The cerealisation of the Rhineland: Extensification, crop rotation and the medieval 'agricultural revolution' in the *longue durée*

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Schlagwörter: *Frühmittelalterliche Landwirtschaft / Fruchtfolge / Agrarrevolution / stabile Isotope der Kulturpflanzen / funktionale Unkraut-Ökologie / Niederrheinische Bucht*

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Introduction

This paper presents results from a research project (*'Feeding Anglo-Saxon England. The Bioarchaeology of an Agricultural Revolution'* hereafter FeedSax), that aims to generate direct evidence for the cultivation regimes that sustained, between c. AD 800–1200, an exceptionally rapid growth of populations, towns, and markets and enabled landowners to amass considerable wealth. Three key innovations made this increase in overall grain yields possible: two- and three-field crop rotation, which enabled a larger proportion of arable land to be brought under cultivation and winter and summer crops to be grown in the same year; increased use of the mouldboard plough, which allowed farmers to cultivate heavier, more fertile soils; and 'low input' cultivation regimes which maintained the fertility of fields by means of regular, short fallow periods (during which sheep grazed on the stubble and weeds in the fallow field) rather than by intensive manuring and tilling. This allowed farmers greatly to extend the area of land under cultivation by decreasing the amount of input – manure and human labour – per land unit, a process referred to here as 'extensification'. The result was substantially greater overall yields despite a decline in yield per unit of land area. In many parts of northern Europe, these innovations eventually culminated in a variety of forms of open field farming.

While the origins and spread of open fields have been debated for well over a century, existing approaches have had to rely primarily on indirect evidence such as later medieval or post-medieval documents and maps, scatters of pottery sherds associated with manuring, and a small number of early medieval sources such as documents recording grants of land (Renes 2010; Banham / Faith 2014; Hall 2014; Dyer et al. 2018). FeedSax seeks to advance this debate by generating direct evidence for the conditions in which crops were grown using a range of scientific methods. Functional ecological analysis of the weed flora that grew in amongst the crops and was harvested with them was undertaken to assess growing conditions in terms of soil fertility, soil working (disturbance), and the seasonality of crop growth. This approach reveals the net impact of practices such as manuring, tillage, and weeding as well as crop sowing times. Stable isotope ratios in preserved (charred) cereal grains – barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), and rye (*Secale cereale* L.) – were also measured in order to investigate the degree to which productivity was boosted by manuring, as reflected in soil nitrogen values. This approach can also help establish whether different cereal crops were grown in the same soil conditions, and thus potentially were grown in rotation in the same fields. Faunal remains from excavated medieval settlements and pollen data have also been examined, although these analyses lie outside the scope of the present paper.

FeedSax focuses primarily on evidence from medieval England; however, a collaboration with the *Labor für Archäobotanik* of the University of Cologne has provided an opportunity to analyse hundreds of archaeobotanical samples from the Lower Rhine Basin within the framework of the project. The archaeobotanical samples analysed derive from settlements excavated over many years, mostly in advance of open cast lignite mining to the west of Cologne *(Fig. 1; Tab. 1)*. This is a region where the adoption of the mouldboard plough and three-course rotation are traditionally dated on the basis of written sources – above all Carolingian polyptychs, inventories of the resources owned by royal and monastic estates – to the later 8th and 9th centuries, although fully developed open field farming involving communal management of arable at the village level is generally not thought to have emerged until sometime between the 10th and 13th centuries (Hildebrandt 1988; Rösener 1992; Henning 1994; Verhulst 2002, 65; Devroey 2003).

This exceptional archive of closely dated crop remains and associated weed assemblages provides a long-term sequence of agricultural change over several millennia against which the medieval data can be assessed. To this end, a functional ecological analysis of the weed flora associated with crops from the Neolithic to the Middle Ages was conducted. The results of these analyses enable us to situate the expansion of cereal cultivation in the heartland of the Carolingian Empire within a much longer chronological framework than is currently possible in England, namely from the introduction of farming in the region in the later 6th millennium BC, through the Iron Age and Roman periods, to the central Middle Ages. In addition, a crop stable isotope analysis of medieval samples was undertaken to investigate crop rotation. This proved to be possible, however, only for the 5th to 8th centuries, as later samples proved to consist largely of single cereals, primarily rye.

The present paper focuses on the results of these analyses and considers where medieval farming fits within a broad trend towards lower input growing conditions that began in later prehistory. In particular, it examines the impact on farming practices of the end of the Roman system of supplying grain to towns and the military, and whether post-Roman farming reverted, as traditionally assumed, to smaller-scale, more intensive cultivation practices (Duby 1954; White 1962). The origins of systematic crop rotation are also considered, as it is one of several innovations thought to have arisen between the Seine and the Rhine during the 8th and 9th centuries, which ultimately enabled substantial cereal surpluses to be produced. The mobilisation of these surpluses has traditionally been regarded as a major factor in the development of the bipartite manor and the shift of agriculturally based wealth from southern to northern Europe (cf. Duby 1954; White 1962; see also Mitterauer 2010). FeedSax provides new, direct evidence against which this chronological sequence can be tested.

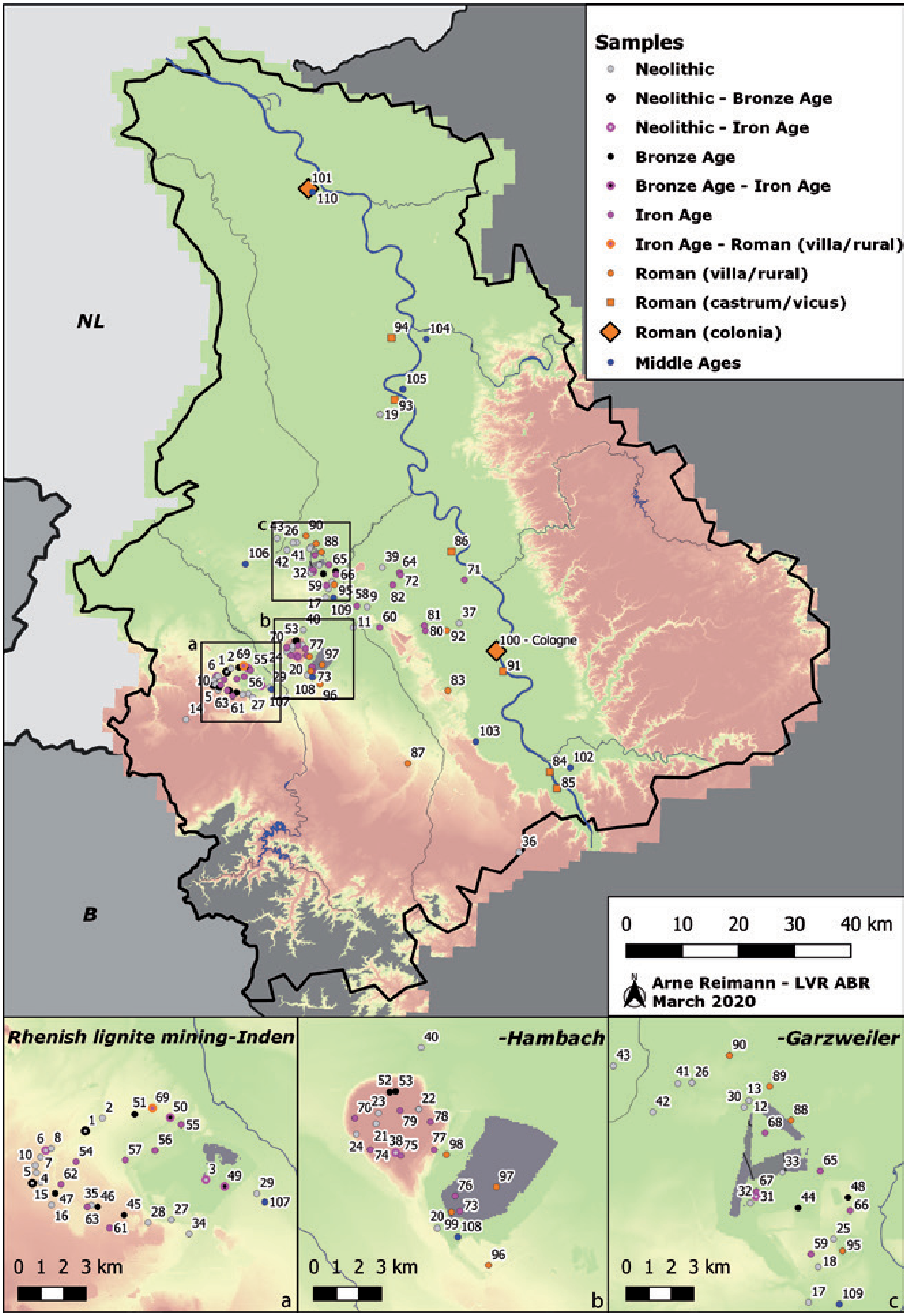

Fig. 1. Topographic map of the Rhineland, showing location of excavations that produced archaeobotanical samples. Coloured gradation from green to brown according to elevation: 0, 85, 170, and 255 m above sea level.

No.	Location	Site (abbrev.)	Phase 1	Phase 2
1	Aldenhoven	AL 1/Ald 1	Neolithic	Bronze Age
2	Aldenhoven 3	Ald 3	Neolithic	
3	Aldenhoven-Langweiler	LW 1	Neolithic	Iron Age
4	Aldenhoven-Langweiler	LW 2	Neolithic	
5	Aldenhoven-Langweiler	LW 3 & 6	Neolithic	Bronze Age
6	Aldenhoven-Langweiler	LW 8	Neolithic	Iron Age
7	Aldenhoven-Langweiler	LW 9	Neolithic	
8	Aldenhoven-Niedermerz	NM 1A	Neolithic	
9	Bedburg-Garsdorf	Gars	Neolithic	
10	Aldenhoven-Langweiler	LW 16	Neolithic	
11	Bergheim-Glesch	Glesch	Neolithic	
12	Borschemich 1 and 6	Borsch 1 & 6	Neolithic	
13	Borschemich 5	Borsch 5	Neolithic	
14	Würselen-Broichweiden	BW 1	Neolithic	
15	Eschweiler-Laurenzberg	LB 7	Neolithic	
16	Eschweiler-Laurenzberg	LB 8	Neolithic	
17	Frimmersdorf 2	FR 2	Neolithic	
18	Frimmersdorf 43	FR 43	Neolithic	
19	Gellep-Stratum, Ossumer Feld	Oss	Neolithic	
20	Hambach 11	HA 11	Neolithic	
21	Hambach 260	HA 260	Neolithic	
22	Hambach 32	HA 32	Neolithic	
23	Hambach 502	HA 502	Neolithic	
24	Hambach 8	HA 8	Neolithic	
25	Morken-Harff	Harff	Neolithic	
26	Hochneukirch 33	Hoch 33 & 28	Neolithic	
27	Inden 1	IN 1	Neolithic	
28	Inden 3	IN 3	Neolithic	
29	Inden-Pier, Güldenberg	WW 134	Neolithic	
30	Jüchen 65 B1	Jüc	Neolithic	
31	Jüchen-Garzweiler	FR 137	Neolithic	Iron Age
32	Jüchen-Garzweiler	FR 98/251	Neolithic	
33	Jüchen-Garzweiler	FR 2001/103	Neolithic	
34	Inden-Lamerdsorf	LAM	Neolithic	
35	Eschweiler-Lohn	LN 3	Neolithic	
36	Meckenheim	Meck	Neolithic	
37	Köln-Mengenich	Meng	Neolithic	
38	Niederzier-Hambach	HA 382	Neolithic	Iron Age
39	Oekoven	Oek	Neolithic	
40	Rödingen	Röd	Neolithic	
41	Wanlo	Wanlo	Neolithic	
42	Wanlo 55	Wanlo 55	Neolithic	
43	Jülich-Wickrath 118	Wick 118	Neolithic	
44	Bedburg-Königshoven	FR 48	Bronze Age	
45	Eschweiler-Lohn	WW 14	Bronze Age	
46	Eschweiler-Lohn	WW 36	Bronze Age	
47	Eschweiler-Lohn	WW 73/09	Bronze Age	
48	Grevenbroich-Gustorf	FR 52	Bronze Age	
49	Inden-Altdorf	WW 127	Bronze Age	Iron Age
50	Jülich-Bourheim	WW 111	Bronze Age	Iron Age
51	Jülich-Bourheim	WW 93/53	Bronze Age	
52	Jülich-Güsten	HA 82/457	Bronze Age	
53	Titz-Rödingen	HA 514	Bronze Age	
54	Aldenhoven-Niedermerz	NM 16	Iron Age	
55	Aldenhoven-Pattern	WW 94/169	Iron Age	
56	Aldenhoven-Pattern	WW 94/7	Iron Age	
57	Aldenhoven-Pattern	WW 88/131	Iron Age	
58	Bedburg-Königshoven	FR 3	Iron Age	
59	Bedburg-Königshoven	FR 51	Iron Age	
60	Bergheim	FR 74	Iron Age	

No.	Location	Site (abbrev.)	Phase 1	Phase 2
61	Eschweiler-Dürwiss	WW 41	Iron Age	
62	Eschweiler-Laurenzberg	WW 51	Iron Age	
63	Eschweiler-Lohn	WW 33 & 34	Iron Age	
64	Frixheim-Anstel	Frix	Iron Age	
65	Grevenbroich-Gustorf	Gust	Iron Age	
66	Jüchen-Garzweiler	FR 84/88	Iron Age	
67	Jüchen-Garzweiler	FR 2000/89	Iron Age	
68	Jüchen-Garzweiler	FR 2007/2	Iron Age	
69	Jülich-Bourheim	WW 94/376	Iron Age	Roman (*villa* / rural)
70	Jülich-Welldorf	HA 503	Iron Age	
71	Köln-Worringen Blumenberg	Blum	Iron Age	
72	Nettesheim-Butzheim	Nett	Iron Age	
73	Niederzier	HA 510	Iron Age	
74	Niederzier-Hambach	HA 490	Iron Age	
75	Niederzier-Hambach	HA 511	Iron Age	
76	Niederzier-Hambach	HA 512	Iron Age	
77	Niederzier-Steinstraß	HA 59	Iron Age	
78	Niederzier-Steinstraß	HA 407	Iron Age	
79	Niederzier-Steinstraß	HA 513	Iron Age	
80	Pulheim-Brauweiler	PR 2005/5000	Iron Age	
81	Pulheim-Sinthern	PR 2003/5002	Iron Age	
82	Rommerskirchen	Rom	Iron Age	
83	Aachen-Süsterfeldstraße	Aac	Roman (*villa* / rural)	
84	Bonn, *Legionslager*	Bo	Roman *(castrum / vicus)*	
85	Bonn, *vicus* IKBB	PR 2006/5000	Roman *(castrum / vicus)*	
86	Dormagen-Römerstraße	Do	Roman *(castrum / vicus)*	
87	Erftstadt-Friesheim	Fries	Roman (*villa* / rural)	
88	Jüchen-Belmen	FR 129	Roman (*villa* / rural)	
89	Jüchen-Kamphausen	Jü	Roman (*villa* / rural)	
90	Jüchen-Neuotzenrath	PR 1999/113	Roman (*villa* / rural)	
91	Köln-Alteburg	FB 1998.001	Roman *(castrum / vicus)*	
92	Köln-Widdersdorf	FB 1999.009	Roman (*villa* / rural)	
93	Krefeld-Gellep	Gell	Roman *(castrum / vicus)*	
94	Moers-Asberg	NI 2010/1044	Roman *(castrum / vicus)*	
95	Morken-Harff, Am Messweg	Ha/Haf	Roman (*villa* / rural)	
96	Niederzier-Hambach	HA 86	Roman (*villa* / rural)	
97	Niederzier-Hambach	HA 132	Roman (*villa* / rural)	
98	Niederzier-Hambach	HA 412	Roman (*villa* / rural)	
99	Niederzier-Steinstraß, München Busch	HA 69	Roman (*villa* / rural)	
100	*Colonia Claudia Ara Agrippinensium* (CCAA)	CCAA	Roman *(colonia)*	
101	*Colonia Ulpia Traiana* (CUT)	CUT	Roman *(colonia)*	
102	Bonn-Bechlinghoven	OV 2007/108; OV 2010/137; OV 2006/173; OV 2007/100; OV 2008/103; OV 2009/138	Middle Ages	
103	Bornheim-Walberberg	OV 2010/142; OV 2011/23	Middle Ages	
104	Duisburg Alter Markt	DUI 6017	Middle Ages	
105	Duisburg-Serm	PR 2015/5000	Middle Ages	
106	Erkelenz-Tenholter Str.	NW 2008/1084	Middle Ages	
107	Inden-Pier	WW 2011/90; WW 2011/91; WW 2014/53	Middle Ages	
108	Niederzier, Wüstweiler	HA 500	Middle Ages	
109	Kaster	Ks/Ksf	Middle Ages	
110	Xanten, Markt	NI 2009/1052	Middle Ages	

Tab. 1. Key to *Figure 1.*

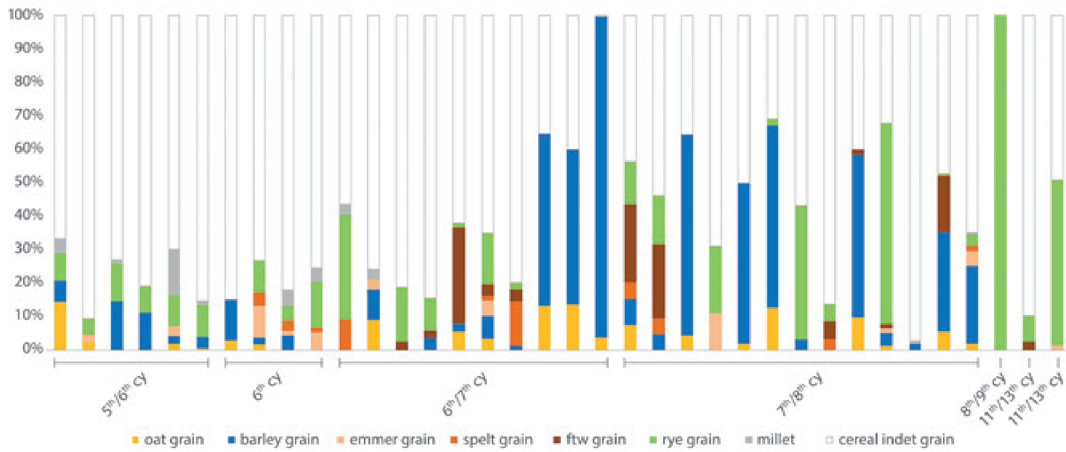

Fig. 2. Bonn-Bechlinghoven: Summary of the cereal grain composition of samples (where n $\geq$ 30 items) in chronological sequence.

Materials and Methods

Prehistoric samples of grains and associated arable weed seeds (n = 389) came from 35 Iron Age sites, eleven Bronze Age sites, and 42 Neolithic sites. The Roman samples (n = 97) came from 20 sites: twelve *villae* or farms, two *coloniae*, Xanten *(Colonia Ulpia Traiana)* and Cologne *(Colonia Claudia Ara Agrippinensium)*, and six *castra* or related *vici*. Most of the samples represent the fills of pits or postholes and include some grain-rich deposits likely to represent redeposited storage material. One set of samples, from Krefeld-Gellep, derived from a *horreum*.

The medieval samples (n = 131) came from seven settlements: one urban site, Duisburg, and six rural sites, Bornheim-Walberberg, Inden-Pier, Erkelenz-Tenholter Straße, Kaster, Niederzier, Wüstweiler, and Bonn-Bechlinghoven. Only two of these, Bonn-Bechlinghoven and Erkelenz-Tenholter Straße, produced sufficient quantities of well-preserved grains suitable for stable isotope analysis. Therefore it was possible to investigate crop rotation only for these two settlements and only in relation to their pre 10th century phases, as later samples were heavily dominated by a single cereal, primarily rye. This may reflect the fact that by the 10th century, high value bread cereals had come to predominate in the Rhineland (Hildebrandt 1988, 277; see also Zerl / Meurers-Balke 2012). We illustrate the diachronic increase in rye at Bonn-Bechlinghoven, the largest crop assemblage, in *Figure 2*. From the 10th century onwards, barley and oats too are regularly documented in larger quantities in settlements of this region (cf. Knörzer / Gerlach 1999, 109; Zerl 2019a).

The excavations at Bonn-Bechlinghoven *(Fig. 1,102)*, between 2007 and 2011, uncovered evidence for 21 farmsteads, including 47 ground-level buildings and 36 *Grubenhäuser,* dating to between the later 5th century and the end of the 9th century (*Fig. 3*; Weiler-Rahnfeld in prep.; preliminary reports i. a. Weiler-Rahnfeld 2009; Weiler-Rahnfeld 2010). A high medieval phase was also identified, although evidence from the beginning of the 10th to the beginning of the 11th century was lacking. Most of the charred plant remains derive from *Grubenhäuser*, although the most grain-rich samples came from three storage pits. None of the samples analysed appears to represent stored cereals charred *in situ*, but sample composition suggests that some if not most were comprised of redeposited stored grain, probably representing the harvests of several productive units.

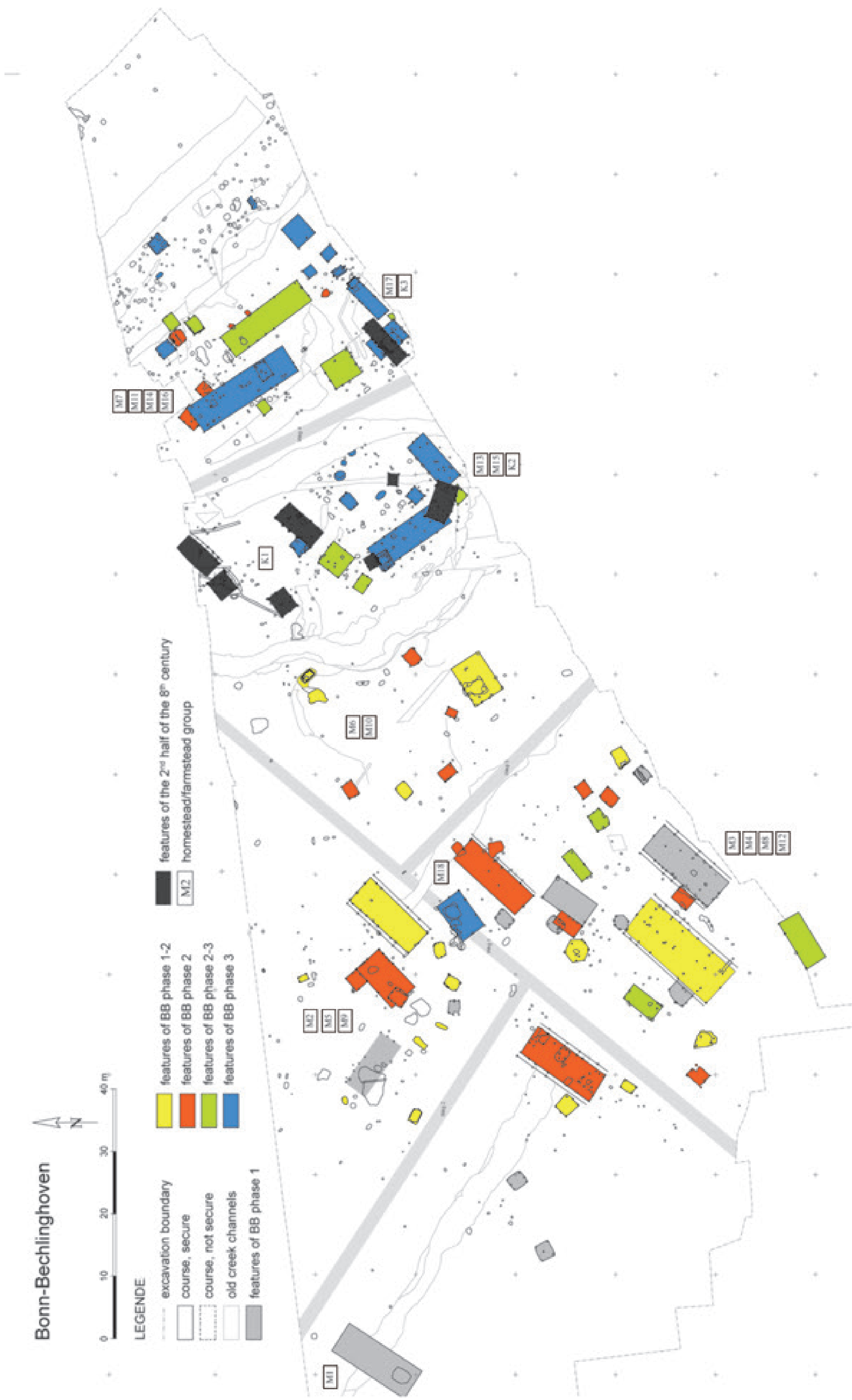

Fig. 3. Bonn-Bechlinghoven: The Merovingian and early Carolingian phases showing former watercourses and reconstructed pathways. Dating of the phases: 1 = AD 460/480–530/550; 2 = AD 530/550–640/660; 3 = AD 640/660–730/740 (after Weiler-Rahnfeld in prep. with some modifications).

The multi-period settlement at Erkelenz-Tenholter Straße *(Fig. 1,106)*, excavated in 2008, produced Iron Age, Roman and medieval settlement remains, including one of the few Carolingian rural settlements known from this part of the Rhineland (Aeissen 2009; Aeissen / Schamuhn 2011). A house, two granaries, a barn, a smithy and numerous pits were identified. Although features of 9th to 10th century date were identified, archaeobotanical remains were only recovered from 8th to 9th century features. Most samples came from postholes associated with two earth-fast timber buildings; none is from a storage context, although it is again likely that most of the samples analysed represent redeposited stored material[1].

The sites at both Erkelenz-Tenholter Straße and Bonn-Bechlinghoven are believed to represent ordinary villages, although their precise status must remain uncertain in the absence of associated written evidence. What excavated farmsteads at settlements such as these represent in terms of holdings is also unclear. There is general agreement that, apart from the great royal and monastic estates, most holdings during the 8th and 9th centuries were highly fragmented and spread across several settlements (Innes 2000, 77). The holdings of numerous different landowners might thus lie "side by side, often … all in the same village" (Zeller et al. 2020, 76).

Functional weed ecology

Two earlier studies provided the foundation for the analyses conducted here. First, a functional ecological study of weed flora developed under traditional agricultural regimes in Asturias, Spain, and Haute Provence, France, successfully differentiated between high- and low-input farming methods (Bogaard et al. 2016). The study used discriminant analysis to develop a model for differentiating fields managed with high inputs per unit area (intensive manuring and weeding) from those, like medieval open fields, receiving low inputs (low / no manuring and weeding). This was achieved on the basis of five functional traits that predict the response of weed species to soil fertility and / or disturbance due to tillage and weeding: specific leaf area (leaf area / leaf dry weight), canopy height and diameter, the ratio of leaf area per node to fresh leaf thickness, and flowering duration *(Fig. 4)*. As this model is based on functional traits rather than weed species *per se*, which may have restricted biogeographical distributions, it can be applied successfully to different climatic zones, as shown by Bogaard et al. (2016). This model is also suitable for archaeobotanical studies since it is based on the presence or absence of weed species in different farming regimes, rather than their ubiquity within individual fields.

In the second study, of modern weed flora in Germany in autumn- and spring-sown crops, functional traits relating to the timing and duration of flowering were found to predict autumn versus spring germination and hence association with different sowing seasons (Bogaard et al. 2001). In particular, weed species with early and short flowering periods are associated with autumn germination and autumn-sown crops, whereas weed species with late and / or long flowering periods are associated with spring germination and spring-sown crops. In conjunction with correspondence analysis, these relationships were used to explore crop and weed associations in medieval archaeobotanical assemblages as evidence of systematic autumn versus spring sowing of particular cereal species, as expected in rotation of autumn- and spring-sown crops.

[1] The dating of the archaeobotanical samples is based on the associated ceramic assemblages.

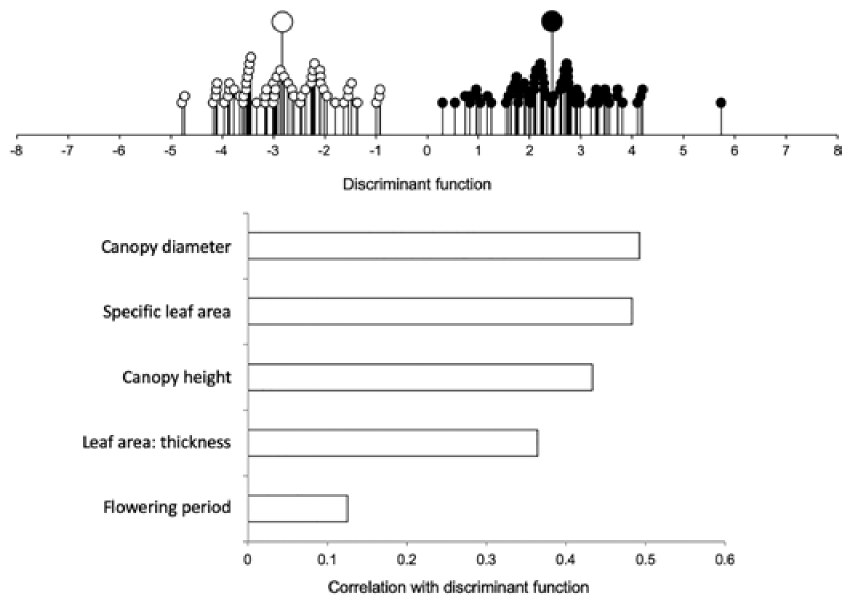

Fig. 4. Upper diagram shows the relationship of Haute Provence fields (open circles) and Asturias fields (filled circles) to the discriminant function extracted to distinguish these two groups (larger symbols indicate group centroids); the bar chart below shows correlations between the functional attribute scores used as discriminating variables and the discriminant function.

Archaeobotanical samples from the University of Cologne archive, containing at least ten seeds of potential weed taxa identified to species level, were entered into the classification phase of the discriminant analysis as unknown cases, in order to assess their similarity to the modern high- versus low-input regimes. Edible fruits and nuts that were probably collected, and other woody perennials unlikely to set seed in arable conditions, were excluded as potential arable weeds. The threshold of ten potential weed seeds is both minimal and arbitrary; higher thresholds and additional criteria for distinguishing potential weeds from other sources of wild taxa support the approach taken here (Bogaard 2004; Zerl 2019b). *Figure 1* shows the distribution of these samples across the region and chronological periods (see *Appendix*, *Table 3*, for details of sites and samples).

Stable isotope analysis

Stable carbon and nitrogen isotope analyses were conducted on 51 cereal grain samples from Bonn-Bechlinghoven (40 samples) and Erkelenz (eleven samples). Samples were selected based on the external and internal morphology which indicated that the seeds were charred at between 230 °C and 300 °C (Stroud et al. submitted). Each sample consisted of five to ten cereal grains, homogenised into a bulk sample (see *online Suppl. Mat.* doi: https://doi.org/10.11588/data/XAHRIG). The samples were pre-screened for contaminants following Vaiglova et al. (2014) using Fourier transform infrared spectroscopy with attenuated total reflectance (Agilent Technologies Cary 640 FTIR instrument with a GladiATR^{TM} accessory from PIKE technologies). No contaminants were detected, and so the samples were run without pre-treatment on a Sercon 20-22 EA-GSL isotope mass spectrometer operating in continuous flow mode at the School of Archaeology's Research Laboratory for Archaeology and the History of Art, University of Oxford. Carbon and nitrogen stable isotopic values were measured separately due to the low percentage of nitrogen in the samples. Samples were drift corrected using an internal alanine standard, while they were normalised to the AIR scale for nitrogen using IAEA-N1 and IAEA-N2; for carbon they were normalised to the VPDB scale using IAEA-CH7 and CH6. A check standard of EMA-P2 was added to all runs to aid the calculation of errors, while every tenth sample was duplicated. Following Szpak et al. (2017), the precision was calculated as ± 0.08 ‰, the accuracy ± 0.13 ‰, and standard uncertainty ± 0.15 ‰ for carbon. For nitrogen, precision was ±0.26 ‰, accuracy was ± 0.5 ‰, and standard uncertainty was ± 0.56 ‰ (see *Appendix*, *Tables 4–7*, and *online Suppl. Mat.* for full analytical conditions).

Results: Trends in extensification based on a functional ecological study of weed flora

The question of whether a trend towards extensification could be established, from relatively 'high-input' and small scale, to 'low-input' and larger scale, was addressed by comparing the discriminant scores of samples from the different chronological periods, as presented in *Figures 5–8*.

Neolithic to Iron Age

The discriminant scores of samples dating to the Neolithic and Bronze Age are shown in *Figure 5*, entered into the classification phase of the discriminant analysis *(Fig. 4)* as unknown cases. A clear contrast is apparent between the Neolithic and the Late Bronze Age samples. The Neolithic samples are concentrated between the modern 'high-input' and 'low-input' groups but include a significant proportion overlapping with the 'high-input' group; in contrast, the Late Bronze Age samples nearly all resemble 'low-input' fields. The few Early Bronze Age samples span the 'high-' to 'low-input' range. The discriminant scores of samples dating to the Early, Middle, and Late Iron Age are shown in *Figure 6*. Samples from these periods exhibit an overall trend towards increasingly 'low-input' growing conditions. A trend towards lower soil fertility and disturbance is therefore apparent all the way from the Neolithic to the Late Bronze Age and continuing through the Iron Age.

Roman to Medieval

This part of the Rhineland lay in the hinterland of the Roman *limes*. It contained not only large numbers of troops needing to be fed but also two sizeable urban populations at the *coloniae* of Xanten and Cologne (Brüggler et al. 2017; Reddé 2018). *Figure 7* shows the discriminant scores for three groups of Roman sites: *castra* and *vici*; the *coloniae;* and farms and *villae*. The samples from *castra* and *vici* continue the late prehistoric trend towards 'low-input' conditions, suggesting distinctively extensive cereal production. It thus appears likely that these communities were provisioned with cereals grown on *villae* geared to surplus production, some potentially arriving via long distance networks specifically responsible for supplying the military. In contrast, the samples from the *coloniae* (Xanten and Cologne) have much more variable scores, including new extremes at both the 'low-' and 'high-input' ends of the spectrum. The very low scores observed in a small group of samples from the *coloniae* appear to derive from a cereal production regime with markedly lower soil fertility / disturbance than even that which provisioned the *castra* and *vici*. The wide spread of scores for samples from farms and *villae* plausibly reflect a range of inten-

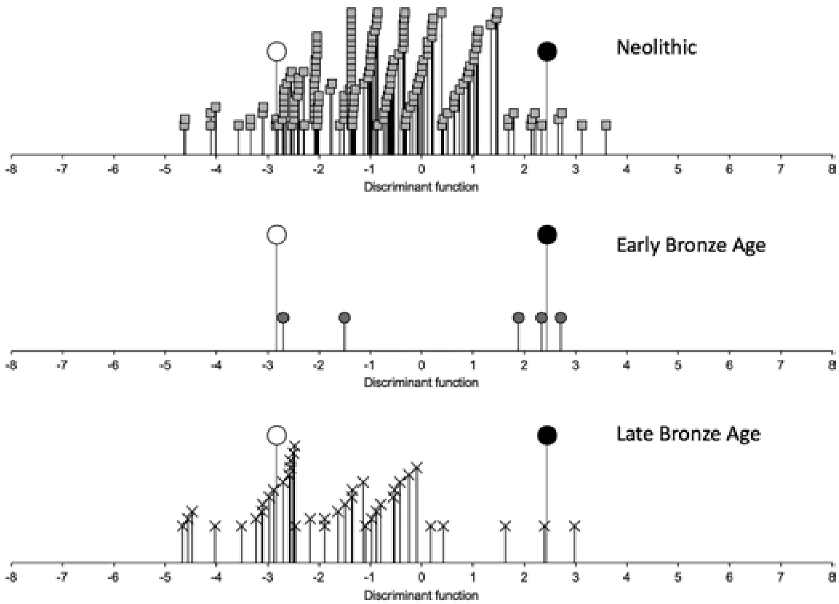

Fig. 5. Discriminant scores of Neolithic and Bronze Age weed assemblages.

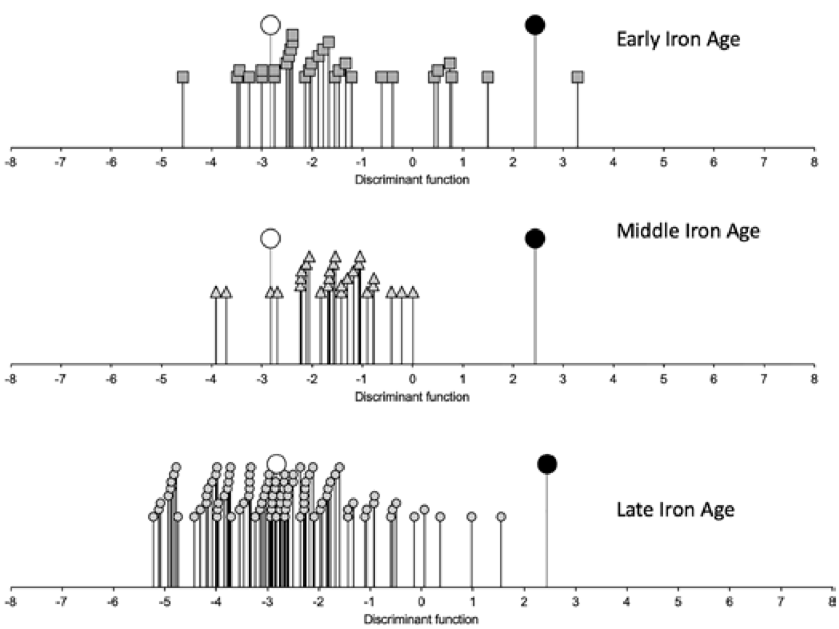

Fig. 6. Discriminant scores of Iron Age weed assemblages.

sive / infield production, perhaps signalling some cultivation of smaller holdings, as well as extensive / outfield production (cf. Reddé 2018).

Figure 8 shows the discriminant scores for the two largest medieval weed assemblages – from Bonn-Bechlinghoven and Bornheim-Walberberg – as well as for the remaining medieval sites. All three groups show a clear emphasis on 'low-input' growing conditions, thus

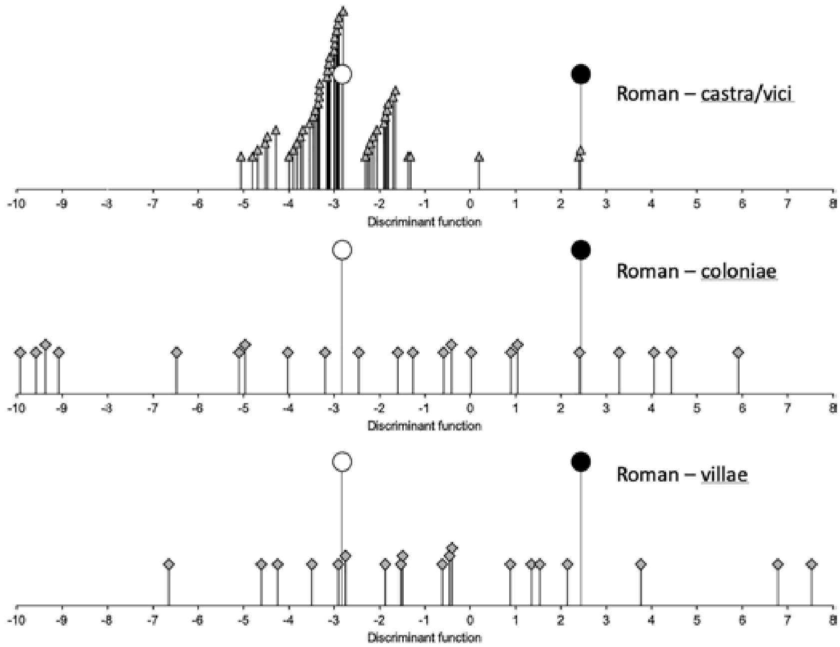

Fig. 7. Discriminant scores of Roman weed assemblages.

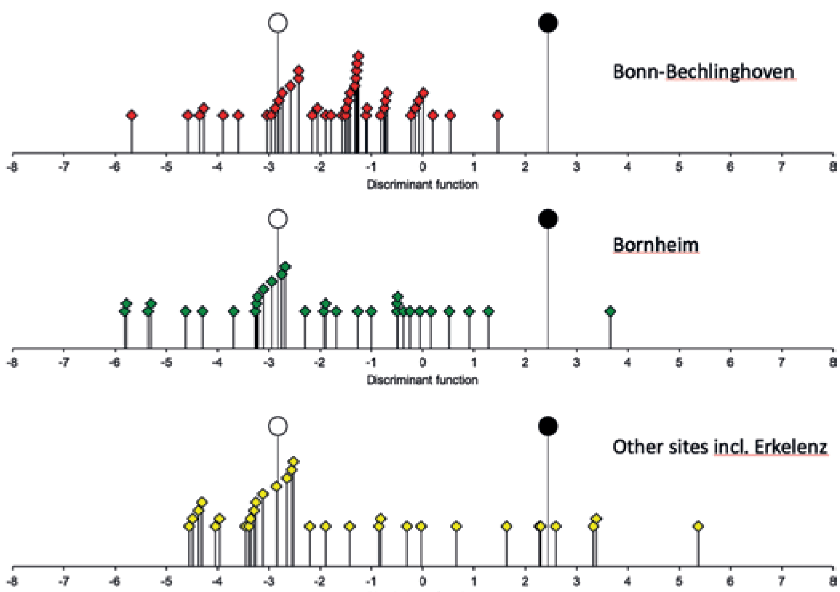

Fig. 8. Discriminant scores of medieval weed assemblages.

maintaining the general chronological trend. They broadly resemble the profile of the Late Iron Age, and without the extreme low-input focus of the Roman *castra* / *vici*. There is, however, a small 'tail' of samples straying into 'high-input' growing conditions that is reminiscent of the Roman farms and *villae*.

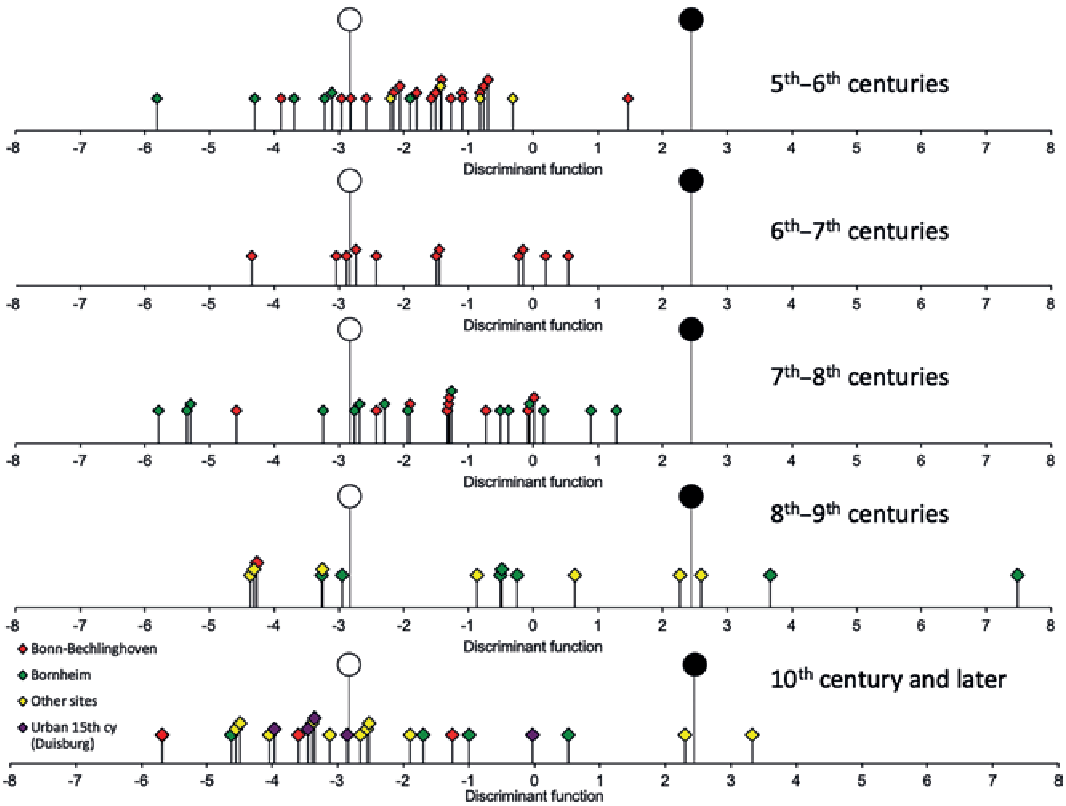

Fig. 9. Discriminant scores of medieval weed assemblages by phase.

The medieval results are broken down by phase in *Figure 9*. Adjacent phases are chronologically overlapping; perhaps for this reason, but also because of small sample numbers, it is difficult to distinguish a clear trend through the 6th to 9th centuries. Certainly, no reversion to 'prehistoric' cultivation conditions is evident in the post-Roman centuries. Comparison of the 5th/6th century samples with the 10th century and later samples does, however, reveal that the 'centre of gravity' within the predominant 'low-input' focus has shifted from relatively high scores in the 5th/6th century to lower scores in the 10th century and later samples. Thus, it is apparent that within the medieval period there was a further, subtle shift towards increasingly 'low-input' growing conditions.

To sum up, there is a broad trend towards lower input growing conditions and management throughout later prehistory, reaching an extreme in some production sectors of the Roman period, with a more subtle continuation or reiteration of this trend within the medieval period itself. In light of regional palynological data (Becker 2005; Kalis / Meurers-Balke 2007; Cheyette 2008; Brüggler et al. 2017), it is clear that the overall trend towards 'low-input' cereal growing is in fact one of spatial expansion in arable production at the expense of woodland: in other words, true extensification. The medieval two- and three-field regimes should therefore be seen as fitting within a broader, long-term trend of extensification. Other complementary approaches are needed to investigate medieval developments further, however, in particular the emergence of systematic rotation of autumn- and spring-sown crops, the topic to which we now turn.

Results: Crop Rotation

Three-field crop rotation is considered by some 'to be the most important innovation of medieval agriculture', but whether it was already practiced in the early medieval period has been much debated (Rösener 1992, 55–56; Henning 1994, 110–112; Devroey 2003, 108–111; Henning 2014, 332). To advance this debate, the crop and weed data for the settlement of Bonn-Bechlinghoven were subjected to correspondence analysis (CA) to assess crop sowing season using weed flowering time / duration categories that predict germination season; this provides information relating to crop rotation complementary to that indicated by the stable isotope data. The correspondence analysis of samples *(Fig. 10)* from all phases of occupation ($5^{th}/6^{th}$ century to 11^{th}–13^{th} centuries) reveals a close association of spring-germinating weeds (late- and long-flowering) with oat and barley, and an association of autumn-germinating weeds (early / short-flowering) with rye and, somewhat more loosely, with wheats (glume and free-threshing), suggesting two distinct sowing times[2]. Further analyses (not shown) of subsets of samples from early and later phases (i. e. $5^{th}/6^{th}$ to 7^{th} centuries, and $7^{th}/8^{th}$ century and later) confirmed that these associations of spring sowing indicators with oat and barley on the one hand, and of autumn sowing indicators with wheats and rye on the other, are apparent throughout the site's occupation. It therefore appears that sowing certain cereals in autumn and others in spring was routinely practised before a systematic rotation of autumn and spring cereals was introduced in the $7^{th}/8^{th}$ century, as indicated by the stable isotope data, discussed below. A correspondence analysis of crop and weed data from Bornheim-Walberberg (not shown) was inconclusive as regards crop sowing times since the distributions of taxa and samples predominantly reflect crop processing differences rather than the growing conditions of different crops. The Erkelenz assemblage was too small to permit correspondence analysis.

The results of the carbon isotopic analysis of material from Bonn-Bechlinghoven and Erkelenz show both similarities and differences. At Bonn-Bechlinghoven, rye (-23.5 ± 0.6 ‰), oats (-25.2 ± 0.2 ‰), and barley (-25.1 ± 0.3 ‰) have $\delta^{13}C$ values which show a separation between rye and the two other species; this was expected due to the known physiological differences between these crops (Hamerow et al. 2020). This physiological difference is also seen when the samples are plotted by phase, with barley and oat having similar values, while rye always has more positive values *(Fig. 11)*. The similar values of barley and oat are interesting as research on modern barley and oat indicates that these two species should be offset when cultivated in the same soil conditions (Hamerow et al. 2020). The Bonn-Bechlinghoven results therefore indicate that barley and oats were not cultivated in the same soil conditions during the $6^{th}/7^{th}$ century phase; it is, however, difficult to demonstrate this solely based on an analysis of carbon. Nitrogen must also be considered.

The stable nitrogen isotope values for Bonn-Bechlinghoven are moderate to high at 5.7 ± 1.2 ‰ (rye), 6.6 ± 0.3 ‰ (oat) and 7.1 ± 1.6 ‰ (barley). The higher barley $\delta^{15}N$ mean value is due to a phase-related phenomenon, with the higher values occurring in

2 Broomcorn millet is a very minor presence in the assemblage and so no conclusions can be drawn about either its status as a crop or its sowing time. Interestingly, in chapter 62 of the *Capitulare de villis vel curtis imperrii*, an estate ordinance from around AD 800 generally attributed to Charlemagne (Mischke 2013, 34–37; http://capitularia.uni-koeln.de/capit/pre814/bk-nr-032/ [last access: 28 February 2021]), millet is not mentioned among the cereals (annona) but among the root crops and garden plants (e. g. legumes [legumines]). Therefore, it can perhaps be assumed that millet was not cultivated in the cereal fields.

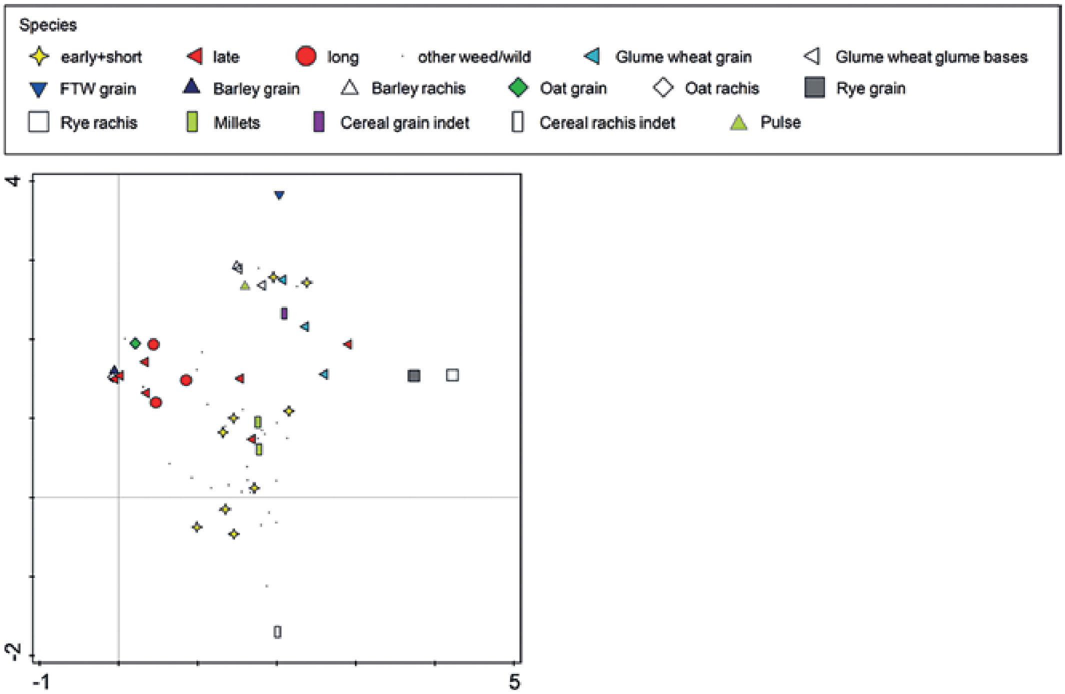

Fig. 10. Correspondence analysis of medieval weed assemblages from Bonn-Bechlinghoven. The first two axes are shown: axis 1 (horizontal) and axis 2 (vertical). Axis 1, which separates autumn- and spring-germinating weeds, accounts for 21 % of all variation in the dataset.

the $6^{th}/7^{th}$ century phase. *Figure 11*, showing the samples by phase, shows the changes in $\delta^{15}N$ values over time, with the samples from the $6^{th}/7^{th}$ century phase showing clear species-specific $\delta^{15}N$ soil enrichment. Oat, rye and barley were cultivated on soils which had different stable nitrogen isotopic ratios, with barley (7.7 ± 0.4 ‰) on more enriched soils and rye (5.1 ± 1.3 ‰) on more depleted soils. An analysis of variance indicates that rye is significantly different from barley *(Tab. 2)*. There is, furthermore, a marked shift in the following phase ($7^{th}/8^{th}$century): barley and rye now had similar values (6 ± 2.4 ‰ and 4.8 ± 0.6 ‰ respectively), a similarity which is even more marked if the single outlying barley sample is removed (4.9 ± 0.4 ‰) (*Tab. 2*, t-test insignificant). The results show a shift from species-specific cultivation conditions for rye, barley and oats – either due to naturally occurring soil differences, or through the preferential addition of manure to barley – to the cultivation of barley and rye on soils with similar ^{15}N enrichment. The explanation proposed here is the introduction of crop rotation in the $7^{th}/8^{th}$ century phase, so that barley and rye were now grown in rotation in the same fields.

Another temporal change shown in the data from Bonn-Bechlinghoven is the enrichment of rye from the moderate levels seen in the $7^{th}/8^{th}$ century phase to higher levels in the $8^{th}/9^{th}$ and 11^{th}–13^{th} centuries. The change seen in rye's $\delta^{15}N$ from the $7^{th}/8^{th}$ century to the $8^{th}/9^{th}$ century phases is statistically significant (t-test $p < 0.05$; *Tab. 2*) and suggests either an increase in the manuring of rye – which is unlikely given that the functional weed data clearly indicate a low-input regime – or an expansion of cultivation in this period onto soils enriched in ^{15}N. A ^{15}N enrichment over time has also been noted by the authors at the early medieval town of Stafford, in England, where, again thanks to functional weed data, it has been linked to the expansion of arable cultivation onto heavier, more fertile soils

Site	Phase	Species	Isotope	Test	DF	Chi, T or F value	P-value	Post hoc test		P-value
Bonn-Bechlinghoven	6–7th	All	Carbon	Kruskal-Wallis	2	Chi-squared = 14.58	**0.001**	Dunn	Oat-barley Rye-barley Rye-oat	0.098 **< 0.001** **< 0.001**
Bonn-Bechlinghoven	6–7th	All	Nitrogen	Kruskal-Wallis	2	Chi-squared = 22.78	**< 0.001**	Dunn	Oat-barley Rye-barley Rye-oat	**< 0.001** **< 0.001** 0.3
Bonn-Bechlinghoven	7–8th	All	Nitrogen	T.test	4.86	T =1.05	0.343			
Bonn-Bechlinghoven	7–8th and 8–9th	Rye	Nitrogen	T.test	3.57	T = -3.1	**0.043**			
Erkelenz-Tenholter Straße	All	All	Carbon	ANOVA	2(8)	F = 11.4	**0.005**	Tukey	Rye-oat Oat-barley Barley-rye	**0.005** **0.013** 0.948
Erkelenz-Tenholter Straße	8–9th	Oat, Rye	Nitrogen	T.test	4.11	T = -1.785	0.147			
Erkelenz-Tenholter Straße	All	All	Nitrogen	ANOVA	2(8)	F = 1.416	0.298			
Erkelenz-Tenholter Straße	8–9th	All	Nitrogen	ANOVA	2(6)	F = 2.245	0.187			

Tab. 2. The results of statistical tests on the Bonn-Bechlinghoven and Erkelenz-Tenholter Straße isotopic data. Significant p-values are shown in bold.

which were potentially seasonally waterlogged (Hamerow et al. 2020). It is not possible to compare the rye samples from Bonn-Bechlinghoven with any other species during the period examined and therefore to establish whether or not such enrichment is species-specific. The weed data do, nevertheless, suggest a general trend towards extensification when samples from the 7th/8th century phase are compared with those from later phases *(Fig. 9)*. Thus, the enrichment in ^{15}N is unlikely to be linked to manuring and could instead be linked to the expansion of rye cultivation onto heavier, naturally ^{15}N-enriched soils by the 8th/9th century phase.

The site of Erkelenz-Tenholter Straße produced samples predominantly from the 8th–9th centuries, with two samples broadly dated to between the 8th and 11th centuries. The three species isotopically examined (barley, rye, and oat) have $\delta^{13}C$ values which are slightly different to those of Bonn-Bechlinghoven, mainly due to the more positive $\delta^{13}C$ value of the barley, which is statistically significantly different from oat ($p < 0.05$) but not from rye *(Tab. 2)*. Caution needs to be applied with respect to the barley value, however, due to the low number of samples ($n = 3$), one of which is only broadly dated. The offset between rye and oat is expected because of the difference found between modern rye and oat cultivated in the same conditions; the similar value of the barley and the rye does not, however, conform to current understanding of barley's physiological offset.

The nitrogen values also present a different picture to those of Bonn-Bechlinghoven *(Fig. 12)*. The $\delta^{15}N$ is low to moderate at Erkelenz, ranging between 3.6 ‰ and 5.9 ‰. Unlike at Bonn-Bechlinghoven, the Erkelenz $\delta^{15}N$ mean values and ranges for barley (4.9 ± 0.9 ‰) and rye (4.8 ± 0.8 ‰) are very similar, while oat is slightly lower and less variable (3.4 ± 0.35 ‰). Thus, there is no statistically significant difference between the

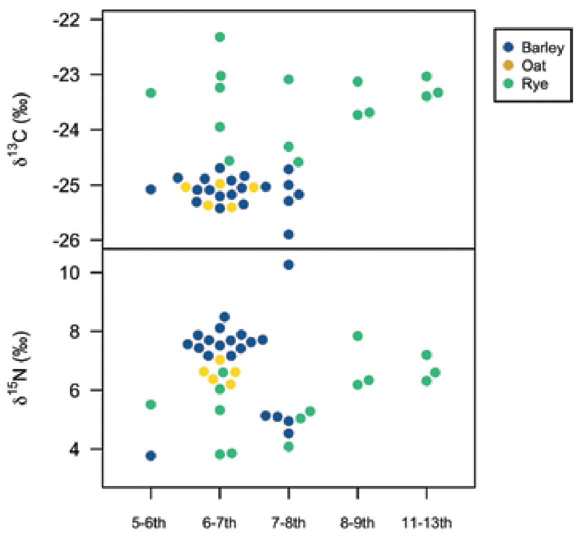

Fig. 11. The δ^{13}C and δ^{15}N values for Bonn-Bechlinghoven cereal samples by chronological phase.

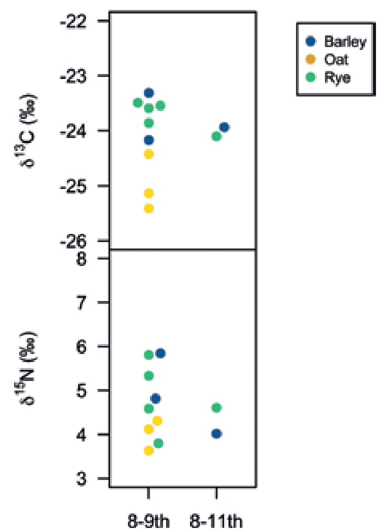

Fig. 12. The δ^{13}C and δ^{15}N values for Erkelenz cereal samples by chronological phase.

three species, regardless of whether the two broadly dated samples are included or not (*Tab. 2*). This indicates that the crops at Erkelenz were cultivated in soils which had similar but low ^{15}N enrichment, results which are consistent with crop rotation in the 8th–9th centuries.

Discussion

The fate of Roman fieldscapes in northern Gaul in the 5th and 6th centuries has been the subject of considerable debate. Some have argued for economic catastrophe and the abandonment of arable, while others emphasise broad continuities in the rural economy (Ouzoulias 1997; 2001). The faunal record is somewhat less ambiguous and appears to reflect at least some return to less specialised, more self-sufficient animal husbandry regimes after the main markets for meat declined (Hamerow 2002, 146–147; Pigière / Goffette 2019). A study of land use in the Elsbach valley, between Elfgen and Belmen (Rhein-Kreis Neuss), also in the lignite mining zone west of Cologne, suggests that "farming activities strongly decreased" in the 4th century, while the 5th and 6th centuries saw woodland regeneration and only small-scale farming (Becker 2005, 234). The 7th and 8th centuries saw some woodland clearance and expansion of cereal cultivation with settlements and their fields returning to the valley in the 9th and 10th centuries when, "due to Carolingian clearing activities and the 3-field-system, the area of arable land expanded" (Becker 2005, 235). It should be noted, however, that the Elsbachtal study is largely based on pollen data and waterlogged macrofossils, and so reflects the local, natural vegetation from one river valley, whereas the FeedSax results present a regional picture seen through the lens of crops and their associated weeds. These results preclude any significant reversion to high-input cultivation regimes as would be expected had there been a substantial reduction in the scale of arable farming in the post-Roman centuries. Instead, the weed flora from the early medieval settlements included in our study reflect a broad continuation of the primarily low-input regimes of the region's Roman farms and *villae*.

With regard to seasonal sowing, the historian Lynn White Jr. observed that there is in the written sources "no indication of … spring planting as a regular custom before documents of 765 and 771; thereafter it is frequently mentioned" (White 1940, 152 no. 1; cf. Hildebrandt 1988, 276). The documents he referred to relate to practices on large monastic and royal estates and cannot be assumed to have been widespread. The results of our analyses of weed flora indicate, however, that consistent sowing of certain cereals in spring and others in autumn was in fact already a well-established practice in this part of the Rhineland by the middle of the 8th century and was not restricted to royal and monastic lands (cf. Devroey 2003). Spring- and autumn-sowing was already practiced at Bonn-Bechlinghoven in the 5th/6th century phase of occupation and continued thereafter, with oat and barley being closely associated with late-flowering, and hence predominantly spring-germinating, weeds (such as *Fallopia convolvulus* [L.] Á. Löve, *Persicaria lapathifolia* [L.] Delarbre, and *Persicaria maculosa* Gray) and rye being associated with early-flowering and hence mostly autumn-germinating weeds (such as *Rumex acetosella* L., *Valerianella dentata* [L.] Pollich, and *Veronica hederifolia* L.); wheat occurs mostly with autumn sowing indicators but also some spring sowing indicators. That wheat should be sown in both autumn and spring is unsurprising given the frequent references to both 'winter wheat' and 'summer wheat' in Carolingian polyptychs. The polyptych relating to Saint-Maur-des-Fossés (FR), c. 869–878 AD, for example, refers explicitly to summer and winter wheat: "Each [holding] does three ploughing services for the winter-wheat, three for the second ploughing, and three for the summer-wheat" (Hägerman / Hedwig 1990, 95)[3].

As for systematic crop rotation, the polyptychs indicate that in northern Francia, two- and three-course rotation was already practiced by the 9th century (Verhulst 2002, 61–64). Verhulst regarded true, regulated three-field rotation – where most or all of the arable belonging to a village was divided into three (or more) roughly equal parts – as exceptional in this early period, however, and argued that communally managed rotation at the village level and use of the mouldboard plough did not become widespread until the 11th century at the earliest (Verhulst 1990, 22–23; see also Devroey 2003, 110). The isotopic analysis of samples from Bonn-Bechlinghoven has demonstrated that while barley, oat and rye were not grown in systematic rotation during the 6th/7th century phase, by the 7th/8th century phase, barley and rye probably were. Although the evidence from Erkelenz-Tenholter Straße was restricted to the 8th/9th century phase, the results suggest that there too, barley, oat, and rye were grown in systematic rotation. While we cannot tell whether the arable of these communities, or of individual farmers, was divided into two, three, or more parts for the purpose of rotation, our results indicate that systematic rotation was practiced in this region by the 8th century.

It is unclear from written sources whether three-course rotation originated on demesne land and whether peasants used it on their own lands (Verhulst 2002, 62–63). The archaeobotanical remains from Bonn-Bechlinghoven and Erkelenz provide direct evidence for the early practice of systematic crop rotation by farmers in what appear to be ordinary villages. The methods used here cannot, of course, tell us how the fields in which these crops were grown were laid out. The archaeobotanical evidence does, however, demonstrate that early medieval agriculture in this region did not revert to small-scale, intensive farming as imagined by Lynn White Jr. when he described peasant practices as "amazingly

[3] It is likely that the 'second ploughing' refers to the preparation of the fallow for winter sowing. The authors are indebted to Nicolas Schroeder for his help in translating this passage, as well as to the University of Leicester website, 'Carolingian Polyptyques' (https://www.le.ac.uk/hi/polyptyques/index.html).

primitive – almost Neolithic" (White 1967, 89). Instead, early medieval farming in this region represented not stagnation or decline, but rather the continuation of a long-term trend towards large-scale, low-input cereal cultivation. The results presented here further indicate that by the 8th century systematic crop rotation was practiced in at least some ordinary villages, and that it pre-dated by at least two centuries the kind of highly extensive, low-input cereal farming associated with open fields.

Supplementary Material

Supplementary Material on the stable carbon and nitrogen isotope analyses conducted on the cereal grain samples can be found online at https://doi.org/10.11588/data/XAHRIG.

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Abstract: The cerealisation of the Rhineland: Extensification, crop rotation and the medieval 'agricultural revolution' in the *longue durée*

This paper presents selected results of a research project designed to generate direct evidence for the spread of low-input cereal farming and crop rotation, key elements of the so-called 'Medieval agricultural revolution'. This type of farming greatly increased overall crop production, enriching landowners and fuelling population growth. The results presented here situate these developments within the *longue durée* of farming in the lower Rhine basin, from the Neolithic to the central Middle Ages. They also have important implications for our understanding of agricultural production during the Roman to post-Roman transition.

Zusammenfassung: Die Zerealisierung des Rheinlands: Extensifikation, Fruchtfolge und die mittelalterliche „Agrarrevolution" in der *longue durée*

In diesem Beitrag werden ausgewählte Ergebnisse eines Forschungsprojektes präsentiert, das direkte Belege für die Verbreitung des Low-Input-Getreideanbaus und der Fruchtfolge im frühmittelalterlichen Europa, Schlüsselelemente der so genannten „Agrarrevolution", liefern soll. Diese Art der Landwirtschaft führte zu einer erheblichen Steigerung der gesamten Pflanzenproduktion, wodurch die Grundbesitzer wohlhabender wurden und das Bevölkerungswachstum gefördert wurde. Die hier vorgestellten Resultate ordnen diese Entwicklungen in die *longue durée* der Landwirtschaftsgeschichte in der Niederrheinischen Bucht ein, vom Neolithikum bis zum Mittelalter. Sie haben bedeutende Auswirkungen auf unser Verständnis der landwirtschaftlichen Produktion am Übergang von der römischen zur nachrömischen Zeit, der „Extensivierung" der Agrarwirtschaft und der Einführung der Fruchtfolge.

Résumé : La céréalisation de la Rhénanie : Extensification, rotation des cultures et « révolution agricole » médiévale sur la longue durée

Cet article présente les résultats choisis d'un projet de recherche conçu pour produire des preuves directes de la diffusion des cultures céréalières à bas niveau d'intrants et de la rotation des cultures, des éléments clés de ce que l'on appelle communément la ‹révolution agricole›, dans l'Europe du Haut Moyen-Âge. Ce type d'agriculture a considérablement accru la production agricole globale, enrichissant ainsi les propriétaires terriens et accélérant la croissance démographique.

Les résultats présentés ici placent ces progrès dans la longue durée de l'agriculture dans le bassin du Rhin inférieur du néolithique au Moyen-Âge central. Ces résultats ont aussi des implications importantes pour notre compréhension de la production agricole pendant la transition romaine à post-romaine, la diffusion des systèmes agricoles à bas niveau d'intrants et l'introduction de la rotation des cultures.

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References of figures:
Figs 1–2; 4–12: authors. – *Fig. 3:* authors after Weiler-Rahnfeld in prep., fig. 11 with some modifications. – *Tabs 1–7:* authors; graphics: O. Wagner (RGK).

Appendix

Period	Site	No. samples included in analysis
Neolithic (LBK)		166
	Aldenhoven 3	1
	Aldenhoven-Langweiler 1	2
	Aldenhoven-Langweiler 2	12
	Aldenhoven-Langweiler 3 & 6	5
	Aldenhoven-Langweiler 8	47
	Aldenhoven-Langweiler 9	11
	Aldenhoven-Niedermerz 1A	1
	Bedburg-Garsdorf	6
	Bergheim-Glesch	3
	Borschemich 1 und 6	1
	Eschweiler-Laurenzberg 7	28
	Eschweiler-Laurenzberg 8	2
	Eschweiler-Lohn	1
	Frimmersdorf 43	4
	Hambach 8	1
	Hochneukirch 33	5
	Inden-Lamerdsorf	3
	Jüchen 65 B1	1
	Jülich-Wickrath 118	2
	Köln-Mengenich	1
	Meckenheim	3
	Morken-Harff	7
	Niederzier-Hambach (HA 382)	5
	Oekoven	2
	Rödingen	2
	Wanlo	8
	Würselen-Broichweiden	2
Neolithic (Grossgartach)		2
	Hambach 260	2
Neolithic (Rössen)		19
	Aldenhoven 1	3
	Aldenhoven-Langweiler 1	2
	Borschemich 5	1
	Frimmersdorf 2	1
	Gellep-Stratum, Ossumer Feld	1
	Inden 1	7
	Inden 3	1
	Inden-Pier, Güldenberg	2
	Wanlo 55	1
Neolithic (Bischheim)		5
	Hambach 502	1
	Jüchen-Garzweiler (2001/103)	1
	Jüchen-Garzweiler (FR 137)	1
	Jüchen-Garzweiler (FR 98/251)	2
Neolithic (Michelsberg)		2
	Hambach 11	1
	Hambach 32	1
Early Bronze Age		5
	Bedburg-Königshoven (FR 48)	4
	Jülich-Güsten (HA82/457)	1
Late Bronze Age		39
	Aldenhoven 1	1
	Aldenhoven-Langweiler 3 & 6	3
	Eschweiler-Lohn (WW 73/09)	1
	Eschweiler-Lohn (WW 14)	13
	Grevenbroich-Gustorf (FR 52)	1
	Inden-Altdorf (WW 127)	12
	Jülich-Bourheim (WW 93/53)	1
	Jülich-Bourheim (WW 111)	6
	Titz-Rödingen (HA514)	1
Early Iron Age		31
	Aldenhoven-Langweiler 1	1
	Aldenhoven-Langweiler 8	1
	Aldenhoven-Niedermerz (NM 16)	1
	Aldenhoven-Pattern (WW 94/7)	1
	Eschweiler-Lohn (WW 33 & 34)	2
	Frixheim-Anstel	1
	Jülich-Bourheim (WW 111)	2
	Köln-Worringen Blumenberg	5
	Nettesheim-Butzheim	1
	Niederzier-Hambach (HA 511)	2

Tab. 3. Sites and archaeobotanical samples included in the weed ecological analysis.

Period	Site	No. samples included in analysis
	Niederzier-Hambach (HA 512)	2
	Niederzier-Steinstraß (HA 513)	1
	Pulheim-Brauweiler	10
	Rommerskirchen	1
Middle Iron Age		27
	Aldenhoven-Pattern (WW 94/169)	2
	Bedburg-Königshoven (FR 3)	3
	Bedburg-Königshoven (FR 51)	1
	Bergheim (FR 74)	2
	Eschweiler-Lohn (WW 36)	1
	Eschweiler-Dürwiss	2
	Jüchen-Garzweiler (FR 84/88)	1
	Jüchen-Garzweiler (FR 137)	1
	Jülich-Bourheim (WW 111)	1
	Köln-Worringen Blumenberg	2
	Niederzier (HA 510)	1
	Niederzier-Hambach (HA 382)	1
	Niederzier-Hambach (HA 512)	1
	Niederzier-Steinstraß (HA 407)	2
	Pulheim-Sinthern	6
Late Iron Age		93
	Aldenhoven-Pattern (WW 88/131)	1
	Eschweiler-Laurenzberg (WW 51)	14
	Grevenbroich-Gustorf	8
	Jüchen-Garzweiler (FR 2000/89)	2
	Jüchen-Garzweiler (FR 2007/02)	3
	Jülich-Bourheim (WW 111)	2
	Jülich-Bourheim (WW 94/376)	2
	Jülich-Welldorf	1
	Niederzier-Hambach (HA 382)	34
	Niederzier-Hambach (HA 512)	6
	Niederzier-Hambach(HA 490)	7
	Niederzier-Steinstraß (HA 407)	1
	Niederzier-Steinstraß (HA 59)	12
Roman *(castra, vici)*		45
	Bonn, *Legionslager*	1
	Bonn, *vicus* IKBB	20
	Dormagen-Römerstraße	5
	Köln-Alteburg	8
	Krefeld-Gellep	9
	Moers-Asberg	2
Roman *(coloniae)*		28
	Colonia Claudia Ara Agrippinensium (CCAA)	9
	Colonia Ulpia Traiana (CUT)	19
Roman *(villae)*		24
	Aachen-Süsterfeldstraße	2
	Erftstadt-Friesheim	1
	Jüchen-Belmen	1
	Jüchen-Kamphausen	1
	Jüchen-Neuotzenrath	2
	Jülich-Bourheim (WW 94/376)	3
	Köln-Widdersdorf	4
	Morken-Harff, Am Messweg	1
	Niederzier-Hambach (HA 132)	1
	Niederzier-Hambach (HA 86)	1
	Niederzier-Hambach (HA 412)	6
	Niederzier-Steinstraß, München Busch	1
Medieval		131
	Bonn-Bechlinghoven	43
	Bornheim-Walberberg	56
	Duisburg Alter Markt	5
	Erkelenz-Tenholter Str.	8
	Inden-Pier	3
	Kaster	12
	Niederzier, Wüstweiler	4

Tab. 3. cont.

Analytical conditions:

Nitrogen and carbon elemental and isotopic compositions were determined using a Sercon 20-22 EA-GSL isotope mass spectrometer operating in continuous flow mode at the School of Archaeology's Research laboratory for Archaeology and the History of Art, at the University of Oxford. Stable carbon and nitrogen isotope compositions were calibrated relative to VPDB ($\delta^{13}C$) and AIR ($\delta^{15}N$) using IAEA-N1 and IAEA-N2 for nitrogen and IAEA-CH6 and IAEA -CH7 for carbon. Check standards of an internal alanine standard ($\delta^{15}N$ -1.56 ± 0.27 ‰ and $\delta^{13}C$ -27.11 ± 0.03 ‰) and EMA-P2 ($\delta^{15}N$ -1.57 ± 0.14 ‰ and $\delta^{13}C$ -28.19 ± 0.14 ‰) were used to determine analytical uncertainty as per Szpak et al. (2017; *Tab. 4* and *Tab. 5*). Every tenth sample was duplicated to help understand measurement precision (*Tab. 6* and *Tab. 7*; Szpak et al. 2017).

Standard	**Number**	**Session**	**$\delta^{15}N$ mean**	**$\delta^{15}N$ SD**
N1	5	190322	0.40	0.34
N2	6	190322	20.30	0.32
P2	5	190322	-1.12	0.06
ALANINE	12	190322	-1.20	0.2
N1	2	181126	0.40	0.03
N2	3	181126	20.30	0.1
P2	4	181126	-1.63	0.06
ALANINE	8	181126	-1.57	0.1
N1	4	180628	0.40	0.4
N2	4	180628	20.30	0.1
P2	4	180628	-0.77	0.24
ALANINE	8	180628	-1.49	0.34
N1	4	190405	0.40	0.36
N2	3	190405	20.30	0.4
P2	3	190405	-0.9	0.17
ALANINE	5	190405	-1.21	0.15

Tab. 4. The mean and standard deviation of the calibration standards and check standards from all nitrogen analytical sessions that contain data presented in this paper.

Standard	**Number**	**Session**	**$\delta^{13}C$ mean**	**$\delta^{13}C$ SD**
CH6	4	190308	-10.45	0.11
CH7	4	190308	-32.15	0.07
P2	4	190308	-28.27	0.11
ALANINE	8	190308	-27.14	0.03
CH6	4	180802a	-10.45	0.09
CH7	4	180802a	-32.15	0.04
P2	4	180802a	-28.35	0.04
ALANINE	8	180802a	-27.15	0.04
CH6	4	181119	-10.45	0.08
CH7	2	181119	-32.15	0.03
P2	4	181119	-28.26	0.08
ALANINE	8	181119	-27.14	0.07

Tab. 5. The mean and standard deviation of the calibration standards and check standards from all carbon analytical sessions that contain data presented in this paper.

ID	Session	$\delta^{13}C$ A	$\delta^{13}C$ B
RC2018	190308	-26.01	-26.14
WHXX3D	190308	-25.02	-25.02
BBV022	180802a	-25.48	-25.37
BBV051	180802a	-24.78	-24.9
BBV099	181119	-25.92	-25.89
BBV105	181119	-24.83	-24.86

Tab. 6. The $\delta^{13}C$ values of the duplicated samples within the analytical sessions from which the data in this paper derives from.

ID	Session	$\delta^{15}N$ A	$\delta^{15}N$ B
YAR010	190322	8.14	8.07
YAR020	190322	8.61	8.64
OAT230	190322	3.58	3.6
BAR0BD	190322	1.03	0.97
BBV099	181126	5.11	5.16
BBV105	181126	8.5	8.47
BBV022	180628	7.56	7.56
BBV029	180628	7.41	7.51
BBV051	180628	8.26	8.16
YAR004	190405	4.64	4.59
RC2018	190405	3.48	3.79

Tab. 7. The $\delta^{15}N$ values of the duplicated samples within the analytical sessions from which the data in this paper derives from.