbers are very low.

The higher proportions of naked wheat already evident in Bischheim continue into Michelsberg, although barley is now slightly more common, as is emmer (Fig. 4a). Einkorn is only present in small quantities (an exception is the site FR 1998/28, which can probably be placed at the transition from Bischheim to Michelsberg according to radiocarbon dating [Scharl et al., 2025]). This shift in dominance from einkorn to emmer is particularly evident in the threshing residues. In the case of pulses and oil plants, only one site (FR 1998/24) provided evidence of lentil and, above all, pea.

The crop spectra compared in Fig. 4 show changes over time that are probably associated with the cultural development from ENL to YNL in the Rhineland. Based on this comparison, the potentially group-specific spectra can be summarised as shown in Fig. 5.

3.3. Analysis of all crop spectra (multivariate statistics)

3.3.1. Redundancy analysis

The result of group-specific crop spectra based on our first analysis (Fig. 5) needed to be tested and analysed in more detail. We wanted to check (1) whether the spectra could have been influenced by other factors (number of samples, sample size, average concentration), and (2) whether the spectra are so characteristic for the individual Neolithic groups that the non-representative sites (n = 33), which were not included in the first analysis (using descriptive statistics, Fig. 4), also follow these patterns. To test these two aspects, we decided to perform a tbRDA (see section 2.4.2). In this way it was possible to include all assemblages in the analysis.

In the initial tbRDA models, we asked to what extent the number of samples and of sampled features per site, as well as the average concentration per assemblage (n/l), had an influence on the results (biplots of these models in supplementary material, Fig. A2–A4). The respective models were tested for significance using an ANOVA-like permutation test (Legendre et al., 2011). No significant influence (number of samples per site: $p = 0.203$; number of features per site: $p = 0.245$; average concentration: $p = 0.154$) could be observed here, which is why we also integrated the assemblages with less than six samples for all subsequent models. However, it should be noted that the test statistics only provide a statement about the overall distribution. Individual assemblages (outliers) that only yielded a small number of samples were critically assessed regarding their taphonomy and the recovery conditions. This showed that in these individual cases their position in the biplot can be explained by these very factors. In order not to distort the overall picture

Phase	Crops, sorted by importance
LBK (ENL)	einkorn – emmer(*) – flax – some pea, opium poppy – [lentil]
Großgartach (MNL)	einkorn – emmer* – some barley, naked wheat – [opium poppy]
Rössen (MNL)	einkorn – emmer* – barley – naked wheat** – [pea, opium poppy]
Bischheim (YNL)	naked wheat** – einkorn – emmer – barley – [opium poppy, pea, lentil]
Michelsberg (YNL)	naked wheat – emmer – barley – einkorn – [pea, lentil]

Fig. 5. The crops cultivated in the Early to the Young Neolithic groups in the Rhineland, ordered according to their probable importance. (*) *Triticum timopheevii* s.l. present based on illustrations; * *Triticum timopheevii* s.l. present; ** *Triticum aestivum* and *Triticum durum/turgidum* present; [] species found only sporadically and in small proportions. For abbreviations see Table 1.

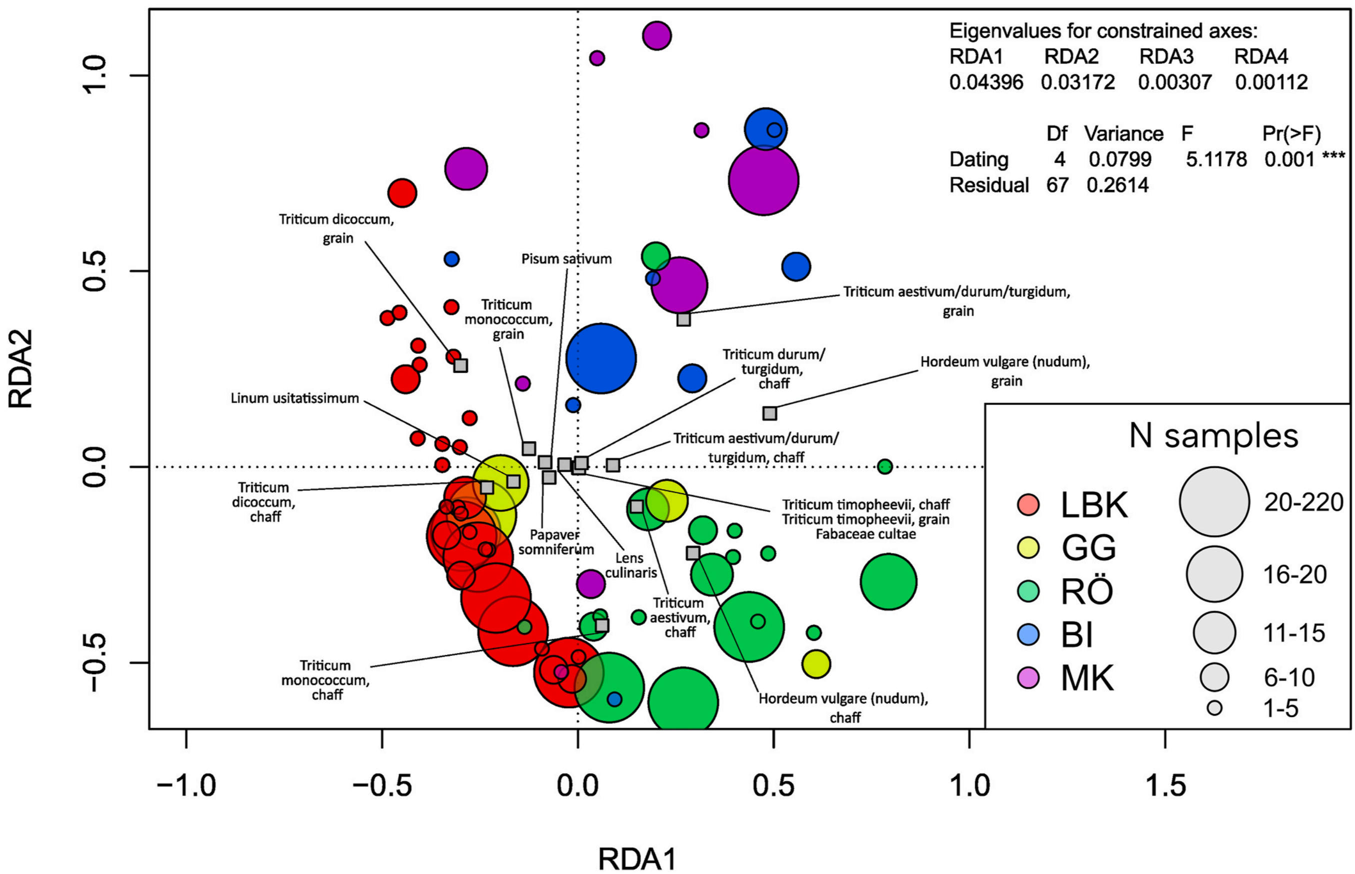

Fig. 6. Biplot of the transformation-based RDA model with the additional variable "dating". The size of the points represents the numbers of samples. For abbreviations see Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

through individual case decisions, these assemblages were also included in all other models.

In a further model we integrated the dating of the assemblages and tested this variable for significance. Fig. 6 shows the biplot of the tbRDA, in which all 72 assemblages are arranged based on their crop spectra (cereals, pulses and oil plants). On the first two axes the information contained in the data set is ordered with very high quality. The influence of assemblage date on the model is highly significant (ANOVA-like permutation test, $p < 0.001$). As the biplot shows (Fig. 6), the sites assigned to the same cultural group are clustered together, while the clusters are mostly separated from each other – even though the few Großgartach assemblages can be assigned to both the LBK and the Rössen groups and the two YNL groups of Bischheim and Michelsberg overlap.

The distribution of the taxa shows that the order is mainly affected by the cereals. The taxa of pulses and oil plants are in the zero point range, and therefore have no influence on the plotted order. It is worth considering whether the poor chances of preservation (and thus the very fragmentary record) of pulses and oil plants in settlements on mineral soils (see section 3.1.) are a reason for the apparent lack of chronological relevance of these crops.

Nevertheless, this insignificance of pulses and oil plants is surprising, as the descriptive analysis suggested that at least flax had a group-specific relevance for the LBK (Fig. 4a). However, the position of the LBK assemblages is only influenced by einkorn and emmer, especially by their chaff. For the position of the Rössen assemblages, naked barley chaff is crucial, but also einkorn chaff to some extent. The Großgartach sites show spectra with characteristics of the LBK and Rössen assemblages. Naked wheat grains mainly affect the position of the Bischheim as well as of the Michelsberg assemblages, which partly also lie closer to the emmer grains.

The arrangement of the assemblages reflects the differences in cereal cultivation from ENL to YNL. However, their distribution is also partly influenced by sample types, since the analysed samples consist mainly of crop processing by-products that accumulated within the settlements and were deposited in the investigated features (mostly pits). In contrast to the free-threshing cereals, it can be assumed that glume wheats were processed within the settlements (see section 3.2.), meaning that their chaff is always well documented in sites that primarily cultivated emmer and einkorn. This applies in particular to the ENL and MNL assemblages, which lie in the lower part of the coordinate system. Since most assemblages located there are also very rich in samples, they also have higher quantities of crop processing by-products (=chaff). Some LBK samples also move into the IV quadrant of the coordinate system – i.e. in the direction of emmer and einkorn grains. These are mainly assemblages with few samples (mostly two) as well as a low concentration of macro remains (n/l) and in which cereal grains occurred more frequently than threshing remains. The spectra consisted most likely of mixed samples (Hubbard, 1976; Hillman, 1984; Jones, 1984; Zerl, 2019) and/or 'settlement noise'.

The distribution of the assemblages in the right half of the coordinate system reflects the change in cereal cultivation after the ENL following the introduction of free-threshing species. However, rachis remains of barley and naked wheat are underrepresented in the assemblages (Fig. 6), as these cereals were generally processed off-site (see section 3.2.). The YNL assemblages are separated from the Rössen assemblages and lie in the upper part of the axial cross, as these contain mainly grains of barley and naked wheat, but significantly fewer threshing remains. On the one hand, this is not surprising due to the higher quantity of free-threshing cereals, on the other hand, the lack of rich crop processing by-products of glume wheats could also be linked to a change in settlement patterns (see discussions in Kreuz et al., 2014; Seidel, 2017; Scharl,

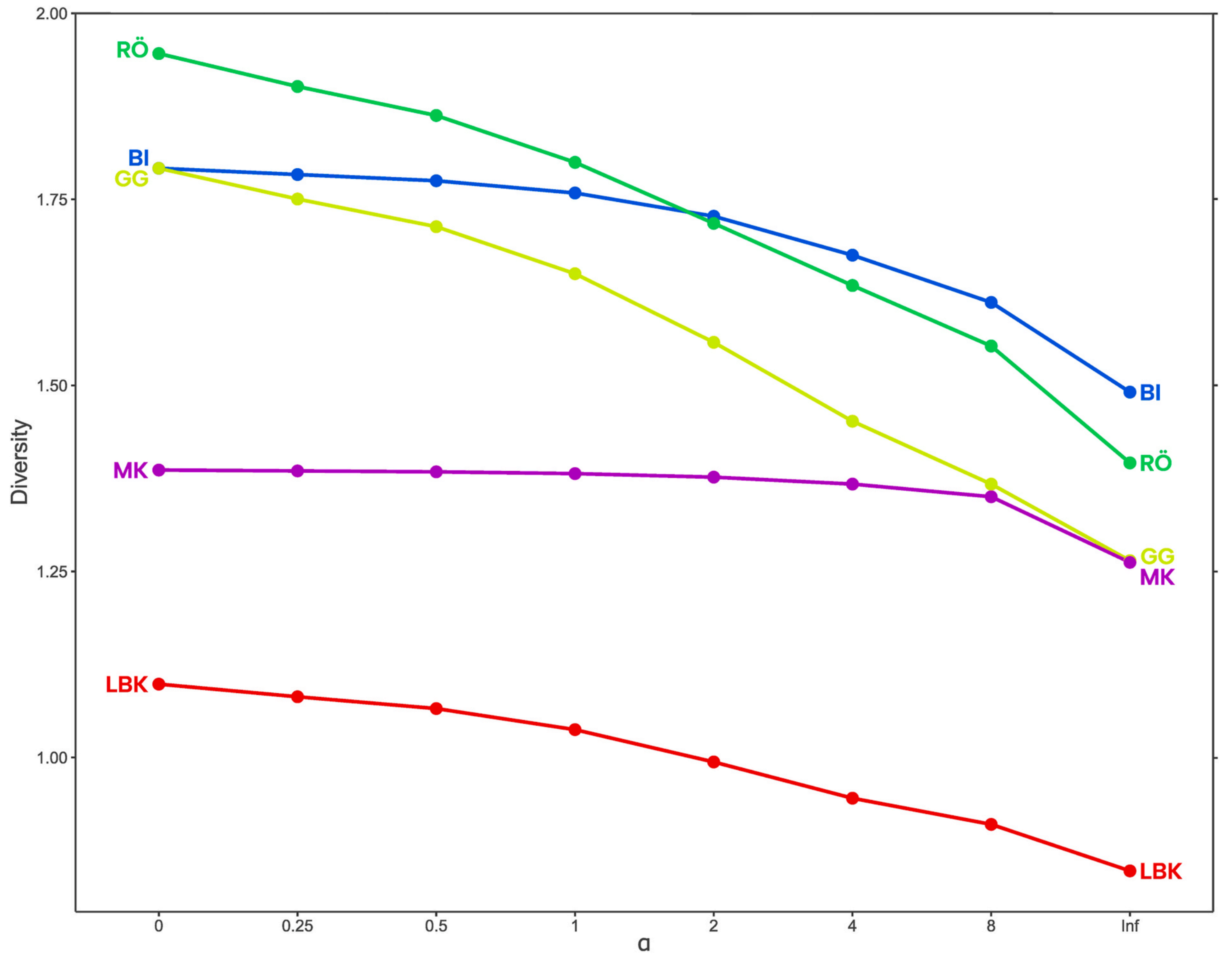

Fig. 7. Renyi diversity profile for the cereal spectra differentiated according to dating. For abbreviations see Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2023). While long-lasting settlements with numerous, often large pits are common in the MNL, evidence of settlements in the YNL is usually sparse. Therefore, it can be assumed that cereal processing waste could accumulate and be preserved better in the large, long-lived Rössen pits, whereas the chance of preservation of charred macro remains in the smaller pits of the shorter-lived YNL settlements is significantly lower. Corresponding to this, the samples from Bischheim sites, but especially from Michelsberg sites, show very low average concentrations of macro remains (n/l) (Fig. 3).

With the redundancy analysis, sites from the ENL, MNL and YNL could be clearly distinguished from each other. As the crop spectra – especially of cereals – reflect a trend of diversification during the 5th mill. BCE, a diversity analysis was carried out to illustrate this more precisely.

3.3.2. Diversity analysis

Based on the results of the tbRDA, which show that only the cereal species provide group-specific information, and since pulses and oil plants are obviously underrepresented for taphonomic reasons, the diversity of the individual Neolithic groups was compared using only cereal data. For this approach, a diversity analysis with a Renyi profile was calculated, differentiated according to date (see sections 2.4.1. and 2.4.2).

As Fig. 7 shows, the spectrum of LBK species is the least diverse – which is not surprising since the LBK only cultivated glume wheats. A clear diversification can be observed during the following Großgartach and Rössen phases/cultures. Diversity in the Bischheim period remains at the same level. However, as the profile lines overlap, no statement can be made about the relationship. The diversity in the Michelsberg period is, nevertheless, lower than in Rössen and Bischheim. According to this diversity profile, Michelsberg differs significantly from Bischheim – even though both groups overlap in the tbRDA due to the same, dominant cereals and therefore appear very similar (Fig. 6). Based on the different levels of diversity, however, one could assume a change in crop cultivation during the YNL.

3.4. The interrelationship between crop diversification and patterns of settlement and land use

As already mentioned, during the period under consideration we also observe a change in settlement and land use patterns. Therefore, the question arose whether the change in agriculture reflected in the cereal spectra can also be explained by environmental factors.

For this purpose, we tested whether various parameters such as soil, parent material, elevation, water balance, precipitation and temperature had a significant influence on the previously described tbRDA-model (Fig. 6). All of them turned out to be non-significant for crop composition. One reason for this may be that the variability of the location parameters is relatively low in the study area due to the generally high homogeneity of the Rhenish loess region. Secondly, the sites from which the archaeobotanical samples were collected are not randomly distributed in the whole settlement landscape, but are mainly concentrated in the areas of the opencast lignite mines (see Fig. 1).

However, using digital soil maps combined with hydrological and geological data, different areas can be mapped for the region, which in turn can be summarised into three groups of different soil landscapes:

Luvisols from loess (area 1, loess >2 m), Luvisols and Pseudogley (area 2, loess <2 m) and Vega, Vega-cambiosols, Gley, Pseudogley (area 3, floodplain). The variation of the loess cover is related to tectonic differences, Pleistocene terraces and the distribution of bedrock. These superordinate soil landscapes can also be applied to the opencast mining areas. In order to make possible trends visible, the soil associations were grouped into two categories of locations. All sites on Luvisols (area 1) were classified as 'typical Luvisols' (Ad-hoc Arbeitsgruppe, 2005), while soilscapes with components of Gley, Vega and Pseudogley (areas 2 and 3) were classified as 'moist' (for soil types at the different sites see supplementary material, Table A1).

In a preliminary tbRDA model with the variables 'dating' and 'moist/typical Luvisol', a low significance can be established for the latter variable (p = 0.086). As Fig. 8 shows, typical loess sites with Luvisols tend to be associated with the phases of the ENL and early MNL (LBK/Großgartach) and moister areas with the later MNL and the YNL (Rössen/Bischheim/Michelsberg). This trend is amplified if all radiocarbon-dated sites (regardless of whether they provided archaeobotanical data) from the study area are included in the analysis.

4. Discussion

The changes in the crop spectra during the Neolithic periods in the Rhineland reflect a phenomenon that can also be observed supraregionally (e.g. Colledge et al., 2005; Kreuz et al., 2005). In this respect, the generally low crop diversity as well as the high homogeneity and lack of innovation in the ENL (LBK) in Central Europe is striking. It shows a noticeable reduction of the pre-LBK crop ensemble of south-eastern Europe. Various cultural and natural factors (environment, climate, cultivation preference, spatial drift, founder effect) are discussed as the causes of this reduction (e.g. Conolly et al., 2008; Pérez-Losada and Fort, 2011; de Vareilles et al., 2022). From the MNL onwards (post-LBK groups), an increase in innovation and cultural (as well as crop) diversity can be observed across Central Europe, which earlier studies attributed, among other things, to population growth and changes in transmission (Conolly et al., 2008).

Studies on crop diversity were often based on summarised supraregional data, whereby the developments in individual cultural groups could not be examined in detail. In the study presented here, it is possible to examine these developments in more detail with the help of extensive data for successive ENL to YNL groups from a comparatively homogeneous landscape (Rhineland). The data quality was achieved by using only primary data, which we either collected ourselves or to which we had direct access and which could therefore be verified. For this reason, we were able to use abundance data to identify proportion shifts in the plant spectra over time, which would not have been possible with presence/absence data as used in many other studies. In addition, tbRDA could be carried out.

4.1. The diversification of the crop spectrum

The developments just described, i.e. the increase in innovation evident in the expansion of the crop (cereal) spectrum after the ENL (LBK), are impressively documented in the Rhineland (Figs. 4–7). At the beginning of the MNL (Großgartach) two new free-threshing cereals (*Hordeum vulgare* and *Triticum aestivum/durum/turgidum*) were introduced; a further step in diversification can be seen in late Rössen and at the beginning of the YNL (Bischheim) with the integration of a tetraploid naked wheat in addition to the already cultivated hexaploid *Triticum aestivum*. The diversity in the following Michelsberg is lower than in Rössen and Bischheim. In this context, it is tempting to speculate whether the high diversity in Bischheim provided the necessary resilience for implementing cultural changes, which become tangible in Michelsberg, amongst others through a modified settlement and economic system.

The cultivation of these free-threshing cereals offered several advantages. One important aspect is to enhance the robustness of the agricultural system in general, as the cultivation of different crops can be seen as risk management (e.g. Halstead and O'Shea, 1989; van der Veen and O'Connor, 1998; Jacomet and Schibler, 2010; Marston, 2011; Scharl

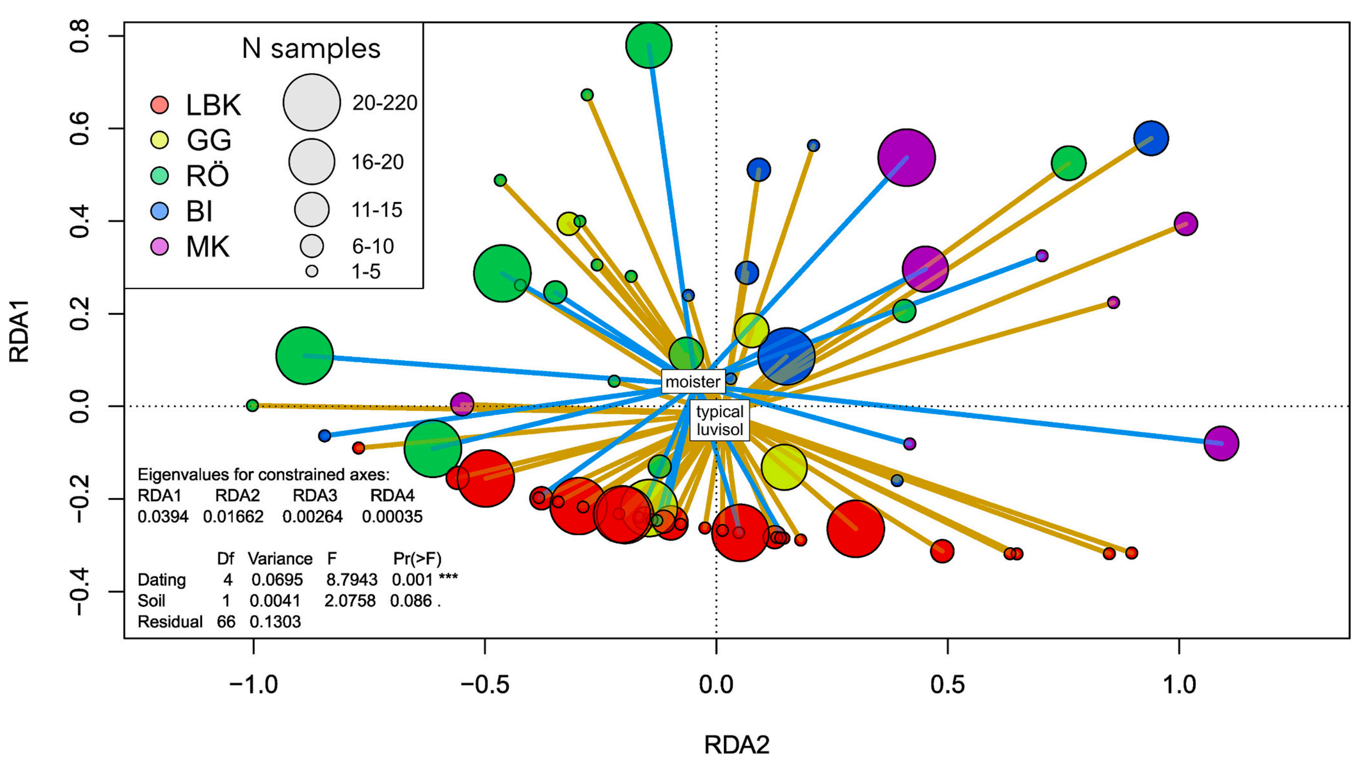

Fig. 8. Biplot of the transformation-based RDA model with the additional variables "dating" and "soils". The size of the points represents the number of samples. For abbreviations see Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2024). Furthermore, higher yields can be achieved by cultivating naked wheat, because it produces more grains per spikelet than glume wheats – usually three, but sometimes more (Maier, 1996; Cappers and Neef, 2012; Lieberei and Reisdorff, 2012). Similarly, barley – in its six-row form – bears three grains per rachis, whereas einkorn and emmer produce only one or two caryopses respectively. Apart from that, the inclusion of the new cereals also introduced greater flexibility in the agricultural system, allowing both winter and summer cultivation.

In the early Neolithic periods glume wheats were most probably cultivated as winter crops. Apart from the weed spectra of emmer/einkorn fields in the LBK and subsequent cultures, which point to autumn sowing (Bogaard, 2004), this is also supported by the dominance of the more winter-hardy einkorn in ENL and MNL sites in the Rhineland, as well as its longer vegetation cycle (Miedaner and Longin, 2022).

In the case of the newly introduced naked barley, however, two mutations in European landraces allow its cultivation as a summer crop (in contrast to its wild varieties and probably also its first cultivars). These mutations induce the silencing of the Ppd-H1 allele, which causes insensitivity to long days and thus enables later flowering in the growing season, as well as the loss of the vernalisation requirement (response to prolonged periods of cold to promote subsequent flowering) (e.g. Turner et al., 2005; Cockram et al., 2007; Jones et al., 2008; Lister et al., 2009). Phenotypes with these genetic variations are better adapted to the environmental conditions of Central, Northern and Western Europe, where the favourable growing period in summer is prolonged. Based on the spatial distribution of different phylogenetic barley groups in Europe, a subsequent arrival of day-length non-responsive strains compared to the first dispersal of Neolithic farming practices can be assumed, possibly the result of networks with the south-east (Jones et al. 2011, 2012, 2013). After the arrival of this new barley variety and its successful integration into the crop spectrum of Neolithic farmers in the loess landscapes, its cultivation could be extended to less favourable regions, enabling agricultural expansion into Northern and Western Europe as well as the Alpine region (Jones et al., 2012). This expansion was also facilitated by the high resilience of barley, especially of the spring variety (Körber-Grohne, 1987). Although barley prefers a temperate climate and fertile soils with good water supply, it can also withstand periods of drought, wetness and cold, as well as drier, saltier, sandier and more acidic soils (e.g. Bottema et al., 1982; Körber-Grohne, 1987; Cappers and Neef, 2012; Bishop et al., 2009).

Alongside barley, the cultivation of naked wheat was also an innovation in the Central European MNL – although initially of lesser importance (Fig. 4). Two species of naked wheat have been identified in the Rhineland based on their chaff (hexaploid *Triticum aestivum* and tetraploid *Triticum durum/turgidum*). In the case of *Triticum aestivum*, which probably arrived in Central Europe from the south-east as part of the Neolithic package (Kirleis and Fischer, 2014; Roushannafas et al., 2023) and was most likely the first naked wheat to be cultivated here, there is no direct evidence of its sowing time. Due to its higher ploidy status, *Triticum aestivum* has greater adaptive potential compared to tetraploid wheat species, allowing it to be grown under a wider range of conditions (Dubcovsky and Dvorak, 2007; Zhou et al., 2020; Roushannafas et al., 2023), which also include the time of sowing. Even in the post-Neolithic prehistoric periods, the cultivation regime is ambiguous, as analyses of the weed flora of naked wheat fields – most likely hexaploid, as only chaff of this type was found – indicate both summer and winter cultivation for the Rhineland (Zerl, 2019). However, since spring sowing of naked barley was apparently integrated into the post-LBK farming system, we can probably conclude the same for the cultivation of (hexaploid) naked wheat. With the emergence of the tetraploid *Triticum durum/turgidum* in the late MNL, spring sowing becomes the most likely practice, as this naked wheat, which presumably came to Central Europe from the Mediterranean region, is warmth-loving and much more sensitive to frost (Maier, 1996; Lieberei and Reisdorff, 2012; Kirleis and Fischer, 2014).

4.2. The diversification of the crop spectrum – triggers, potentials and risks

Regardless of where the impulse or the know-how for the diversification of the crop spectrum and therefore the changes in agriculture came from, various external and internal triggers that could lead to the uptake, integration and acceptance of these innovations must be discussed. As external triggers, changing environmental conditions, such as climate, could have resulted in the adoption of new cereal species. However, these considerations are not relevant for the sites in our study, as the period in question falls within the middle Holocene with relatively stable conditions. High-resolution climate data from dendrochronological studies do not indicate any climatic anomalies for the 5th mill. BCE (Broich, 2021; Scharl et al., 2024). As an internal trigger an increase in population density can be discussed. However, calculations of population density in the Rhineland do not suggest a direct link between changes in arable farming and an increase in population size (Broich, 2021). Rather, other factors may have favoured transformation, such as the collapse of networks, as evidenced by the dissolution of the flint supply networks at the end of the LBK (e.g. Zimmermann et al., 2020). This resulted in new cultural contacts and an expansion of mobility, which can be seen as a driver of innovation (e.g. Scharl, 2023). Another factor is an increase in agricultural experience, which allowed for cultural choices, i.e. a move away from traditional LBK farming practices and the integration of new crops and cultivation regimes. This can also be discussed in connection with the development of agricultural risk management strategies (Scharl et al., 2024).

Apart from an increase in flexibility of the agricultural system, whereby the workload of agriculture (tillage, sowing, harvesting) is distributed more evenly over the months, the inclusion of free-threshing cereals in the crop spectrum offers more advantages when it comes to their further handling. Their processing is less time-consuming than that of glume wheats, as threshing is not required (e.g. Hillman, 1981, 1984; Jones, 1984). This meant that part of the cereal harvest could be stored ready for preparation and did not have to be dehusked daily before consumption, as was the case with the glume wheats. In addition, the caryopses of free-threshing cereals have a lower weight and volume than the spikelets of glume wheats, which can make storage and, if necessary, transport easier (Cappers and Raemaekers, 2008). However, one disadvantage of storing fully threshed, naked cereal grains is their higher susceptibility to pests (Häberle et al., 2022). This might have necessitated different storage conditions within the settlements.

4.3. The diversification of the crop spectrum – changes in settlement patterns and internal structures

Although experiments have shown that naked cereal grains can successfully be stored in storage pits (silos) in the same way as glume wheats, we see a small decline in the archaeological record in storage pits accompanying houses (Biederer, 2022). While individual storage features are visible in most settlements, some sites contain clusters of silos (e.g. Dohrn-Ihmig, 1983; Lönne, 2003). These could be interpreted as collective efforts for the storage of cereals or indicate an economic function for nearby buildings. Additionally, in many Rössen sites extensive pit complexes (originally for clay extraction) show remnants of several storage pits (e.g Lönne, 2003; Riedhammer, 2017; Kuper, 2018; Biederer, 2022). This may support the idea of collective strategies for long-term cereal storage, with secondary use of these areas for clay extraction leading to a poorer preservation of storage pits in the MNL.

There are also changes in the settlement structures related to above-ground storage. The ENL residential buildings have a section with an elevated floor, presumably serving as a granary, which is absent in MNL houses (Biederer, 2022). Instead, some sites show small outbuildings that might have served as storage buildings. As these are not present in all settlements, they were probably not necessary; instead, different strategies for storage within buildings can be assumed (Lönne, 2003).

Finally, we would like to share a few considerations on the interrelationships between settlement patterns, landscape, land use and agriculture. Initially, we hypothesised that the colonisation of areas generally considered marginal would go hand in hand with the cultivation of more robust cereals, and that this innovation would therefore mainly take effect in marginal areas. But it seems that the situation is more complex. During the period under consideration, even in the Central European loess landscapes, an expansion of settlements into areas less suitable for crop cultivation can be observed from Großgartach onwards (Scharl et al., 2024) – in our study this is shown by the occurrence of MNL-settlements in the Pseudogley-Luvisol area and the floodplains. This also correlates with the introduction of new cereals. With these more robust cereals (especially barley), it was probably not necessary to stay on the best soils in the loess area, but settlers were able to use a greater variety of ecotopes, including floodplains. We should keep in mind that livestock farming could have played an important role, which we have not yet been able to trace due to poor preservation of animal bones in our study region.

5. Conclusion

Our analysis provided new results on transformations in the crop spectrum from the ENL to the YNL in the Rhineland. As we were able to show by using multivariate statistics (tbRDA), there are significant differences between the Neolithic phases. Unexpectedly, our study revealed that the agricultural changes that characterised the MNL (introduction of free-threshing cereals) were already evident at the beginning of this period (Großgartach). The integration of new cereals made agriculture more flexible, allowing not only the cultivation of winter but also of summer crops and the potential use of a higher variability of soils, as well as a possible reduction in labour input. A steady increase in the diversity of cereals was also demonstrated by a diversity analysis. This analysis also showed a diversity peak in Bischheim, followed by a collapse in Michelsberg, indicating a further transformation of the agricultural system. Further fundamental changes can be seen in other aspects of the YNL archaeological record (e.g. settlement structures, animal husbandry, exchange networks; see Schier, 2010).

At least in the Rhineland, the developments in the MNL were not influenced by environmental factors, but may rather reflect cultural and economic choices (risk management, increase of production) based on the experience that people had already gained with the agricultural system at that time. Initial pedological analyses indicate the use of a higher diversity of ecotopes in the MNL, which could be attributed to a conscious decision. Future research is planned to gain a broader basis and to investigate possible causes.

The methodological approach used for this analysis not only allows the utilisation of representative data, which are typically required for descriptive statistics, but also enables the inclusion of the complete data set. We can prove that the sample size has no statistically significant influence on the result of our analysis using multivariate statistics (here tbRDA).

CRediT authorship contribution statement

Tanja Zerl: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stefan Suhrbier:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Silviane Scharl:** Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Manuel Broich:** Writing – review & editing. **Hannah Lindemann:** Writing – review & editing. **Nadine Nolde:** Writing – review & editing. **Anna Schick:** Writing – review & editing. **Astrid Stobbe:** Writing – review & editing, Funding acquisition. **Astrid Röpke:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition.

Reproducible results

The Associate Editor for Reproducibility downloaded all materials and could reproduce Figs. 6–8 presented by the authors.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2025.106369.

Data availability

The data that support the findings of this study as well as the R code are included as part of the paper (supplementary material).

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