Farming during turbulent times: Agriculture, food crops, and manuring practices in Bronze Age to Viking Age Denmark

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Archaeobotanical and stable isotope analysis on plant remains from 39 sites spanning the Bronze, Iron, and Viking Ages in Denmark has been undertaken in order to investigate the development and resilience of agricultural practices, particularly through the 1250-year-long Iron Age (500 BC – AD 750). During this time, an increase in the spectrum of food resources can be seen in the archaeobotanical material. At the same time, soil enrichment of fields of barley, which increased markedly during the Bronze - Iron Age transition, remains consistent until the Viking Age. A more broad-spectrum diet appears to tie in with agricultural extensification comprising increased scales of land use and fallowing alongside possibly less intense tillage of fields. These practices appear to have made agriculture resilient to climatic fluctuations during our study period, with the possible exception of a shift following volcanic eruptions in AD 536/540.

Keywords: Iron Age, Viking Age, stable isotopes, manuring practices, archaeobotany, ancient agriculture

Highlights:

- Charred plant remains show an increase in food resources in Iron Age Denmark

- Stable isotopes show consistent soil enrichment in fields of barley
- Agriculture seems resilient to climatic fluctuations during the Iron Age

1. Introduction

The Iron Age in Denmark (500 BC – AD 750, Table 1) saw a number of significant economic, technological, societal, and climatic changes, some causing major upheaval in the fabric of contemporary communities, others laying the foundation for the modern nation state. Changes during this time included a reshuffling of power dynamics and the loss of trading and cultural contacts following the decline of the Roman Empire, as well as major population migrations on the back of global climatic deterioration following major volcanic eruptions in AD 536/540 and the onset of the Late Antique Little Ice Age.

Settlement patterns during the earlier part of the Iron Age take the shape of gradually larger, nucleated communities, some with evidence towards a hierarchical social organisation, though fencing around individual farmsteads indicates that some areas of production may still have been kept at household level (Hansen 2019, Holst 2010, Näsman 2009, Rindel 1999). Some settlements spanning centuries of habitation can be seen to have shifted location regularly within their own catchment area, presumably to turn land enriched by human or animal waste over to agricultural use. The early Iron Age sees high frequencies of sheep/goat and cattle, with geographical differences in the distribution of animals, such as certain areas (Lolland and northern Jutland) favouring sheep/goats, whereas pigs and cattle are more common in middle and eastern Denmark (Kveiborg 2008:66, Martens 2020:54-55; Klingenberg *et al.* 2017:126). During the later Roman Iron Age, the economic strategy appears to have centered more on cattle, coupled with an increase in stable size, a tendency lasting well into the Germanic Iron Age (Ethelberg 2012, Fabech and Ringtved, 2009:171, Macheridis 2022:81-84, Strömberg and Carlie 2019:131). Recent studies of animal husbandry suggest a continued focus on cattle farming from the Late Iron Age into the Viking Period but accompanied with a marked increase in pigs as an important livestock species (Macheridis 2022: 75ff.)

In later Iron and Viking Age Denmark, a process towards secondary state formation took place, following the gradual centralisation of previously autonomous chiefdoms, and reflected in the appearance of increasingly urbanised settlements and the construction of large-scale fortifications by supra-household institutions in the late 900s. The Iron Age also witnessed technological innovations and changes such as the introduction of the mould-board plough from around AD 200 and the consequent abandonment of the Celtic field system sometime during the Roman Iron Age (Larsen 2015, Rasmussen *et al*. 2015).

Archaeological periods	**Year**
Nordic Early Bronze Age	1700 – 1200 BC
Nordic Late Bronze Age (BA)	1200 – 500 BC
Pre-Roman Iron Age (PRIA)	500 – 1 BC
Early Roman Iron Age (ERIA)	1 BC – AD 150
Late Roman Iron Age (LRIA)	AD 150 – 350
Early Germanic Iron Age (EGIA)	AD 350 – 550
Late Germanic Iron Age (LGIA)	AD 550 – 750
Viking Age (VIK)	AD 750 – 1050

Table 1. Chronology covered in this paper.

Climatic data shows that towards the end of the relatively mild and stable Bronze Age, the weather systems over the northern hemisphere changed to a colder and rainier climate (eg. van Geel *et al*. 2004, Groenman-van Waateringe and van Geel 2017). This event occurred around 800 BC and is generally known as the 2.8K event (van Geel *et al*. 1996). In Denmark the 2.8K event caused major lake level changes and a rising groundwater table "flooding" low-lying areas, forcing people to abandon affected fields and settlements (Christensen and Mortensen 2011, Beck 2018, Mortensen *et al*. 2019). In the same period the sandy areas in western and northern Jutland were heavily affected by increased storm activity and aeolian sand covering vast areas including farmland (Clemmesen *et al*. 2001, Goslin *et al*. 2018, Mortensen *et al*. 2019).

With the Roman warm period (*c*. 250 BC – AD 400), aeolian sand activity seems to cease and a period of a more stable and warmer climate began (Mortensen *et al*. 2019). This relatively mild period dominated the next centuries but came to a very abrupt end in AD 536, when the first of several volcanic eruptions covered the earth in a dust veil blocking out sunlight. This event caused the global temperature to drop between 1.4 °C and 2.7 °C and had a significant impact on the environment all over the Northern hemisphere (Sigl *et al*. 2015, Helama *et al*. 2019, Dull *et al*. 2019), with regional reconstructions from Southern Scandinavia showing a temperature drop of 3.5 °C (van Dijk *et al*. 2022). It also affected plant growing conditions in Denmark and is clearly reflected in Danish dendrochronological data (Larsen *et al*. under review). The colder climate lasted until AD 660 and the period between AD 536 and AD 660 has been named the Late Antique Little Ice Age (Büntgen *et al*. 2016). After AD 660 the climate gradually improved with a relatively warm period until the onset of the Little Ice Age in the 13th century.

Agriculture formed the underlying economy throughout this periodically turbulent time. In this paper, we study the archaeobotanical remains from 39 archaeological sites in Denmark dating from the Bronze Age to the Viking Age, in order to investigate whether any of the wider socio-economic and climatic developments may have affected agricultural practices. In particular, we explore the introduction and persistence of major crops, and the proliferation of wild taxa, and determine the stable carbon and nitrogen isotope values of barley grains to ascertain whether any changes in agricultural practices can be detected over time. Stable carbon isotope ($\delta^{13}C$) values of plants are affected by stomatal conductance that is influenced by water availability (e.g., Farquhar *et al*. 1989, Ferrio *et al*. 2005), and photosynthetic activity, which can be impacted by light levels (van der Merwe & Medina 1991). Lower plant $\delta^{13}C$ values can therefore result from higher levels of precipitation, deliberate watering and/or growth in soils with better water retention and can also be associated with growing in lower light levels. Nitrogen isotope ($\delta^{15}N$) values of plants reflect the $\delta^{15}N$ value of the soil, which itself reflects the $\delta^{15}N$ value of any soil amendments and the effect of nitrogen cycling processes (Högberg 1997). Higher plant $\delta^{15}N$ values can therefore result from the addition of manure/compost that is enriched in ^{15}N (Bogaard *et al*. 2013), recent forest clearance by burning (Szpak 2014), aridity (Craine *et al*. 2009), and/or seasonal waterlogging of soils (Finlay & Kendall 2008). Isotopic analysis of archaeobotanical remains can therefore provide insights into past cultivation practices, including the intensity of manure application and watering regimes (Bogaard *et al*. 2013, Wallace *et al*. 2015).

2. *Materials and methods*

2.1. Archaeobotanical analysis

The archaeobotanical assemblage, which forms the basis of the present study, comprises finds of charred plant remains spanning the Early Bronze Age to the Viking Age, with the primary focus on sites dating to the Iron Age. The selection of sites was based on their richness in plant remains, enabling both an archaeobotanical assessment as well as the opportunity to sample cereal grains for successful stable isotope analysis and AMS dating, respectively. A total of 477 samples from 39 sites are presented here, primarily from settlements (single buildings or groups of farmsteads), and from contexts including post holes, pits, pots, cellars, furnaces, and occupation layers.

The charred plant remains were retrieved by manual or machine flotation, except in the cases of very large concentrations of grains from storage contexts where flotation was unnecessary. Samples were analysed at the National Museum of Denmark or Moesgaard Museum, using stereomicroscopes and available modern seed reference collections. The dataset was accessed through the National Museum/Moesgaard Museum combined archaeobotanical database, with added published reports from, especially, older excavations.

The dataset is compiled from analyses carried out within research and rescue archaeology projects throughout Denmark over the past 90 years, until 2020. The level of sample analysis in the dataset varies from (in a few, older cases) preliminary scans of sample content to in-depth analysis, and methods of quantification vary between exact numbers of individual items, groupings of abundance (e.g. “1–100 items”), and more qualitative descriptions (e.g. “few” or “many”). The sites and samples are not, therefore, directly quantitatively comparable. What we present below is a “broad-stroke” overview of the arrival and relative importance of individual plant food species throughout the Iron Age. Two Bronze Age and three Viking Age sites have been included for comparative reasons.

2.2. Isotope analysis

The carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope values of 235 individual (single) charred naked/hulled barley grains from 75 different contexts were determined (Supplementary Table 1). Isotope values were determined on three grains from most contexts, with some contexts represented by up to eight isotopic measurements and some by only one. The individual grain identification codes (IDs) comprise the context ID followed by the randomised grain number (1–10). The contexts include post holes, pits, pots, furnaces, and occupation layers from 39 archaeological sites dated to between the Early Bronze Age and Viking Age (1500 BC – AD 1050). Barley grains from 70 contexts are directly associated with radiocarbon-dated cereal grains, either from the same primary deposit of cereal grains or the same archaeological context. Radiocarbon ages were calibrated using OxCal 4.4, IntCal 20 (Reimer *et al*. 2020; Supplementary Table 2) and are displayed in figures as the median age.

All grains were photographed in dorsal, lateral and ventral views (these images will be deposited in Oxford Research Archive once publication is accepted and a doi will be provided here) then cross-sectioned at right angles to the ventral groove and photographed to assess whether they were likely to have been charred at temperatures and for time durations that are compatible with previous experimental work on the effect of charring on the isotope values of modern grains (Charles *et al*. 2015; Stroud *et al*. 2023). Only grains that resemble modern experimentally charred grains heated between 230 and 260°C (see Stroud *et al*. 2023:

Fig. 5) were selected for isotopic analysis. Cereal grains were measured in three dimensions (X and Y from dorsal view; Z from lateral view; Supplementary Figure 1). Following the regression equations given in Ferrio *et al*. (2004: Fig. 1), estimated pre-charring grain weight was calculated for length versus breadth (X vs Y; Supplementary Table 3; Ferrio *et al*. 2004) and length versus thickness (X vs Z; Supplementary Table 3).

Forty-one grains, at least one from each archaeological site, were scraped clean with a scalpel, crushed, and analysed using Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) to look for the presence of carbonate, nitrate and/or humic contamination (Vaiglova *et al*. 2014). Sediment removed from four grains was also analysed. No evidence for contamination was observed (Supplementary Datasheet) and so the remaining grains were scraped clean with a scalpel before being crushed using an agate mortar and pestle.

The homogenised powders of the barley grains were weighed into tin capsules for isotopic analysis on a Sercon 20–22 isotope ratio mass spectrometer coupled to a Sercon GSL elemental analyser at the Research Laboratory for Archaeology and the History of Art, University of Oxford, UK. Three-point normalisation of $\delta^{13}C$ determinations to the Vienna Peedee Belemnite scale (VPDB) and $\delta^{15}N$ determinations to atmospheric AIR was carried out using the internal laboratory reference materials alanine (DL-Alanine, $\delta^{13}C$ = −27.11 ± 0.12‰; $\delta^{15}N$ = −1.56 ± 0.20‰; Sigma Aldrich), seal bone collagen ($\delta^{13}C$ = −12.60 ± 0.29‰; $\delta^{15}N$ = 16.30 ± 0.20‰) and cow bone collagen ($\delta^{13}C$ = −24.28 ± 0.13‰; $\delta^{15}N$ = 7.76 ± 0.27‰). Measurement uncertainty was monitored using two reference materials: P2 ($\delta^{13}C$ = −28.19 ± 0.14‰; $\delta^{15}N$ = −1.57 ± 0.19‰; Elemental Microanalysis) and leucine ($\delta^{13}C$ = −28.23 ± 0.07‰; $\delta^{15}N$ = 6.35 ± 0.14‰; internal reference material from Sigma Aldrich). The accuracy ($u(bias)$) of the carbon runs was ± 0.27‰, while the precision (u (R_w)) was ± 0.10‰. Total analytical uncertainty for $\delta^{13}C$ values was ± 0.29‰. For nitrogen runs the accuracy was ±0.38‰, while precision was ±0.25‰ and overall analytical uncertainty for $\delta^{15}N$ values was ±0.45‰. Statistical analyses were performed in R version 4.2.2. We apply no correction to the grain isotope values to account for the effect of charring (see Nitsch *et al.* 2015), to allow comparison with the isotope values determined in other studies. The small offset between the $\delta^{13}C$ and $\delta^{15}N$ values of charred and uncharred cereal grains (0.1 and 0.3 ‰, respectively) is unlikely to have a significant impact on interpretations. Raw and normalised isotope data of samples and reference materials are in Supplementary Table 1. The R script for calculating accuracy and precision using data in Supplementary Table 1 is in https://github.com/AmyStyring/IronAgeDenmark-project.git. Statistical analyses were performed in R v.4.2.2 and the R script used is in https://github.com/AmyStyring/IronAgeDenmark-project.git.

3. *Results*

Figure 1 presents the location of the 39 sites discussed here, while Figure 2 shows the chronological range of the sites, based on calibrated AMS ^{14}C dates.

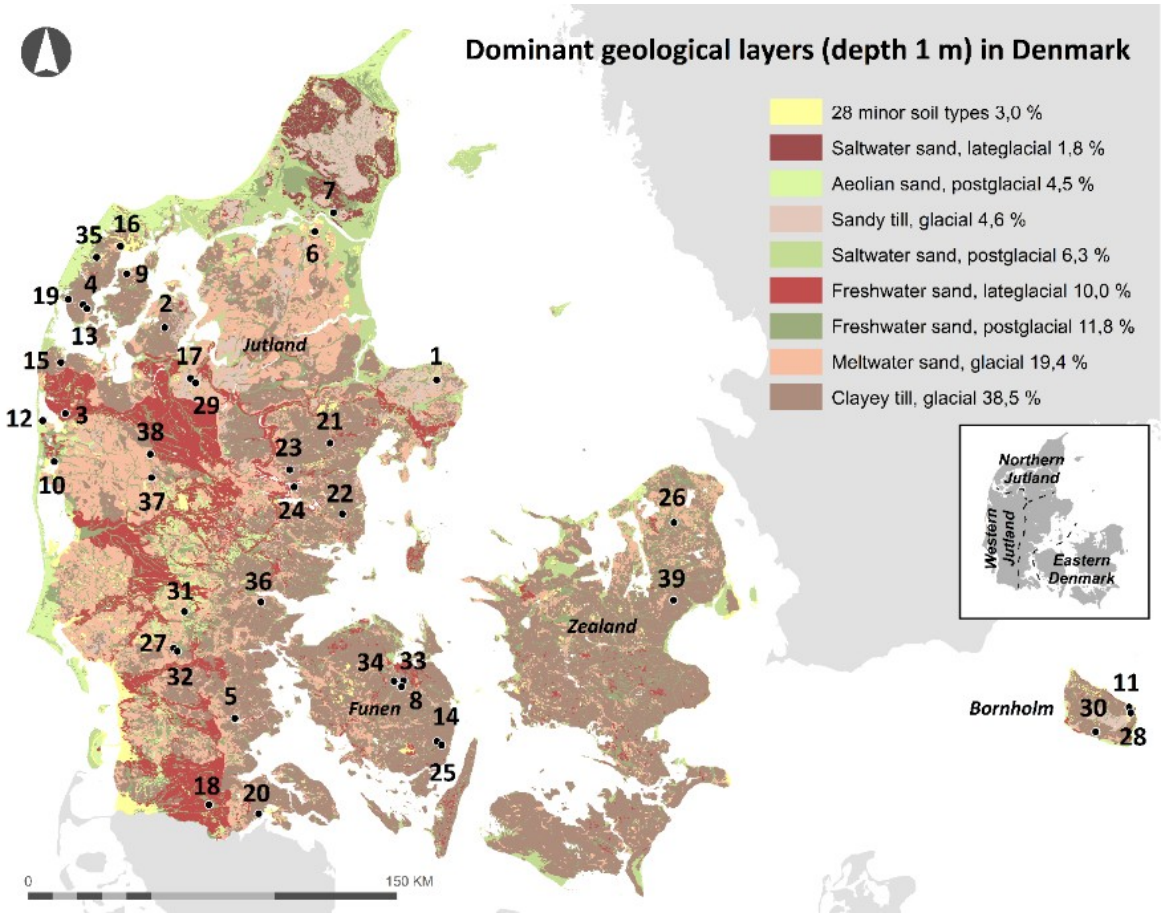

Figure 1. *Map of Denmark showing dominant geological layers (depth 1 m) and the location of the analysed archaeological sites. Site numbers refer to Fig. 2. Geological map after Pedersen et al. 2011.*

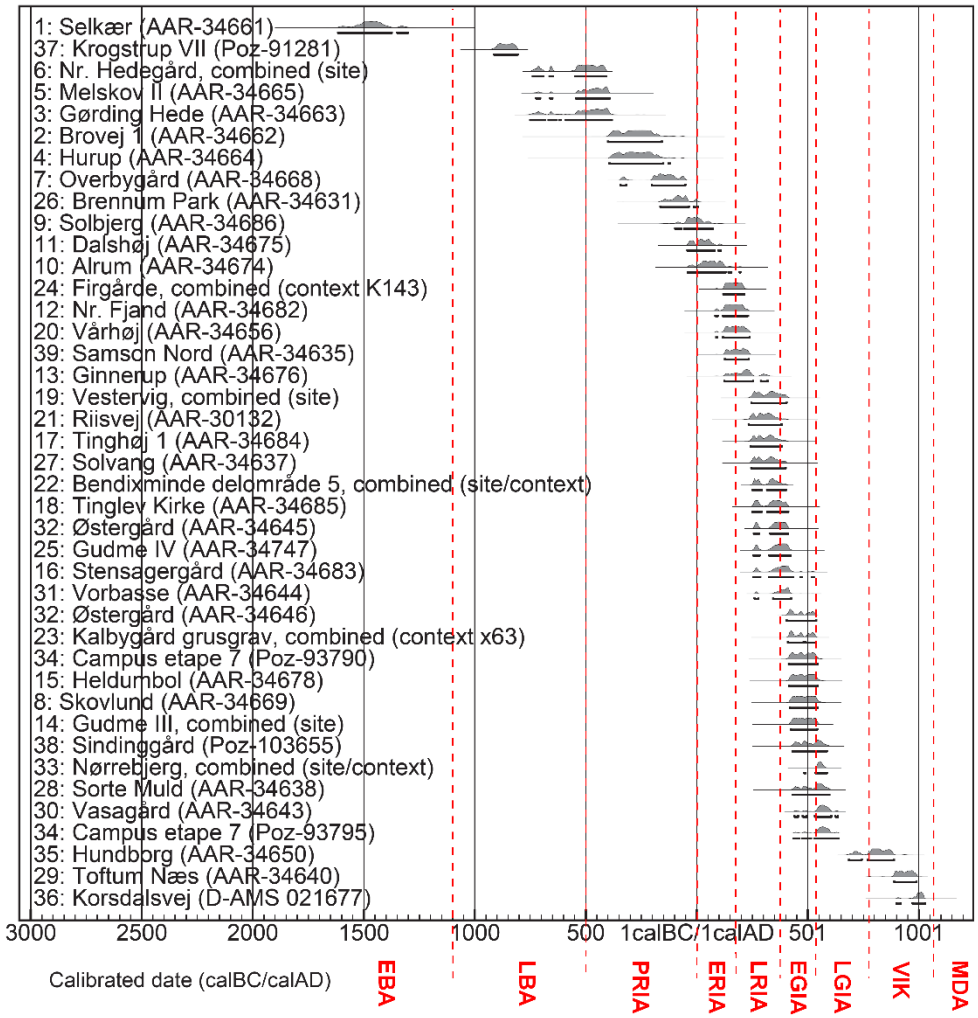

Figure 2. *Archaeological sites discussed in this paper listed in chronological order based on the AMS dates from the archaeobotanical samples (Supplementary Table 2; Reimer et al. 2020, Bronk Ramsey 2009). Site numbers refer to location on Figure 1. For some sites, dates were combined using the function 'R_Combine' in OxCal 4.4. In chronological order the combined ^{14}C dates are as follows: 6) Nr. Hedegård: AAR-34667, AAR-34666; 24) Firgårde: AAR-28238, AAR-28239, AAR-28240; 19) Vestervig: AAR-34657, AAR-34658, AAR-34659; 22) Bendixminde delområde 5: AAR-27892, AAR-27888, AAR-27887; 23) Kalbygård grusgrav: AAR-26393, AAR-26394; 14) Gudme III: AAR-34632, AAR-34677; 33) Nørrebjerg: Poz-98623, Poz-98625, Poz-98626, Poz-98532, Poz-98430, Poz-101299, Poz-101298. Two sites, Østergård and Campus etape 7, cover two distinct periods and are therefore listed twice.*

As seen in Figure 1, the geographical spread of sites is skewed towards the west, with the majority of sites situated in Jutland, a sprinkle of sites across Funen, and a few sites only in northern Zealand, and on the island of Bornholm. The Jutland peninsula is therefore the region best represented archaeobotanically. From a geological perspective, however, the assemblage of sites is divided relatively equally along the main stationary line of the Weichselian glaciation, separating Western Jutland from the rest of Denmark. The chronological span of the sites presented in Figure 2 shows that most of the sites are situated within a 600-year-span, that is, the Early and Late Roman and Early Germanic Iron Age.

3.1. Food plants

Bronze-to-Viking Age food plants are presented below within discrete chronological groups. Where observations are based on published studies, these have been cited, while the remaining finds derive from our unpublished database of archaeobotanical finds. While we consider the dataset to be generally representative for the presence of the major food plants, minor plants such as millet, pea, and flax may well have been more consistently present than we see here.

Five Bronze Age sites are included in the assemblage. A significant amount of emmer wheat (*Triticum diccoccum*) chaff was recorded at EBA Selkær (no. 1 on Figs. 1 and 2) along with smaller amounts of bread wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) chaff. Barley grains are mainly of the naked variety (*Hordeum vulgare* var. *nudum*), as they are at LBA Krogstrup (no. 37), Nørre Hedegård (6), Melskov II (5), and Gørding Hede (3).

The Pre-Roman Iron Age sites Brovej 1 (2), Hurup (4), Overbygård (7), and Brennum Park (26) generally show a predominance of naked barley, with smaller amounts of bread wheat, and at Solbjerg (9) smaller amounts of hulled barley (*H. vulgare* var. *vulgare*) were also found, along with a few grains of oats (*Avena sativa*) (Robinson 1993).

Early Roman Iron Age Dalshøj (11) is the earliest site in the assemblage where hulled barley outnumbers the naked variety, and it is also significant in the substantial presence of oats, described as both wild and cultivated. There are plenty of emmer wheat grains and a few seeds of millet (*Setaria* spp.) as well as flax (*Linum usitatissimum*), gold-of-pleasure (*Camelina sativa*), and rye (*Secale cereale*), which all make their first appearance in the assemblage here (Helbæk 1957, Henriksen 1992). Plant remains from contemporary Alrum (10) include barley, oats, and bread/club wheat (Helbæk 1954).

The Late Roman Iron Age is represented by 14 sites. At Firgårde (24), significant amounts of chaff from rye were observed from iron smelting installations, and at Nørre Fjand (12), concentrations of barley and oats along with smaller amounts of rye were observed (Henriksen 1992). Vårhøj (20) contains predominantly hulled barley, but also a few seeds of raspberry (*Rubus idaeus*) and elder (*Sambucus* sp.). Also at Vårhøj, two seeds of oregano, *Origanum vulgare*, have been identified. At Samson Nord (39), seeds of gold-of-pleasure are present, accompanied by barley and flax. From Ginnerup (13) large amounts of both naked and hulled barley were observed along with a smaller concentration of oats, as well as two flax seeds. At Vestervig (19), hulled barley predominates in samples from a burned-down building, with a few oats consistently in the samples as well. At Riisvej (21), hulled barley and oats have been observed (Jensen and Thastrup 2020:96-99). At Tinghøj (17), a concentration of hulled barley was found in a pit together with a smaller concentration of pale persicaria (*Persicaria lapathifolia*), which was also found in substantial numbers in another pit on the site, along with a concentration of gold-of-pleasure. From Solvang (27), large concentrations of indeterminate barley were found in a cellar, while an even larger concentration of naked barley was found within a house. Bendixminde 5 (22) (Jensen and Thastrup 2020:89-96), Tinglev Kirke (18), and Østergård (32) are characterized by predominantly hulled barley remains, though from Tinglev Kirke we also see the consistent presence of oats. Gudme IV (25) is characterized by barley with smaller amounts of emmer wheat, and a few seeds of flax and gold-of-pleasure (Henriksen 2015).

In the Germanic Iron Age, at Vorbasse (31) roughly equal amounts of hulled barley and rye are present. Samples from Kalbygård grusgrav (23) contain a mixture of hulled barley, gold-of-pleasure, flax, and some oats. At Heldumbol (15), Gudme III (14) and Skovlund (8), hulled barley dominates the crop assemblage. Crops at Nørrebjerg (33) are represented by rye and bread wheat, though hulled barley and gold-of-pleasure are also consistently present in the samples. Sindinggård (38) presents a mixture of rye and hulled barley, while at Sorte Muld (28), the predominant crop is oats followed by hulled barley, and smaller amounts of millet (*Setaria italica*). Unspecified barley was noted from Stensagergård (16) (Robinson and Boldsen 1989).

In the early Late Germanic Iron Age, at Vasagård (30), a cache of indeterminate barley grains was found, and emmer wheat is also consistently present. Campus etape 7 (34) is characterised by the presence of hulled barley, gold-of-pleasure, and bread wheat. The two sites are followed by a hiatus for the remainder of the Late Germanic Iron Age, most likely the effect of the 536/540 volcanic eruptions discussed in section 4.4.

The three Viking Age samples in the assemblage follow the pattern of a generally broader crop spectrum. At Hundborg (35), hulled barley, rye, and oats were observed, along with bread wheat, a concentration of bog-myrtle (*Myrica gale)*, and a few peas (*Pisum sativum*), the latter two making a first appearance in the assemblage. At Toftum Næs (29), roughly equal amounts of rye, hulled barley, and oats were observed, with oats the dominant crop at Korsdalsvej (36).

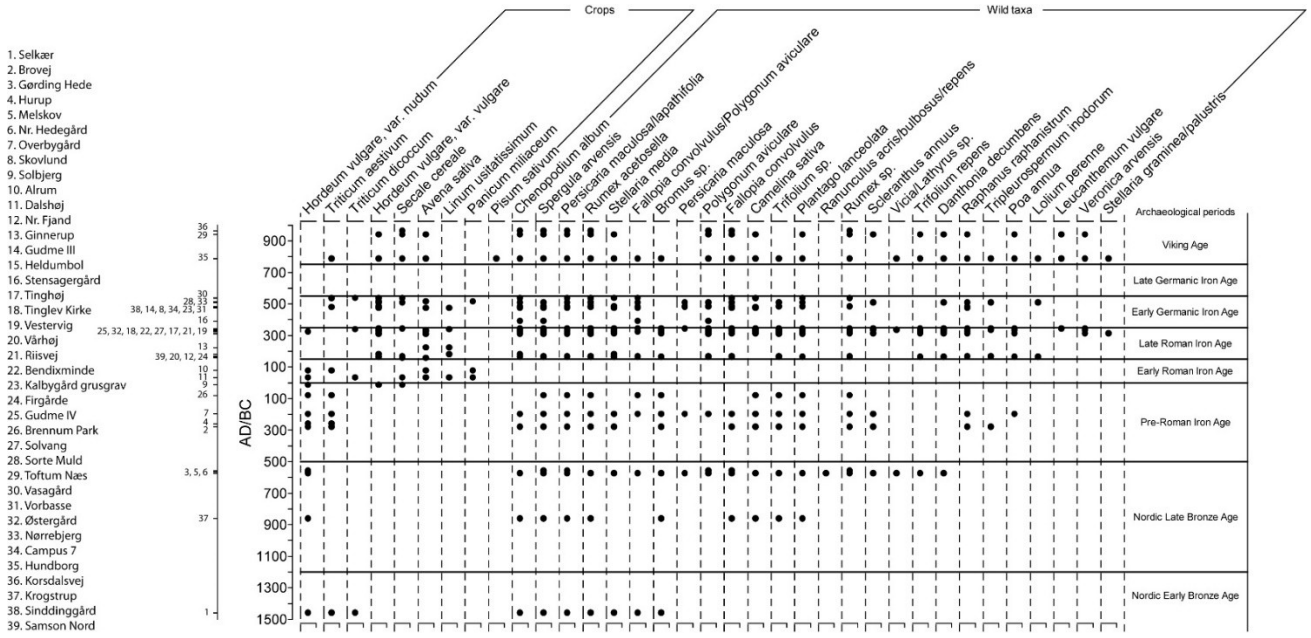

Figure 3*. Crops and wild taxa in the archaeobotanical assemblage, sorted after first appearance. The group of wild taxa include only those that were present as more than 100 items in total.*

3.2. Wild taxa

Of the wild plants present in the assemblage, Figure 3 lists the most common taxa found per period. While the range of wild taxa was relatively restricted in the Early Bronze Age, the number of taxa more than double at the end of the Bronze Age and continue to increase during the Iron Age. The absence of wild taxa in the Early Roman Iron Age is most likely due to sampling procedures in two older cases, Dalshøj and Alrum, where concentrations of crops appear to have been handpicked rather than retrieved by systematic sampling (Helbæk 1954).

3.3. Isotope analysis

Isotope values with corresponding metadata for the individual barley grains can be found in Supplementary Table 3. The determined $\delta^{15}N$ values of barley grains dated to the Iron Age (500 BC – AD 750; n = 204) range between 2.1 and 15.3 ‰, with a mean $\delta^{15}N$ value ± standard deviation (sd) of 6.7 ± 2.0 ‰. There are two barley grains with $\delta^{15}N$ values greater than 14 ‰ that can be identified as outliers using a quantile-quantile plot. The remaining $\delta^{15}N$ values (n = 202) are normally distributed (W = 0.989, p-value = 0.106). The determined barley grain $\delta^{13}C$ values range between −25.5 and −20.9 ‰, with a mean $\delta^{13}C$ value ± sd of −23.0 ± 0.9 ‰. The barley grain $\delta^{13}C$ values are normally distributed (W = 0.99, p-value = 0.168). When $\delta^{13}C$ values are normalised relative to fluctuations in the $\delta^{13}C$ value of atmospheric CO_2 to give $\Delta^{13}C$ values, the barley grain $\Delta^{13}C$ values range between 14.9 and 19.6 ‰, with a mean $\Delta^{13}C$ value ± sd of 17.0 ± 0.9 ‰. There is no correlation between %C or %N and isotope values, nor between the atomic C:N ratio of grains and isotope values (see Supplementary Figures 2–4), which means that there is no reason to suspect that patterning in the isotope values is due to compositional differences among the barley grains or exogenous contamination.

Figure 4 shows the barley grain $\delta^{15}N$ values against the median age of the archaeological context. Barley grains from contexts for which there is no directly determined radiocarbon age are displayed in white and are not included in any further statistical analysis that explores a relationship between barley grain isotope values and date. Barley grain $\delta^{15}N$ values from the same context can differ markedly, with differences ranging from 0.2 to 7.7 ‰ and standard deviations ranging from 0.1 to 5.5 ‰ (mean sd = 1.2 ‰). There seems to be an increase in barley $\delta^{15}N$ values between the Bronze Age and Pre-Roman Iron Age, while barley $\delta^{15}N$ values are relatively consistent throughout the Roman and Germanic Iron Ages and Viking period. A linear mixed-effects model, including a random effect of archaeological site and excluding samples with no directly associated radiocarbon date, finds no relationship between barley grain $\delta^{15}N$ values and date during the Iron Age (500 BC – 750 AD; Beta = −0.000378, SE = 0.000920, t = 0.411, p = .681). There is also no effect of region (Northern Jutland, Western Jutland, Eastern Denmark) or barley type (hulled, naked).

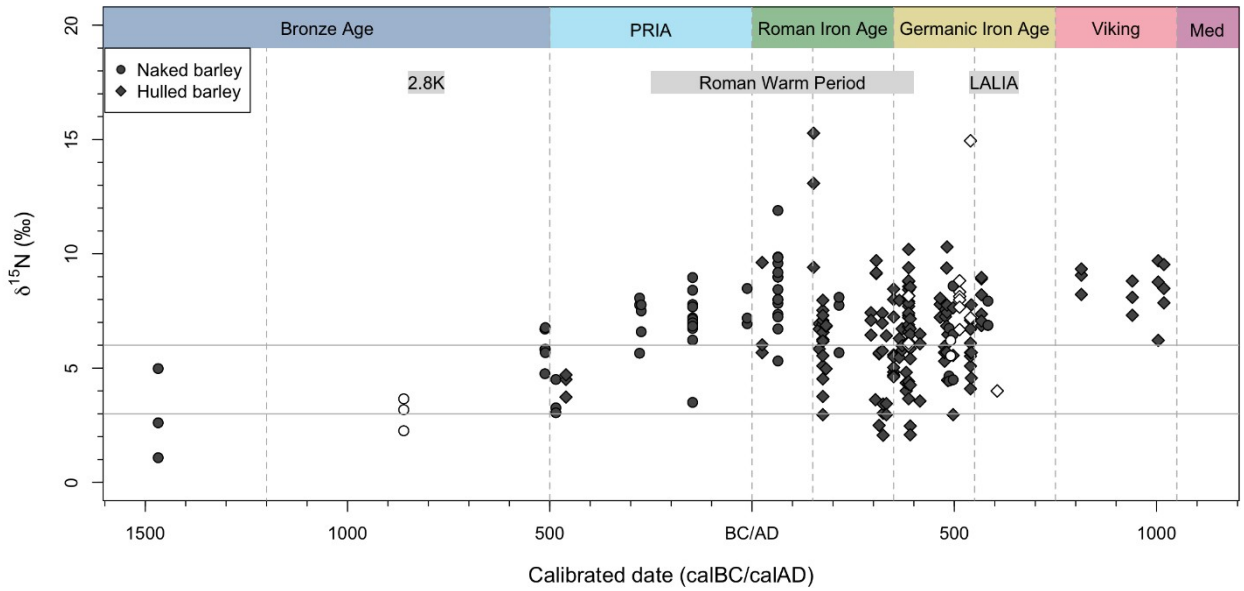

Figure 4. *Single barley grain $\delta^{15}N$ values plotted against the median age of the archaeological context. Barley grains from contexts for which there is no directly determined radiocarbon age are displayed in white. Grey lines at $\delta^{15}N$ = 3 and 6 ‰ correspond to medium and high levels of manuring in modern experimental plots, respectively (Bogaard et al. 2013). 2.8K = 2.8K climate event; LALIA = Late Antique Little Ice Age, PRIA = Pre-Roman Iron Age, Med = Medieval period.*

Barley grain $\delta^{13}C$ values from the same context can also differ markedly, with differences ranging from 0.06 to 2.7 ‰ and standard deviations ranging from 0.03 to 1.3 ‰ (mean sd = 0.6 ‰). Figure 5 shows the barley grain $\Delta^{13}C$ values against the median age to normalise for the variation in the $\delta^{13}C$ value of atmospheric CO_2 over time. Barley $\Delta^{13}C$ values are relatively consistent between the Bronze Age and Late Germanic Iron Age, with a possible increase in $\Delta^{13}C$ values in the Late Germanic Iron Age and Viking period, although there are relatively few samples for this time period. A linear mixed-effects model, including a random effect of archaeological site and excluding samples with no directly associated radiocarbon date, finds no relationship between barley grain $\Delta^{13}C$ values and date during the Iron Age (500 BC – AD 750; Beta = 0.000311, SE = 0.000356, t = 0.873, p = .384). There is also no effect of region (Northern Jutland, Western Jutland, Eastern Denmark) or barley type (hulled, naked).

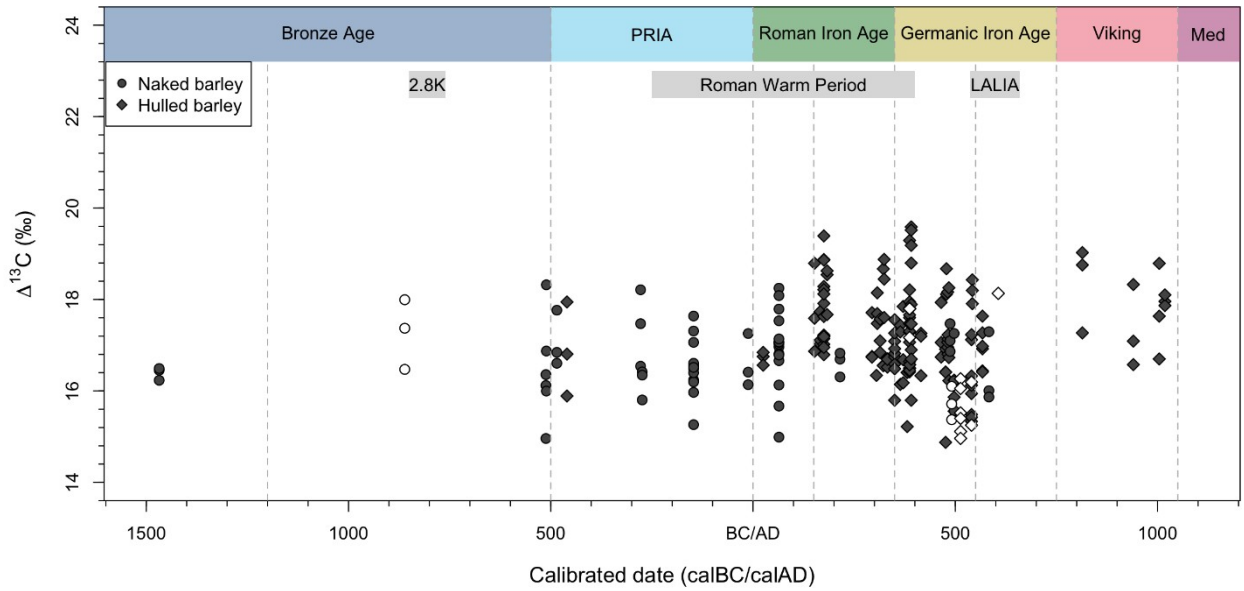

Figure 5. *Single barley grain $\Delta^{13}C$ values plotted against the median age of the archaeological context. Barley grains from contexts for which there is no directly determined radiocarbon age are displayed in white. 2.8K = 2.8K climate event; LALIA = Late Antique Little Ice Age, PRIA = Pre-Roman Iron Age, Med = Medieval period.*

Figure 6 shows the bulk (5–10 grains) or mean single-entity $\delta^{15}N$ values per context against the midpoint of the 2σ calibrated date range for barley grains analysed in this study and previous studies whose isotope values were compiled by Gron *et al.* (2021: Table S2). The midpoint of the date range is used in this instance because the median age is not provided in Gron *et al.* (2021). This shows that while the $\delta^{15}N$ values of barley were fairly consistent throughout the Neolithic and Bronze Age, there was an increase in barley $\delta^{15}N$ values between the Bronze Age and Iron Age. The relatively high $\delta^{15}N$ values of barley in the Iron Age determined in this study are consistent with those in Gron *et al.* (2021).

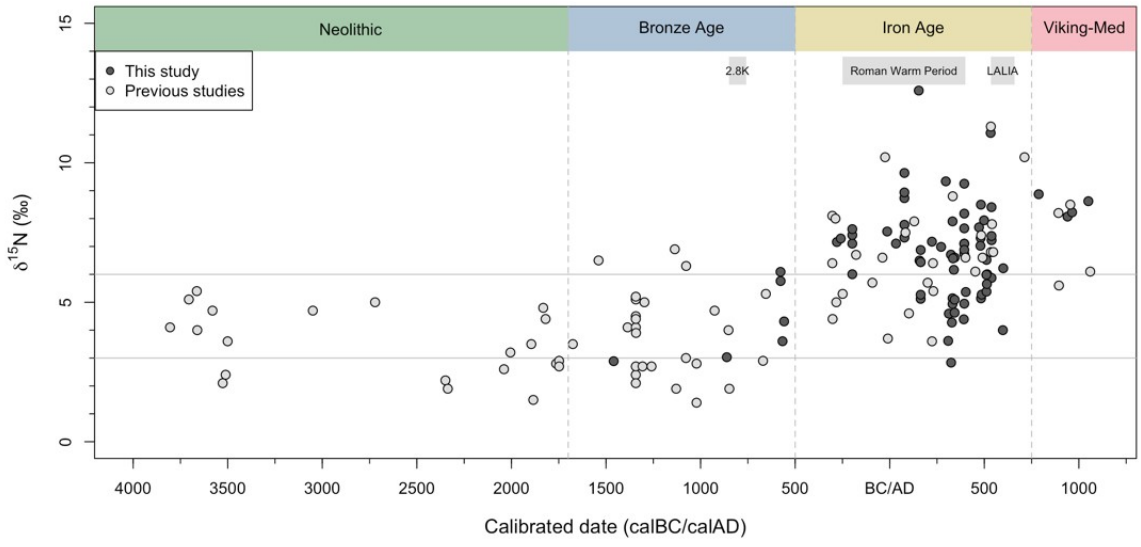

Figure 6. *Bulk or mean single-entity barley grain $\delta^{15}N$ values per context plotted against the midpoint of the 2σ calibrated date range. Data come from this study and Gron et al. (2021), who compiled isotopic data from: Kanstrup et al. (2014), Gron et al. (2017), Filipović et al. (2019) and Larsson et al. (2019). Grey lines at $\delta^{15}N$ = 3 and 6 ‰ correspond to medium and high levels of manuring in modern experimental plots, respectively (Bogaard et al. 2013). 2.8K = 2.8K climate event; LALIA = Late Antique Little Ice Age, Med = Medieval period.*

Figure 7 shows the bulk (5–10 grains) or mean single-entity $\Delta^{13}C$ values per context against the midpoint of the 2σ calibrated date range for barley grains analysed in this study and previous studies whose isotope values were compiled by Gron *et al*. (2021: Table S2). This shows a slight decrease in $\Delta^{13}C$ values of barley during the Neolithic and Bronze Age and a slight increase in $\Delta^{13}C$ values between the Iron Age and early medieval period.

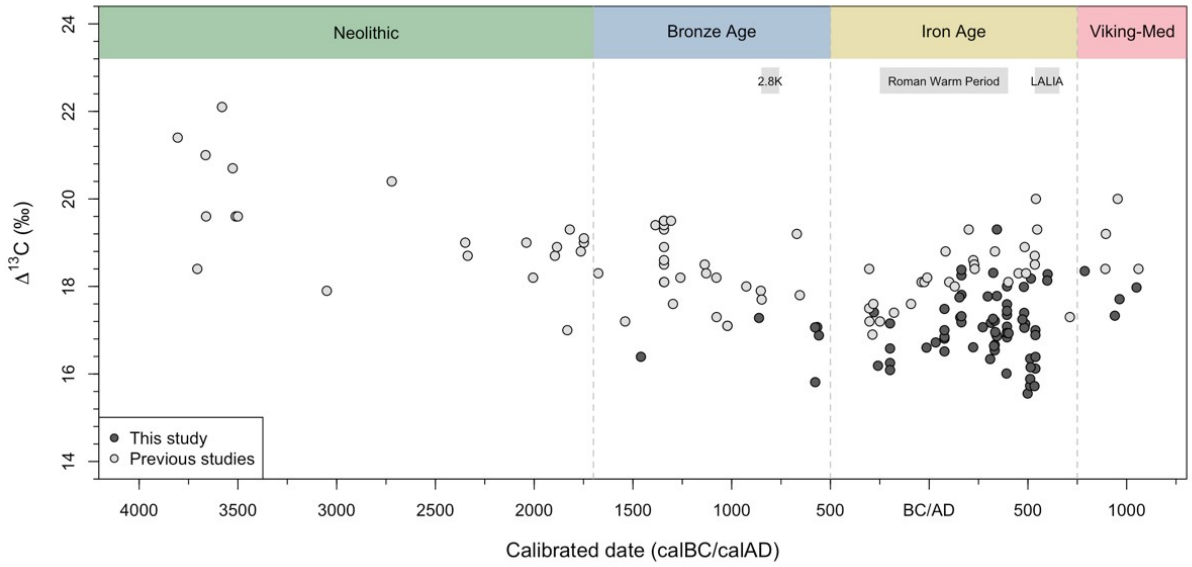

Figure 7. *Bulk or mean single-entity barley grain $\Delta^{13}C$ values per context plotted against the midpoint of the 2σ calibrated date range. Data come from this study and Gron et al. (2021), who compiled isotopic data from: Kanstrup et al. (2014), Gron et al. (2017), Filipović et al. (2019) and Larsson et al. (2019). 2.8K = 2.8K climate event; LALIA = Late Antique Little Ice Age, Med = Medieval period.*

We also considered the relationship between estimated pre-charring weights of hulled barley and date, as per Gron *et al*. (2021; see Supplementary Figure 5). We only consider hulled barley because the equations in Ferrio *et al*. (2004) were derived from the experimental charring of hulled (but not naked) barley. A linear mixed-effects model, including a random effect of archaeological site and excluding samples with no directly associated radiocarbon date, finds no relationship between the estimated pre-charring weight of hulled barley grains and date during the Iron Age (500 BC – AD 750; Beta = –0.00344, SE = 0.00273, t = 1.26, p = .210).

4. Discussion

To sum up from the recorded food plants in Figure 3, barley is the overall dominant crop throughout the Iron Age, in both its naked and hulled varieties, and a shift from the former to the latter can be seen in the Late Roman Iron Age. This shift is likely due to hulled barley generally giving a higher yield than the naked variety and being more resistant to crop diseases (Riehl 2019) but may also stem from an increase in beer consumption. From the Early Roman Iron Age onwards, new crops, such as rye and oat, begin to play a larger role, and other crops, such as millet and flax, make an appearance in our dataset. The range of wild taxa increases from the Bronze to the Iron Age.

Less visible in the archaeological record are finds of nuts, fruit, berries, and leafy greens, which undoubtedly contributed to the overall diet but are rarely preserved. Taxa such as blue- or lingon-berry (*Vaccinium myrtillus/vitis-idea)*, raspberry or blackberry (*Rubus idaeus/fruticosus)*, crowberry (*Empetrum nigrum*), and hazelnut (*Corylus avellana)* show up sporadically in the dataset throughout the Iron Age.

4.1. Broadening the crop spectrum during the Iron Age

What is clear from the archaeobotanical assemblage presented in Figure 3 is that while some crops are replaced by others over time, the overall range of crops broadens. This could certainly be due in part to taphonomic and contextual reasons – we have a much larger assemblage of sites from the Roman and Early Germanic Iron Age, and crop range varies quite significantly between individual sites – but it is nevertheless quite clear that from the Early Roman Iron Age onwards, the crop spectrum expands from primarily naked barley and bread wheat to a wider crop spectrum that also includes emmer, oat, rye, millet, and flax, and sees a shift from naked to hulled barley. Rye is a notable new food crop, appearing in the Early Roman Iron Age; as the only crop in the assemblage, it is a winter crop, providing not only an extra food resource, but also extra protection against famine in the case of spring/summer crop failure. Similarly, millet, a drought-resistant summer crop with a growth cycle slightly different from the other spring/summer crops, helps spread out intense labour periods of sowing and harvesting over several intervals during the year.

A broad crop spectrum means a reduced risk of overall crop failure through reliance on species with slightly differing ecological requirements. A strategy related to this would have been to include wild taxa in the food spectrum to establish an even more diverse diet as a risk management strategy in the face of famine. The conceptual difference between a food crop and a weed is known to be quite fluid. Ethnographic studies have shown that tolerance of (non-toxic) field weeds among food crops tends to increase in times of crop failure or famine, and the mixing of a food crop with other crops (e.g. a “maslin”) that would usually have been considered inferior, or what farmers would consider a weed in times of plenty, is a common risk management strategy by recent smallholder farmers in the Caucasus and around the Mediterranean (Jones and Halstead 1995, Halstead 2014, McAlvay *et al*. 2022). During lean years in Scandinavia, birch bark is known to have been mixed in with wheat flour for bread in Sweden, and rye bread in Denmark was often made from a barley-rye flour mixture, sometimes fleshed out with field weeds such as rye brome (*Bromus secalinus*) and corncockle (*Agrostemma githago*) as well as acorns (Brøndegård 1978).

Some of the archaeobotanical finds in our assemblage may represent such finds of “maslins” or types of famine food. At Early-Late Roman Iron Age Nørre Fjand, Hans Helbæk noted half a litre of seeds from fat hen, which he argued may have been collected for food (Helbæk 1954). From Early-Late Roman Iron Age Alrum, Helbæk also noted about a litre of seeds from pale persicaria, for which he made the same

suggestion (*ibid*.). At Late Roman Iron Age Tinghøj, concentrations of pale persicaria were found mixed with hulled barley in one pit, and with gold-of-pleasure in another. Pale persicaria is consistently found in samples from the Late Roman Iron Age sites and, in other studies, has also been found in the guts of the famous bog bodies of Grauballe and Tollund Man (Helbæk 1950, Helbæk 1958, Harild *et al*. 2007). The fact that the best-known finds of pale persicaria and fat hen in a food context stems from bog bodies of sacrificed men has traditionally lent the mixing of crops and wild taxa a certain ritualistic flavour. However, we cannot disregard the more prosaic use of maslins and famine foods as a risk management strategy to avoid crop failure and starvation.

The increased range of wild taxa can partly be explained by the similar increase in new crops, i.e. they may have been accompanying field weeds. This does not, however, explain why wild taxa were deliberately kept in storage contexts – as pure assemblages or maslins – in several of the sites discussed here. They were clearly invested with some significance, be it purely economic or economic/ritual. It is beyond the scope of this paper to discuss the role of the Iron Age bog bodies, but the use of a maslin or other "famine food" as the last meal of what is generally believed to have been victims of sacrifice may have had some significance – a reminder of past famine years in the hope to avoid a future one, perhaps.

4.2. Soil enrichment practices

The relatively high $\delta^{15}N$ values of charred barley grains from Iron Age sites across Denmark analysed in this study (Figure 4) are consistent with the increase in cereal $\delta^{15}N$ values observed at other sites across southern Scandinavia between the Bronze Age and Pre-Roman Iron Age (Gron *et al*. 2021). The sites dated to the Iron Age are in similar locations to those dated to the Neolithic and Bronze Age, so it is unlikely that the higher barley grain $\delta^{15}N$ values in the Iron Age are due to differences in soil N cycling among sites. The lack of differences in barley grain $\delta^{15}N$ values between regions, which have different underlying geologies (Figure 1), also argues against soil properties being the main factor influencing the $\delta^{15}N$ values. Waterlogging of soils could result in higher crop $\delta^{15}N$ values, but although crops in wetter years may have grown in periodically waterlogged patches in fields, there is no evidence from the weed flora to suggest that barley was grown particularly on waterlogged soils in the Iron Age. Instead, as previously surmised, it seems likely that the higher barley grain $\delta^{15}N$ values was a result of an increased intensity in the application of household waste and/or animal manure, associated with the establishment of permanent so-called Celtic fields in the Late Bronze Age (Gron *et al*. 2021). In the Iron Age, the mean charred barley grain $\delta^{15}N$ value of 6.8 ‰ (95% confidence interval 6.5–7.0 ‰) is consistent with barley fields receiving a high level of manure (35+ tons/ha; Bogaard *et al*. 2013). Almost all the barley grains have $\delta^{15}N$ values greater than 3 ‰, which is consistent with some degree of manuring. Although there are no $\delta^{15}N$ values for wild herbivores at the Iron Age sites that could give an indication of the $\delta^{15}N$ values of unmanaged plants (sensu Styring *et al*. 2017), a compilation of the bone collagen $\delta^{15}N$ values of red deer and roe deer from Denmark dated to between the Mesolithic and Neolithic (n = 68 from the dIANA database https://www.oasisnorth.org/diana.html, accessed January 2023; Supplementary Table 4) and red deer and roe deer (n = 56) from Maring & Riede (2019) gives a mean $\delta^{15}N$ value of 4.3 ‰ (95% confidence interval 4.1–4.5 ‰) and a maximum $\delta^{15}N$ value of 6.4 ‰ (Supplementary Table 4). If a conservative offset between diet and bone collagen $\delta^{15}N$ values of 3 ‰ is subtracted from these values, it implies that unmanaged vegetation has a $\delta^{15}N$ value of no greater than 3.4 ‰, which is consistent with the "no manuring" band in

Bogaard *et al*. (2013) and in Figure 4. The increase in barley grain δ^{15}N values between the Bronze Age and Iron Age in Denmark mirrors the increase in human δ^{15}N values between the two periods in Limfjord, northern Jutland (van der Sluis and Reimer 2021). This supports the authors' suggestion that the increase in human δ^{15}N values was due to the consumption of fertilized plants rather than a greater reliance on animal protein.

During the Iron Age, the barley grain δ^{15}N values provide no evidence for a change in the intensity of manuring, despite an increase in the size of farms and their stable areas, and an increased emphasis on cattle husbandry, as mentioned in the Introduction. This could result from a form of agricultural extensification, whereby the amount of land under cultivation increased, necessitating greater absolute quantities of manure to achieve consistent amounts applied per unit area (reflected in consistent barley grain δ^{15}N values). Larger, less intensively tilled, fields, combined with the practice of fallowing, may also be an explanatory factor and would have resulted in the increased diversity of field weeds. This form of agricultural extensification in the Iron Age is similar to that in south-west Germany, where crop δ^{15}N values are significantly higher in the Iron Age compared to the Neolithic, but weed functional traits indicate a decrease in soil fertility, due to expansion onto less fertile soils and/or insufficient replenishment of nutrients, and decreased disturbance of the soil due to ard ploughing and/or fallowing (Styring *et al*. 2017). Unfortunately, the lack of weed seeds on many of the sites discussed here precludes a study of functional weed ecology (a minimum of ten potential weed seeds identified more or less to species level is required for each context).

4.3. The role of the mouldboard plough in agricultural extensification

It is generally presumed that the introduction of the mouldboard plough, a much more efficient agricultural tool than the ard, is the reason for a change in field layout from Celtic fields surrounded by banks to much longer fields that made for much more efficient ploughing (Larsen 2015). Compared to the ard, the mouldboard plough was more efficient in both breaking open new soils and in turning the soil, meaning better opportunities for agricultural extensification as it became easier to expand the area under cultivation and achieve more efficient soil ventilation, weed management, and manuring practices as the manure could be ploughed deeper into the ground, from where it could slowly release its nutrients.

It is not entirely clear, however, when the mouldboard plough was introduced to Denmark; it may have been as early as AD 200 (Larsen 2015), when field layouts change, though there is no material evidence for this tool until the 1100s. During the Medieval Period, however, the mouldboard plough had effectively replaced the ard.

If it was in use by AD 200, it seems to have had negligible effects on the barley grain δ^{15}N values, which is unsurprising given that the depth of tillage is unlikely to affect plant δ^{15}N values (Szpak 2014). It could be the reason why the diversity of weeds increased because it would have enabled much larger areas of land with different soil properties to be taken into production. Deeper ploughing may have meant that the lack of increase in manuring intensity did not adversely affect crop yields because nutrients could be used more efficiently (Thurston 2007).

4.4. The role of climatic shifts

The climatic data outlined above showed a shift with the 2.8K event to a colder and rainier climate followed by more stable and warmer conditions with the onset of the Roman Warm Period (250 BC–AD 400). This was again followed by a dramatically colder climate during the Late Antique Little Ice Age (AD 536–660). After further centuries of warming, the climate again became colder with the onset of the Little Ice Age in the 13th century AD. In short, throughout the 2500 years we have been investigating here, the climate fluctuated between warm and cold. Agricultural practices appear to have been resilient enough to withstand these changes. The only possible significant change we see that correlates with a climatic fluctuation is the complete absence of data in the mid Late Germanic Iron Age following the 536 event and the onset of the Late Antique Little Ice Age. This could be a coincidental lack of excavated sites from this period but the complete lack of data here could also reflect the actual absence of settlements as a result of a dramatic depopulation – by migration or death – of this region.

A recent study of agriculture during the Early and Late Iron Age transition (c. 550 AD) in Southwestern Norway (Westling 2024) has shown a similar drastic decrease in settlements from around 536. The archaeobotanical assemblage discussed in Westling (*ibid*.), covering AD 400-1050, has shown that while oat and barley were staple crops throughout this time, barley becomes the dominant crop in the years following the 536 event, and interestingly, sites with a greater reliance on barley than oat appear to have been more likely to survive the years of hardship following this event. While in Denmark agricultural resilience appears to have been enabled through a broad-spectrum diet until AD 536, in Norway a much greater reliance on the hardy barley crop was the answer to the mid-sixth century crisis.

5. Conclusions

The dataset presented here of charred plant remains from Denmark indicates a stable and resilient agrarian economy throughout the Iron Age. The crop spectrum and accompanying weed seed diversity increase gradually, and manure application per unit area of land, at least for the important barley crop, is consistently high but does not increase during the Iron Age. These strands of evidence suggest that a large-scale agricultural system that supported a broad range of food resources on highly manured soils was robust to the socio-economic and climatic changes that took place during the Iron Age. The only time during our 2500-year study period where a possible breakdown of agricultural resilience can be detected follows volcanic eruptions in AD 536/540, after which, and until the Viking Age, a complete lack of data may reflect a situation of abandonment of farms and large-scale depopulation of the region.

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Supplementary Material

Supplementary Table 1. Raw and calibrated carbon and nitrogen isotope data for archaeological charred barley grain samples and reference materials.

Supplementary Table 2. New radiocarbon dates presented in this paper.

Supplementary Table 3. Metadata and stable isotope values of archaeological charred barley grains sampled from sites in Denmark.

Supplementary Table 4. Stable isotope values of fauna extracted from the dIANA database (https://www.oasisnorth.org/diana.html, accessed January 2023).

Supplementary Figure 1. Length (X), breadth (Y), and thickness (Z) measurements taken of each grain prior to analysis. Measurement Z is taken perpendicular to X and Y.

Supplementary Figure 2. Barley grain $\delta^{15}N$ values plotted against their C:N atomic ratios.

Supplementary Figure 3. Barley grain $\delta^{15}N$ values plotted against their %N.

Supplementary Figure 4. Barley grain $\delta^{13}C$ values plotted against their %C.

Supplementary Figure 5. Estimated pre-charring weights of hulled barley grains plotted against the midpoint of the 2σ calibrated date range. Barley grains from contexts for which there is no directly determined radiocarbon age are displayed in white. 2.8K = 2.8K climate event; LALIA = Late Antique Little Ice Age, PRIA = Pre-Roman Iron Age, Med = Medieval period.

Supplementary Datasheet. Details of FTIR analysis of a subset of the archaeological charred barley grains.

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