Vegetation History and Archaeobotany (2023) 32:583–596
https://doi.org/10.1007/s00334-023-00923-3

ORIGINAL ARTICLE

Were prehistoric cereal fields in western Norway manured? Evidence from stable isotope values ($\delta^{15}N$) of charred modern and fossil cereals

Lene Synnøve Halvorsen[1,2] · Pål Tore Mørkved[3] · Kari Loe Hjelle[1]

Received: 29 October 2022 / Accepted: 21 March 2023 / Published online: 8 May 2023

Abstract
Charred cereal grains from archaeological contexts in western Norway were selected for stable carbon and nitrogen isotope analysis. Single grain analysis was used on 76 grains from 16 sites covering the Late Neolithic (2300–1800 BCE) to the Middle Ages (1030–1537 CE). The cereals from archaeological contexts (postholes and agricultural layers in soil profiles) indicate increasing $\delta^{15}N$ values with time. In the Late Neolithic–Early Bronze Age $\delta^{15}N$ values for *Hordeum vulgare* var. *nudum* range from 1.2 to 8.9‰, and in the Early Iron Age the values range from 0.7 to 13.6‰. The values of *Hordeum vulgare* var. *vulgare* range from 4.3 to 6.1‰ in the Pre-Roman Iron Age to 3.3–8.7‰ in the Middle Ages. The $\delta^{15}N$ values of fossil cereals were compared to modern cereals grown in test-plots in western and north-western Norway. The results from the modern cereals show a clear difference between cereals grown in low level and high-level manured fields. *Hordeum vulgare* var. *nudum* dated to the Late Neolithic, show $\delta^{15}N$ values mostly falling within the range of modern day ecologically grown cereals with a low-level manuring regime. Cereals from later time-periods show higher $\delta^{15}N$ values equivalent to modern day moderate- to high-level manuring regimes. Our results indicate manuring and possible use of marine resources and the existence of permanent fields from the Late Bronze Age (1200 BCE) onwards.

Keywords Cereals · Manuring · Nitrogen · Carbon · Norway · Stable isotope measurements

Introduction

Pollen and plant macrofossils have been used both separately and together to assess past agricultural practices such as grazing and cultivation, to identify the type of crop plants cultivated and to separate between permanent and shifting cultivation (Viklund 1998; Jones 2002; Kreuz and Schäfer 2011; Halvorsen and Hjelle 2017). Based on the demands of the different arable weed taxa identified, inferences regarding agricultural regime, nutrition levels and fertilisation of fields can be drawn and contribute to archaeological discussions on prehistoric farming societies. With stable isotope analysis, further insights into past land-use practices can be made. Stable isotope values of nitrogen in crops from archaeological sites can provide information about nutrition levels and intensity of manuring and thus on prehistoric food-producing systems (e.g. Bogaard et al. 2007, 2016; Fraser et al. 2011; Kanstrup et al. 2014; Gron et al. 2017). Interpretations of the intensity of manuring are based on measurements of modern material. Nitrogen isotope values ($\delta^{15}N$) represent the difference in ratio between the heavier and lighter stable isotopes of nitrogen in samples compared to N_2 in air (e.g. Coplen 2011). Generally, soil nitrogen is the main source of nitrogen in plants, except for plants with nitrogen-fixing capabilities such as legumes, which have microbial bacteria that can convert atmospheric N_2 into ammonia (Virginia and Delwiche 1982; DeNiro 1987; Styring et al. 2014). Studies have shown how manuring can significantly increase $\delta^{15}N$ values of crops by up to 10‰ (Bogaard et al. 2007; Fraser et al. 2011; Styring et al. 2017). This occurs due to bacterial decomposition of the manure, which leads to preferential loss of the lighter ^{14}N, leading to enrichment of ^{15}N within the N source pool of the soil available to plants (Fraser et al.

Communicated by F. Bittmann.

Lene Synnøve Halvorsen
lene.halvorsen@uib.no

[1] Department of Natural History, University Museum, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway

[2] Department of Biological Sciences, University of Bergen, P.O. Box 7803, 5020 Bergen, Norway

[3] Department of Geosciences, University of Bergen, P.O. Box 7803, 5020 Bergen, Norway

2011). Other processes, such as salt spray and burning of vegetation, may also increase the $\delta^{15}N$ values of crops and vegetation (Handley et al. 1999; Szpak 2014).

Modern manuring experiments in northern and middle Europe have shown that $\delta^{15}N$ values above 6‰ in cereals indicate high levels of manure or repeated manuring. Values below 2.5–3‰ $\delta^{15}N$ indicate no or little manuring, or residual effects of previous manuring (Fraser et al. 2011; Bogaard et al. 2013). Stable isotope measurements of bone material from wild herbivores can give an indication of natural plant $\delta^{15}N$ values (Styring et al. 2016). Natural vegetation has $\delta^{15}N$ values around 0‰ (close to atmospheric N_2), whereas herbivores have values of 3–5‰ due to trophic enrichment. Red deer bones (13 samples) from the Mesolithic to the Iron Age from western Norway show mean stable $\delta^{15}N$ values of 3.8 ± 0.5‰ and 3.9 ± 1.0‰ (before and after the transition to agriculture) (Rosvold et al. 2010), indicating that the natural vegetation had $\delta^{15}N$ values close to atmospheric N_2. This is also supported by comparable $\delta^{15}N$ values of bones of wild boar from the same periods (Rosvold et al. 2010), and bones of sheep/goats and cattle from the Middle Ages (MA) in Norway (Naumann et al. 2014; van der Sluis et al. 2016).

Soil profiles with agricultural/cultural layers and postholes of prehistoric houses are the main sources of cereal assemblages in western Norway (Prøsch-Danielsen and Soltvedt 2011; Hjelle et al. 2016; Halvorsen and Hjelle 2017). Votive offerings and cereal storages with pure cereal grain assemblages occur but are rare (Prøsch-Danielsen and Soltvedt 2011). The bedrock is generally acidic (Moen et al. 1999), which leads to poor preservation of uncharred organic material. In addition, the topography restricts areas available for habitation and agriculture to the area between sea-level and the mountains, which may be a quite narrow area of land. Thus, the same areas have been used throughout time (cf. Diinhoff 2004) and traces of prehistoric activity might be disturbed or destroyed by activities such as ploughing in more recent time-periods. Based on cereals and weeds in pollen and macrofossil assemblages from soil profiles as well as macrofossil assemblages from house remains, fertilisation of fields from the Late Neolithic/Early Bronze Age (LN/EBA; see Table 1 for time-periods) has been proposed, with increased intensity from the Pre-Roman Iron Age (PRIA) (Halvorsen and Hjelle 2017). In the present paper we attempt to substantiate these interpretations through stable isotope data of cereals from some of the same contexts.

The main cereal type found in prehistoric contexts in the study area is naked barley (*Hordeum vulgare* var. *nudum,* hereafter called *H. nudum*). Hulled barley (*Hordeum vulgare* var. *vulgare,* hereafter called *H. vulgare*) is found from the PRIA, and oat (*Avena*) from the Iron Age. Compared to naked barley, hulled barley is considered to be better suited for an agricultural regime that includes high levels of manuring as it has higher requirements for fertilisation to give a reasonable yield (Gustafsson 1998; Viklund 1998). Thus, this grain type is thought to follow the introduction of three-aisled buildings with a byre section where the animals were stalled during winter and manure was easily collected (Olausson 1998). In western Norway, three-aisled houses became common in the Early Bronze Age (Diinhoff and Slinning 2013; Olsen 2013). Household waste and not manure may have been the primary source of fertilisation in the LN-EBA, whereas intensive, full-scale agriculture with permanent fields and manuring started towards the end of the Bronze Age in southern Scandinavia (Grabowski 2011; Kanstrup et al. 2011) and probably also in our study area. In addition to a higher yield when manured compared to *H. nudum*, *H. vulgare* is more resistant to attack by pathogens (Bakkevig 1992).

Table 1 Time-periods and abbreviations used in the text

Time-period	Age, calibrated BCE/CE	Abbreviation
Early Neolithic	4000–3300 BCE	EN
Middle Neolithic	3300–2300 BCE	MN
Late Neolithic	2300–1800 BCE	LN
Early Bronze Age	1800–1200 BCE	EBA
Late Bronze Age	1200–500 BCE	LBA
Iron Age	500 BCE –1030 CE	IA
Pre-Roman Iron Age	BCE 500–1 CE	PRIA
Viking Period	780–1030 CE	VP
Middle Ages	1030–1537 CE	MA

Together with $\delta^{15}N$, carbon isotope values ($\delta^{13}C$) are commonly measured and included also in our study. The $\delta^{13}C$ values have been used to identify irrigation levels in arid areas (e.g. Araus et al. 1997; Ferrio et al. 2005; Bogaard et al. 2013; Wallace et al. 2013). Although water availability is generally not a limitation, dry summers occur also in western Norway, and measurements of $\delta^{13}C$ may potentially inform on climate conditions/watering practices in prehistory.

Since the 1950s, there has been a politically founded incentive to channel cereal production to areas in eastern and middle Norway that have the best suited soil, climate, and topographic conditions for cultivation. Western and northern Norway were considered better suited for livestock and grass production for fodder, which now represent ca. 80% and 15% respectively of the agricultural production in these areas (Rognstad et al. 2016). In recent years, a few farms have started low-scale cereal production in western Norway, mostly for fodder, but also supplying local breweries.

Through measuring $\delta^{15}N$ and $\delta^{13}C$ values of modern cereals with known manuring regimes, we aim to obtain reference data regarding $\delta^{15}N$ and $\delta^{13}C$ values for western Norway. The resulting values are discussed in relation to the stable isotope values of fossil cereals from different time-periods from archaeological contexts, with the aim of making inferences regarding manuring and land-use practices in early management systems.

Material and methods

Study area and material

The study area is situated between 59° and 63°N and 005° and 009°E in western Norway. Charred cereal grains dated from the LN to the MA form the basis of our study (Fig. 1, Table 2). The analysis is destructive, and only sites with enough cereal grains to retain grains for future research were selected. Following this, 16 archaeological sites with cereal assemblages were selected from the database at the University Museum of Bergen. From the archaeological sites, cereals were retrieved from house contexts (cultural layers from MA, otherwise postholes) or agricultural/cultural layers in soil profiles, the latter referred to in the following simply as soil profiles (Table 2). From the sampled houses, grains from two contexts were analysed if possible. From the soil profiles, two cereal grains were selected from each context/layer if possible. The number

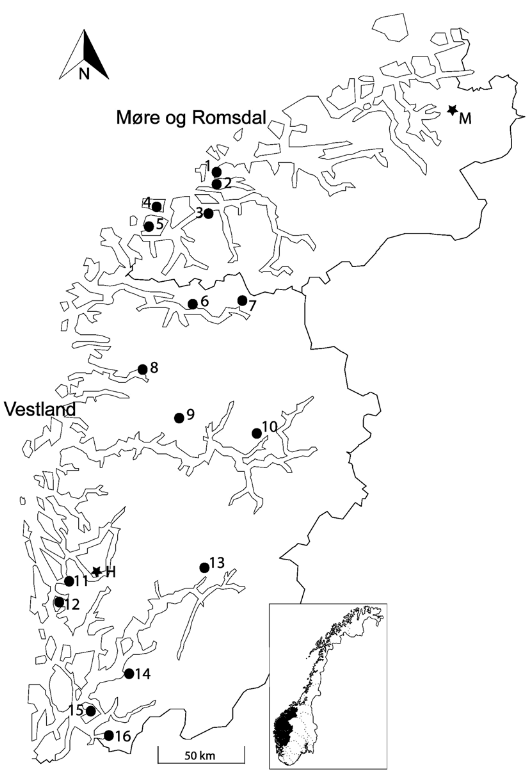

Fig. 1 Map showing the geographical setting of the sites included in the paper. Numbering of the sites follows information given in Table 2. The modern cereal test-sites are marked M = Mogstad and H = Havrå

of cereals analysed from each site is given in Table 2. Both soil profiles and house contexts are nearly equally represented in the data covering the LN/EBA and VP/MA, whereas only one soil profile and several house contexts are included in the data covering the LBA and PRIA. The medieval period is poorly represented in rural areas of western Norway, and samples from the medieval town of Bergen were included to increase the amount of data from this period. We assumed these cereals were grown in manured fields and expected the $\delta^{15}N$ values to reflect this. However, these grains have probably been imported to Bergen, and will not represent local cereal cultivation.

The modern cereals of our study were grown in test-plots in two areas in western Norway (Fig. 1). The site Mogstad in Surnadal (ecological farming using only cattle manure) was maintained by NIBIO (Norwegian Institute of Bioeconomy research) in collaboration with a local farmer (Solemdal et al. 2021). The site had previously been used for conventional cereal farming for ca. 20 years and started ecological farming in 2019. The second site, Havrå in Osterøy, is in the south-western part of the study area. Havrå is a traditional cluster farm and a protected cultural environment managed by Osterøy Museum and Stiftinga Havråtunet. Only cattle manure is used at the site. Palaeobotanical and archaeological studies at Havrå have shown activity from the LN/EBA transition with increased farming during the Iron Age (Hjelle 1999; Øye et al. 2002), and written sources mention the farm in 1303 CE (Skre 1994). The farm was traditionally run until the 1940s, followed by a gradual decline in activity with cereal farming ceasing in 1950 (Austad et al. 2012). Since 1989 a small area of the farm is run after traditional practices and cereal farming (*Avena*) resumed in 1995 (Jensen et al. 2012). An overview of cereal varieties and the amount of manure used at these two sites is given in Table 3. The modern cereal grains from the northern site were collected in the test-plots in September 2020, whereas grains from an already harvested field were taken at Havrå, also in September 2020.

In western Norway, the main climatic gradient is from west to east rather than from south to north. Most study sites have an oceanic climate (precipitation > 1,200 mm per year, mean annual temperature 6.1–7.7 °C, Tables 2, 3). A few sites in the inner fjord areas have a weakly oceanic climate (precipitation 500–1,200 mm per year, mean annual temperature 5.7–6.3 °C) (Moen and Odland 1993), thus all sites are within zone Cfb (temperate oceanic climate) of the Köppen-Geiger climate classification (Peel et al. 2007; Beck et al. 2018). The vegetation is characterised by mixed deciduous and pine forests, spruce plantations, coastal heathlands, and open grass-dominated agricultural land. The soils in the coastal areas are marine beach deposits or of morainic origin, whilst sites in the inner fjord areas have (glacio-)fluvial deposits.

Table 2 Overview of the study sites: site numbers correspond with those in Fig. 1

Site no	Site	Geographic coordinates	Precipit. (mm/yr)	Mean temp. (°C)	Elevation (m a.s.l.)	Sample name (context)	Cereal type (no. grains)	Archaeological time-period
1	Søvik, Haram	N 62° 32.805 E 006° 17.101	1,340	7.1	28	1–1 (h)	*H. nudum* (4)	LN-EBA
2	Sperre, Ålesund	N 62° 29.535 E 006° 18.215	1,270	7.1	7.5	2–2 (h)	*H. nudum* (2) *H. vulgare* (1)	PRIA
3	Barstadvika, Ørsta	N 62° 21.585 E 006° 15.907	2,340	6.7	13	3–1 (h)	*H. vulgare* (2) *Avena* (2)	MA
4	Hjelmeset, Herøy	N 62° 19.822 E 005° 39.426	1,900	6.9	4.5	4–1 (h)	*H. nudum* (3) *H. vulgare* (2)	PRIA
5	Ytre Hauge, Sande	N 62° 14.099 E 005° 34.661	2,340	6.9	3	5–1 (h)	*H. nudum* (4)	LN-EBA
6	Indre Henden, Eid	N 61° 51.847 E 006° 13.572	1,790	6.8	35	6–3 (h) 6–4 (h)	*H. nudum* (2) *H. nudum* (2)	LN-EBA LN-EBA
7	Kyrkjeeide, Stryn	N 61° 55.132 E 006° 46.965	1,270	5.8	11	7-t (p) 7-b (p)	*H. vulgare* (2) *Avena* (2) *H. vulgare* (2) *Avena* (2)	MA VP–MA
8	Hornesvika, Førde	N 61° 27.899 E 005° 49.891	2,390	6.3	9	8–1 (h)	*H. nudum* (2)	PRIA
9	Ekrene, Høyanger	N 61° 14.630 E 006° 5.555	1,480	6.8	130	9 (h)	*H. nudum* (4)	LN-EBA
10	Kvåle, Sogndal	N 61° 13.931 E 007° 4.606	1,450	6.8	45	10-t (p) 10-b (p)	*H. vulgare* (2) *H. nudum* (2)	PRIA LN-EBA
11	Rosenkrantzgate, Bergen	N 60° 23.822 E 005° 19.502	2,470	8.1	5.5	11–1103 (h) 11–1893 (h)	*H. vulgare* (4) *Avena* (2) *H. vulgare* (2) *Avena* (2)	MA MA
12	Dolvik, Bergen	N 60° 18.598 E 005° 15.962	1,850	8.3	32	12-CL1 (p)	*H. nudum* (4)	LN
13	Hollve, Granvin	N 60° 33.962 E 006° 43.449	1,480	6.4	32	13–1 (p)	*H. nudum* (2)	LN
14	Skåla, Rosendal	N 59° 59.295 E 006° 0.484	1,820	7.3	20	14-A501 (p) 14-L (h) 14-K (h) 14-T (h)	*H. nudum* (4) *H. nudum* (2) *H. nudum* (2) *H. nudum* (2)	LN PRIA LBA LN-EBA
15	Kvitevoll, Kvinnherad	N 59° 47.474 E 005° 43.884	1,780	7.3	55	15–9 (h)	*H. nudum* (3) *H. vulgare* (1)	PRIA
16	Etnesjøen, Etne	N 59° 39.796 E 005° 56.566	2,200	8	7	16-VI (h)	*H. vulgare* (4)	PRIA

H house context, *p* soil profile context. Abbreviations of archaeological time-periods are given in Table 1. Climate data from Norwegian Centre for Climate Services (seklima.met.no). Sample name (context) refers to site no. and context name/number (context type in brackets

Laboratory methods

Single-grain analysis of 76 charred fossil cereal grains were carried out (Table 2, ESM 1 Table 1.3). Half of the grains from each context were subjected to ABA (Acid–Base-Acid) pre-treatment following the protocol described in Fraser et al. (2013b), the remaining grains were analysed without pre-treatment (Fraser et al. 2013a), and any visible contaminants were removed before analysis. Twenty-two grains (two single grains and two assemblages of 10 grains) from each of the eight modern cereal types were selected for analysis (ESM 1 Table 1.4). The modern cereals were wrapped in aluminium foil and charred at 245 °C for 4 h in sand-filled crucibles (following Fraser et al. 2013a; Nitsch et al. 2015). Initial tests showed this to be the appropriate temperature for achieving complete charring with little distortion in shape.

The measurements for $\delta^{15}N$ and $\delta^{13}C$ were done at the Department of Geosciences at the University of Bergen using a Thermo Scientific Flash 1112 Elemental Analyser connected to a Delta V plus isotope ratio mass spectrometer (IRMS). Homogenised samples were weighed into tin capsules (0.4–1.4 mg of crushed fossil cereal grain, modern

Table 3 Modern cereal varieties and the manuring regimes of the experimental plots

Site	Geographic coordinates	Precipit. (mm/yr)	Mean temp. (°C)	Elevation (m a.s.l.)	Manure type and amount	Cereal types
Mogstad (M)	N 62° 59.4942 E 008° 49.4664	1,350	5.6	12	Cattle manure, 20 t/ha (2020) 30 t/ha (2019)	*Hordeum vulgare* 6-row *Hordeum nudum* 2-row *Hordeum vulgare* 2-row *Avena*
Havrå (H)	N 60° 26.3684 E 005° 34.5294	2,030	7.7	74	Cattle manure, 73 t/ha (every year). 3-year crop rotation with potatoes	*Avena*

Letters in brackets refer to letters in Fig. 1. *Hordeum vulgare* 6-row = *H. hexastichon*; *Hordeum vulgare* 2-row = *H. distichon*

grains 1.2–3.8 mg), combusted at 1,020 °C, catalysed by chromium oxide and silvered cobaltous oxide (Elemental Microanalysis, UK) to form CO_2 and N-gasses, before N-oxides were reduced to N at 650 °C using metallic copper (Elemental Microanalysis, UK). Water was removed and gasses were separated by a GC column before entering the IRMS. A cut-off value of 1,000 mV in the amplitude of mass 28 ($^{14}N_2$) was implemented as lower values were considered to give unreliable readings. Multiple measurements were performed for samples with sufficient material. A full list of number of measurements is given in ESM 1.

IAEA-N1 (ammonium sulphate, $\delta^{15}N = +0.43‰$), IAEA-N2 (ammonium sulphate, $\delta^{15}N = +20.41‰$) and IAEA-600 (caffeine, $\delta^{15}N = +1.0‰$) were used to calibrate the N-measurements, and USGS-24 (graphite, $\delta^{13}C = -16.05‰$), IAEA-CH6 (sucrose, $\delta^{13}C = -10.45‰$) and IAEA-600 (caffeine, $\delta^{13}C = -27.77‰$) to calibrate the C-measurements. A House Glycine standard (mean and SD measured over eight runs, $\delta^{15}N = 0.98 \pm 0.21‰$ and $\delta^{13}C = -29.87 \pm 0.37‰$) was used as a check standard. See ESM 1 Tables 1.1–1.5 for calibration results. A correction factor of 0.31‰ was applied to all measured $\delta^{15}N$ values to account for charring following the recommendations of Nitsch et al. (2015).

The $\Delta^{13}C$ (carbon discrimination) of cereal grains from different time-periods (until 2010) can be assessed using data from the AIRCO2_LOESS data calibrator (Ferrio et al. 2005). The calibrator accounts for past variations in $\delta^{13}C$ in the atmosphere and estimates the isotopic composition of CO_2 in the atmosphere at the time the plants were growing (age of the sample). As the AIRCO2_LOESS data calibrator only supports data for time-periods until 2010, the $\Delta^{13}C$ values for the modern cereals were calculated using the isocalcR package in R (Mathias and Hudiburg 2022).

Data analysis

The $\delta^{15}N$ values of the pre-treated fossil cereals were compared to the non-treated using a pairwise t-test to check for differences. In addition, the $\delta^{15}N$ values of modern single-grain and 10-grain bulk samples were compared for differences using the same test. The $\delta^{15}N$ values of the single fossil grains were tested for correlation with age using linear regression. All tests were run in R (R Core Team 2015), code and results are given in ESM 2.

Results

Fossil cereals

The t-test of the two treatments of fossil grain $\delta^{15}N$ values show a p-value of 0.93 (see ESM 2 for results), thus there is no statistically significant difference between the pre-treated and the non-treated grains, and the treatment status is not shown in the figures. A full list of cereals and pre-treatment is given in ESM 1 Table 1.3.

The results show variations in fossil grain $\delta^{15}N$ values both within sites and from site to site for both cereal types (Figs. 2, 3, ESM 1 Table 1.3). For *Hordeum*, there is a slight increase in $\delta^{15}N$ values through time and there is a statistically significant correlation between age and $\delta^{15}N$ values (correlation = 0.2897446, p-value = 0.02737, $r^2 = 0.08395$), also indicated in the boxplot (Fig. 4). Generally, the $\delta^{15}N$ values of cereals from the LN-EBA sites are above 3‰, but for five sites some of the $\delta^{15}N$ values are below this threshold (range = 1.21–8.93, see Table 4). Two sites dated to LBA-PRIA have cereals with $\delta^{15}N$ values below 3‰, and five above 6‰. Three of the seven sites dated to LBA-PRIA, have measurements of both *H. nudum* and *H. vulgare*. At one site, the $\delta^{15}N$ value of *H. nudum* (13.6‰ $\delta^{15}N$) is much higher than those of *H. vulgare* (around 6‰). From VP-MA there are measurements for both *Avena* and *H. vulgare*, and the range in $\delta^{15}N$ values are high for both cereals. At one site *Avena* has $\delta^{15}N$ values below 3‰, the other sites all show cereal $\delta^{15}N$ values above 3‰. When comparing the threshold lines of manuring intensity after Fraser et al. (2011) and Bogaard et al. (2013), low manuring intensity is indicated

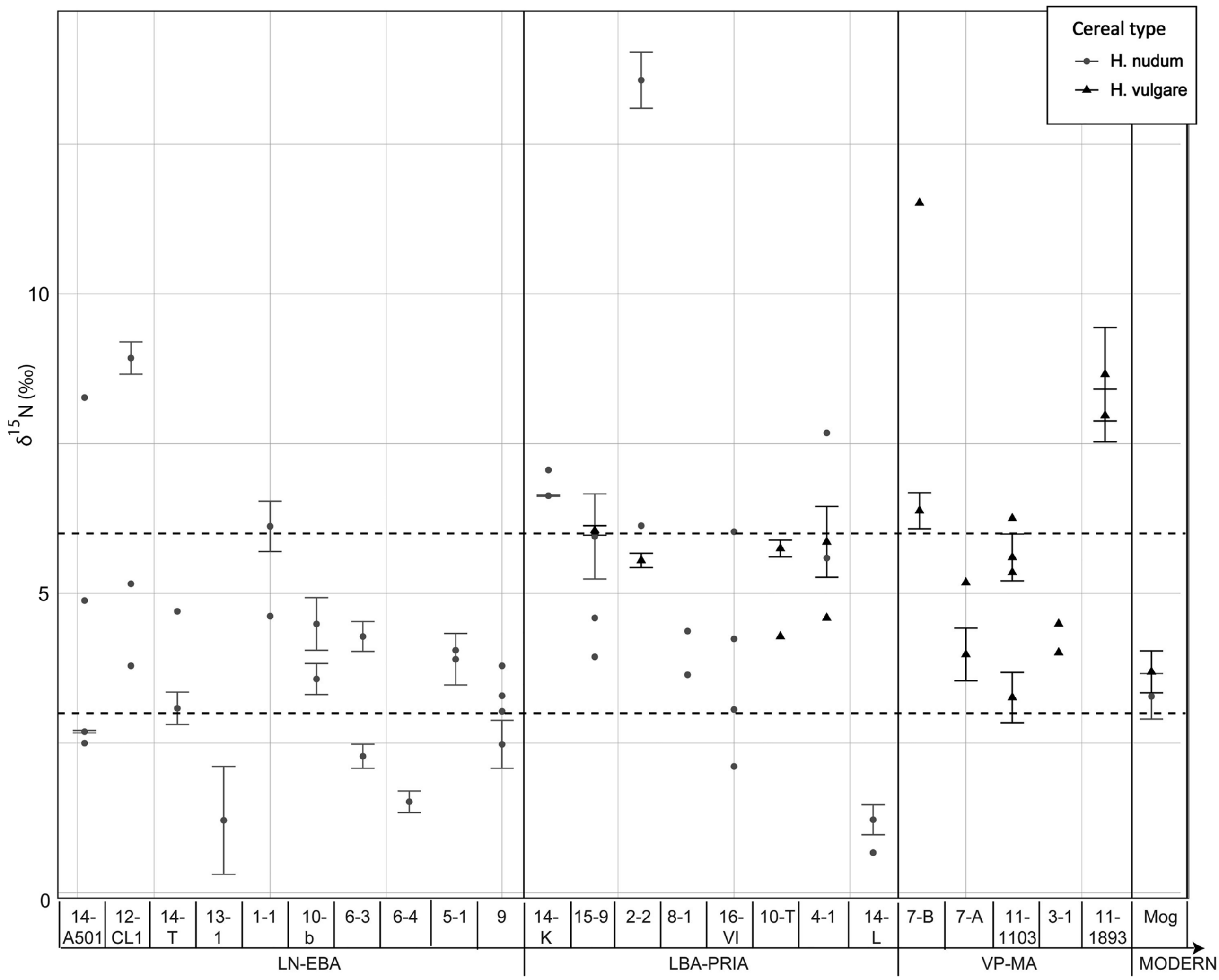

Fig. 2 Plot showing the $\delta^{15}N$ values of fossil *Hordeum* ordered by age with the modern results in the right-hand panel for comparison. Sites are placed along a relative time scale, oldest to the left, youngest to the right. Numbers refer to sample names given in Table 2. Bars represent 2σ standard deviations of the measurements for cereal grains with multiple measurements (see ESM 1 Table 1.3 for full list of measurements). Dashed lines represent the threshold levels of manuring intensity (high, medium and low/none) after Fraser et al. (2011) and Bogaard et al. (2013)

for LN-EBA, medium intensity in LBA-PRIA and medium to high in VP-MA.

The investigated sites are located at different distances to the shoreline, and a tendency of higher $\delta^{15}N$ values at sites within 300 m distance compared to sites at longer distances is indicated in Fig. 5.

The $\Delta^{13}C$ results (Figs. 6, 7) show that the cereals from most sites have $\Delta^{13}C$ values higher than 17.5‰ in all time-periods, but with large variations. At two sites in LBA-PRIA, *H. nudum* has $\Delta^{13}C$ values below 17.5‰, and four sites have $\Delta^{13}C$ values between 17.5 and 18.5‰. In VP-MA, four sites have *Hordeum* $\Delta^{13}C$ values between 17.5 and 18.5‰, one site has *Avena* $\Delta^{13}C$ values close to 17‰ and one site has *Avena* $\Delta^{13}C$ values between 17.5 and 18.5‰. For *Hordeum*, a decreasing trend from LN-EBA to LBA-PRIA, and then stable, or increasing values in VP-MA is indicated. There is a weak correlation between $\Delta^{13}C$ values and age for the complete dataset (using only *Hordeum*), and age does not seem to explain variations in $\Delta^{13}C$ values well. However, when looking at the period from LN-EBA to PRIA and VP-MA separately, there is a good correlation and age seems to explain the changes in $\Delta^{13}C$ values well. All models are statistically significant, for results see ESM 2.

Modern cereals

The results of the t-test of the $\delta^{15}N$ values from the single-grain and 10-grain bulk sample measurements of the modern cereal types and varieties, show that there is no statistically significant difference (see ESM 2). Thus, the results were

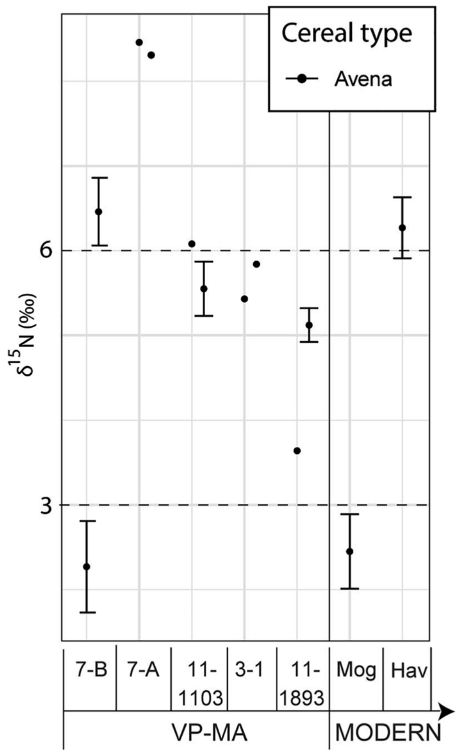

Fig. 3 Plot showing the $\delta^{15}N$ values of fossil *Avena* ordered by age with the modern results in the right-hand panel for comparison. Sites are placed along a relative time scale, oldest to the left, youngest to the right. Numbers refer to sample names given in Table 2. Bars represent 2σ standard deviations of the measurements for cereal grains with multiple measurements (ESM 1 Table 1.3 for full list of measurements). Dashed lines represent the threshold levels of manuring intensity (high, medium and low/none) after Fraser et al. (2011) and Bogaard et al. (2013)

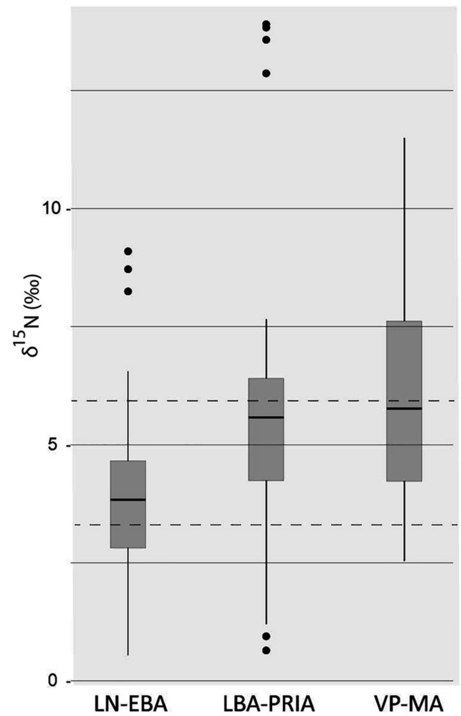

Fig. 4 Boxplot of $\delta^{15}N$ values for fossil *Hordeum* grouped after time-periods. Bars represent the 2σ standard deviations of all measurements in each time group, dots are measurements that fall outside the normal distribution within each time-period. Time-period abbreviations from Table 1. Dashed lines represent the threshold levels of manuring intensity (high, medium and low/none) after Fraser et al. (2011) and Bogaard et al. (2013)

pooled for the different cereal varieties in Figs. 2, 5. The modern *Hordeum* $\delta^{15}N$ values from Mogstad are close to 3‰ $\delta^{15}N$, and the $\delta^{15}N$ value of *Avena* is below 3‰. At Havrå (only *Avena)* the values are slightly higher than 6‰ $\delta^{15}N$. A full list of measurements of the modern cereals is given in ESM 1 Table 1.5.

Discussion

Limitations of the data

The number of fossil cereal grains from each site is limited, and bulk analysis using assemblages of 10 or more grains was not possible. Thus, single-grain analysis was chosen. Measuring single grains will emphasise the difference between the grains and can indicate the probability of grains from the same context coming from different fields or types of fertilisation regime. Previous work has pointed out potential drawbacks with measuring single grains, as grains from different parts of a spikelet can show large differences in $\delta^{15}N$ values (Bogaard et al. 2007; Heaton et al. 2009; Nitsch et al. 2015). There may also be differences between plants, as well as variations within the cereal assemblage (e.g. Kanstrup et al. 2014). Nevertheless, recent studies have shown that single-grain analysis can give an indication of levels/intensity of manuring if present (Kanstrup et al. 2014; Gron et al. 2017; Treasure et al. 2019). We assume that this is the case for our study. In addition, this could give important information regarding agricultural practices that would be lost when analysing cereal assemblages of several grains. The variability in the results of our study may be related to differences in pedological settings between sites or in age (Fraser et al. 2013a). The observed variation is probably real in the sense that some cereal plants may have received more fertiliser than others or were affected by other environmental factors, and it highlights the variability of the material (see discussion below). Following this, we think the single grain analysis is important to understand the variation in datasets that is made invisible in mean values of larger samples.

Table 4 Mean, range, and variance in δ^{15}N values (in ‰) for the different cereal types through time. See Table 1 for time-periods

	H. nudum			*H. vulgare*			*Avena*		
	Mean	Range	Variance	Mean	Range	Variance	Mean	Range	Variance
VP-MA	–	–	–	6.13	3.26–11.52	5.05	5.05	2.27–8.66	3.16
LBA-PRIA	5.09	0.67–13.57	8.25	5.35	4.28–6.05	0.44	–	–	–
LN-EBA	4.03	1.21–8.93	3.31	–	–	–	–	–	–

The two modern test sites differ regarding manuring levels; at Mogstad 20t/ha was added in 2020, whereas at Havrå > 70t/ha was added (Table 3). The cereals from the modern experiments are from just one growing season (2020), which in Norway was a challenging year with a chilly spring, early summer drought and a wet late summer and autumn. At Mogstad, the weather conditions with early summer drought may have caused a low effect of the manuring at this site, especially for *Hordeum*, as high enough manuring levels early in the growing season is important for *Hordeum* in ecological farming (Solemdal et al. 2021). Thus, the δ^{15}N values from Mogstad might be at the lower end of what would be expected of an ecological farming regime. However, the two test-sites were probably equally affected by the weather conditions and the relationships between the two management regimes as captured by our results are probably reliable. The high rainfall in the later part of 2020 may have led to lower δ^{15}N values (Handley et al. 1999; Szpak 2014) and could also be reflected in the high Δ^{13}C values for *Hordeum* at Mogstad. The manuring level at our test site Mogstad is comparable to sites with low annual levels (15–20 t/ha of manure) of manuring and the manuring level at Havrå is well above the high levels of more than 35 t/ha per year in test plots of *Hordeum* from other regions (Fraser et al. 2011; Bogaard et al. 2013). There are hardly any studies involving *Avena* in manuring experiments, but Kolmanič et al. (2022) show how application of 30 t/ha of cattle manure every 3 year in crop rotation leads to δ^{15}N values in *Avena* of around 6‰ (ranging from ca. 4.8–8‰). This means that our modern test sites do not indicate that the use of 3 and 6‰ δ^{15}N as limits for identification of manuring levels is wrong for our region.

The effects of ploughing and tilling on δ^{15}N values is considered negligible, whereas burning/shifting cultivation is thought to potentially cause increased δ^{15}N values in the period shortly after burning, especially if the nutrient level of the soil is high (Szpak 2014). At two of the sites, both dated to LN-EBA, there are signs of burning in the form of identified clearance layers and plant macrofossils that substantiate this in the sediment record (sites 12 and 13, see Halvorsen and Hjelle 2017). The measured δ^{15}N values at these two sites are contrary; the results from site 13 indicates little or no manuring whereas those from site 12 indicate manuring. It thus seems that burning

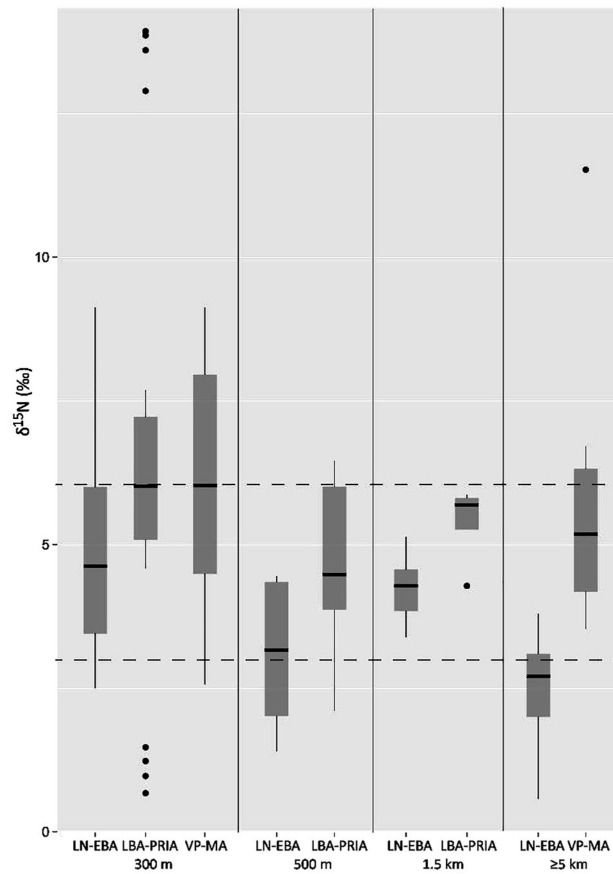

Fig. 5 Boxplot of δ^{15}N values for fossil *Hordeum* grouped after time-period and distance to the sea. Bars represent the 2σ standard deviations of all measurements in each time group, dots are measurements that fall outside the normal distribution within each time-period. Time-period abbreviations from Table 1. Dashed lines represent the threshold levels of manuring intensity (high, medium and low/none) after Fraser et al. (2011) and Bogaard et al. (2013)

did not affect the δ^{15}N values at site 13, whereas burning may have caused elevated δ^{15}N values at site 12, probably due to good soil properties at this site. The analysed cereals at both sites are from clearance layers, so there could be other factors influencing the results and leading to higher δ^{15}N values at site 12, for example burning in combination with manuring from grazing livestock. At site 13, the analysed cereals and the charcoal interpreted as a clearance layer may represent two different activity phases. The clearance could be a later activity than the

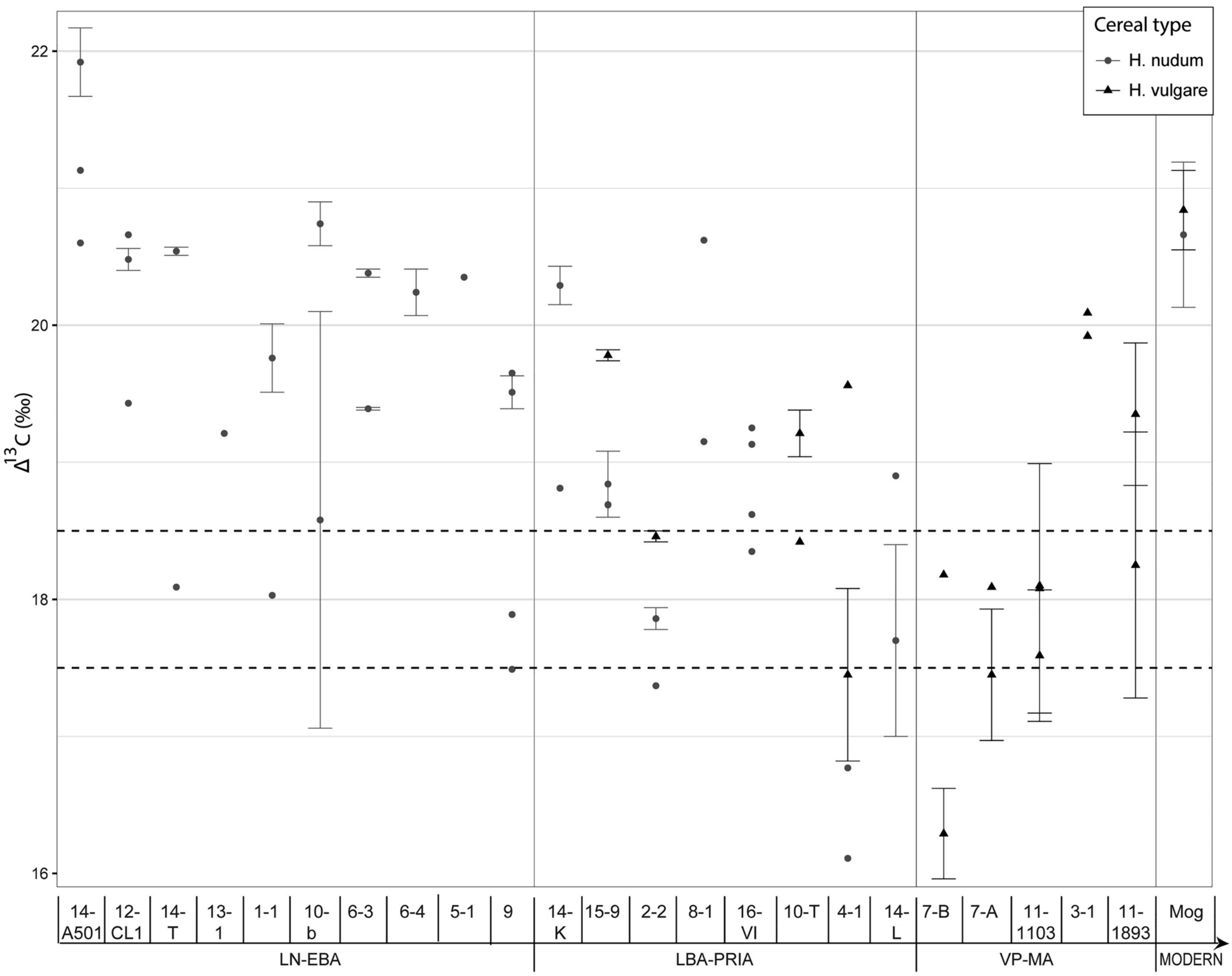

Fig. 6 Plot showing the estimated $\Delta^{13}C$ values from the $\delta^{13}C$-measurements for *Hordeum*. Sites are placed along a relative time scale, oldest to the left, youngest to the right. Numbers refer to sample names given in Table 2. Bars represent 2σ standard deviations of the measurements for cereal grains with multiple measurements (see ESM 1 Table 1.3 for full list of measurements). Dashed horizontal lines represents threshold level indicating good and dry growing conditions for barley after Wallace et al. (2013)

one represented by the analysed cereal grains, explaining the low $\delta^{15}N$ values.

Possibility of manuring in early management systems

From the isotopic signature of red deer and wild boar found by Rosvold et al. (2010), it is possible to infer a $\delta^{15}N$ value around 0‰ for the natural vegetation in western Norway. Thus, $\delta^{15}N$ values above this probably reflect amelioration of the soils, possibly through manuring of the cereal fields. This means that the threshold levels of manuring intensity (high, medium and low/none) after Fraser et al. (2011) and Bogaard et al. (2013) might be applicable for our region. In the youngest time-periods (VP-MA), cereals (except one grain of *Avena*) show $\delta^{15}N$ values above 3‰, and a few grains also higher than 6‰ (Figs. 2, 3). This is the case both for *Avena* and *H. vulgare* and could be a sign of medium to intensely manured cereal fields. The bulk of the cereal grains from the LBA-PRIA show comparable $\delta^{15}N$ values, although with a few exceptions. This suggests a well-developed management system where fertilisation provided the basis for permanent cultivation, which is also indicated in pollen and macrofossil data from the area (Halvorsen and Hjelle 2017). This indicates that the cultivation systems of the Viking Age and the Middle Ages have their roots in the LBA/PRIA management systems.

Enough fertiliser to keep the soil organic might have been difficult to come by. The use of plaggen soil, where peat/organic material is added to soil for cultivation (Blume and Leinweber 2004) might have been practiced at this time. Based on the presence of pollen and spores reflecting forest

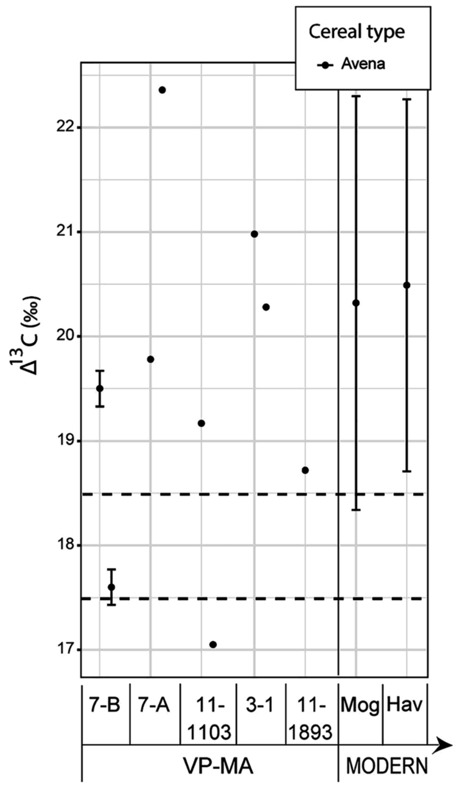

Fig. 7 Plot showing the estimated Δ^{13}C values from the δ^{13}C-measurements for *Avena*. Sites are placed along a relative time scale, oldest to the left, youngest to the right. Numbers refer to sample names given in Table 2. Bars represent 2σ standard deviations of the measurements for cereal grains with multiple measurements (see ESM 1 Table 1.3 for full list of measurements). Dashed horizontal lines represents threshold level indicating good and dry growing conditions for barley after Wallace et al. (2013)

vegetation, Kvamme (1982) postulated plaggen soil formation in western Norway in the Viking Age, a practice also suggested from in the coast of western Norway based on macrosporangia of *Selaginella* (Hjelle and Halvorsen 2013). Micromorphological studies have documented the addition of plant material to enhance soils since the Bronze Age (Sageidet 2009). In the LBA-PRIA, accumulation of thick deposits took place at several sites in western Norway (Diinhoff 1999). This build-up of material would not be possible without adding organic material to the soil. Thus, it is reasonable to assume that plaggen formation was part of the agricultural system in the PRIA, and probably also in the LBA.

The older time-periods (LN-EBA), show large variations in the isotope data, and generally the δ^{15}N values are lower than in later periods (Fig. 4). However, most sites have δ^{15}N values above 3‰, and are within the range of or higher than the ecologically grown modern cereals at Mogstad. There has probably been variation in land-use practices in both space and time within the LN-EBA, where intensively managed fields close to the settlements received livestock manure and household waste, and a more extensive management practice with fallow periods took place in areas further afield (cf. Viklund et al. 2013). Additionally, variations in δ^{15}N values within sites could be related to manure availability, and uneven spreading of manure on the fields. If manure was spread in lumps, some plants could receive more (or less) manure and thus nutrients than a neighbouring plant in the same field. Additional explanations can arise from the archaeological contexts (i.e. houses): the sampled cereals could have come from different cultivation years, and perhaps there was variation in the amounts of manure between years. The cereals found in different contexts may also reflect different uses of the grains, with cereals cultivated for different purposes having different demands or availability of manure. This variation could potentially be evaluated together with archaeological data from each site, to gain additional information about activity and social life.

The sea contains higher proportions of the heavier isotopes of C and N compared to air, and salt spray is known to lead to elevated δ^{15}N values (Heaton 1987; Britton et al. 2008), although in areas with high rainfall this effect may be somewhat diluted (Heaton 1987). Several of our sites are situated close to the coastline, but mainly sheltered from the outer coast and the prevailing westerlies, and with moderate to high rainfall. Salt spray may therefore not have been of major importance. However, the proximity to the sea means kelp and other seaweeds would be easily available, and the use of such material as fertilising agents is known from coastal areas (Kaland 1979; Bakels 1997; Guttmann et al. 2005). Kelp and other seaweeds are enriched in ^{13}C and ^{15}N (Schulting et al. 2017; Sharp 2017), and it has been shown that use of seaweed, alone or mixed with manure, or the use of fish remains (cf. Gröcke et al. 2021), increases the δ^{15}N values of cereals. As plants get their CO_2 from the air, the δ^{13}C values, however, remain unchanged (Blanz et al. 2019). In Fig. 7 higher δ^{15}N values at the sites closest to the sea is indicated for all time-periods. However, it is important to remember that the figure does not consider topographic differences, aspect, or soil properties and that it is not known whether cereal plots were placed in sheltered areas away from the sea or not. However, the figure indicates the possibility that seaweed was used at all sites situated along the coast. A combination of livestock manure mixed with seaweed has probably been used for as long as cultivation has taken place in western Norway.

As the δ^{15}N values indicate that manuring has taken place in areas in the region from the LN-EBA, a fully developed farming system was probably established in western Norway at that time. Pollen analysis indicates that cereal cultivation was introduced to the region already during the EN, but it was not until ca. 2400/2300 BCE that the agrarian economy was fully established (Hjelle et al. 2006, 2018;

Prøsch-Danielsen et al. 2018; Bergsvik et al. 2020, 2021). Also, from this time macrofossil remains of charred cereals are found in the region. Although with a fully established farming system in LN-EBA, the increase in $\delta^{15}N$ values from LBA-PRIA and onwards indicated in our data suggests that manuring became a more regular part of the management system from then on. This probably reflects the importance of farms as an economic factor in the society in the Iron Age (Solberg 2000; Myhre 2004). Open farmed landscape characterised western Norway in this period (Hjelle et al. 2018), and could suggest a high degree of contact between well-established farming societies. Our data are limited to one site for the LBA, but high consistency in the macrofossil records (Halvorsen and Hjelle 2017) and a marked increase in cultivated fields in the region (Hjelle et al. 2018), suggest that the same practices go back to the LBA. This indicates that the development in western Norway is comparable to southern Scandinavia and that the practice of manuring is a result of the development of three-aisled houses in this period (Grabowski 2011; Kanstrup et al. 2011).

Water availability

Previous studies have used $\Delta^{13}C$ values to elucidate water management in dry areas (Araus et al. 1997, 2014; Ferrio et al. 2005; Aguilera et al. 2012). For barley (*H. vulgare* and *H. nudum*) a $\Delta^{13}C$ value exceeding 18.5‰ is considered to indicate cereals grown under conditions with plenty of water, and values below 17.5‰ $\Delta^{13}C$ to indicate drought (Wallace et al. 2013). Currently, there have not been any studies regarding $\Delta^{13}C$ values in *Avena* in relation to water status, thus only *Hordeum* $\Delta^{13}C$ values are considered in our interpretations. Today, most areas in western Norway are not restricted in water availability. From our data this seems also to be the case in prehistory. From the PRIA a more unstable climate with fluctuating precipitation (including dry periods) has been shown (De Jong et al. 2009). In this period, cereals from two sites display $\Delta^{13}C$ values possibly indicating dry conditions.

At site 4, two *H. nudum* and one *H. vulgare* grains have $\Delta^{13}C$ values below 17.5‰, which indicates drought/water stress. This is also the case for one *H. nudum* grain at site 2, and one *H. vulgare* grain at site 7. These sites also have *Hordeum* with $\Delta^{13}C$ values either above 18.5‰ or between 17.5 and 18.5‰, which could reflect the variability of the field where the cereals were grown, where some areas were drier than others. However, it is probably more likely that they represent different years where some years have been drier at the time of grain filling than others.

The modern *Hordeum* from Mogstad shows $\Delta^{13}C$ values well above 18.5‰ in a year that had early summer drought and high levels of precipitation in the late summer (and autumn). This perhaps indicates that the later part of the growing season influenced the $\Delta^{13}C$ values more than the early parts. From this, one could postulate that the fossil grains of our study were grown under drier conditions than at Mogstad. However, precipitation is not the only factor that can potentially influence $\Delta^{13}C$ values (see Flohr et al. 2019 and references therein) and finding one explanation for all sites through all time-periods is not possible within the framework of this study.

Conclusion

This study has shown indications of low to moderate levels of manuring in western and north-western Norway from the LN and EBA (2300–1200 BCE), by comparing $\delta^{15}N$ values of charred, fossil cereals with measurements of modern cereals grown under known manuring regimes. This implies that people had knowledge of the positive effects of manuring of crops from the time of the expansion in arable farming in western Norway in the LN. Site-to-site variation in the LN and EBA is evident, and not all sites display elevated $\delta^{15}N$ values. This suggests that manuring was prioritised in some places and not in others or a limited availability of livestock manure. Many of our sites are situated along the coast, and it is likely that the use of marine resources to amend soil quality was a widespread practice. From the PRIA onwards (after 500 BCE), and probably some hundred years earlier, there is clear evidence of manuring in all investigated areas. Although livestock manure probably is the main source of the elevated $\delta^{15}N$ values of the cereals at our sites in this period, utilisation of marine resources (kelp, other seaweeds and fish) was possibly common. This practice, established at latest in the PRIA, was still in use in the MA and is probably comparable to the traditional management systems continuing into the early twentieth century.

For future studies it would be beneficial to use larger assemblages of cereal grains to lower the grain-to-grain variability and investigate if this corroborates the findings of the present study. This, however, assume that high quantities of fossil grains are available. The data from the modern-day plots are from only one growing season and it would be interesting to repeat the measurements from these test plots over several years to verify the results.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00334-023-00923-3.

Acknowledgements Beate Helle is thanked for aid with illustrations and Cathy Jenks for linguistic corrections. Stable isotope analyses were done at the Norwegian National Infrastructure project FARLAB (Facility for advanced isotopic research and monitoring of weather, climate, and biogeochemical cycling, Project No. 245907) at the University of Bergen, Norway. The authors thank Frode Grønmyr at Landbruk Nordvest and Marit Adelsten Jensen at Havrå for collecting the modern cereals and supplying information about manuring regimes. Two anonymous reviewers are thanked for their input on a previous version of the manuscript.

Declarations

Conflict of interest The authors have no conflicting or competing interests relating to the contents of the article.

References

Aguilera M, Ferrio JP, Pérez G, Araus JL, Voltas J (2012) Holocene changes in precipitation seasonality in the western Mediterranean Basin: a multi-species approach using $\delta^{13}C$ of archaeobotanical remains. J Quat Sci 27:192–202

Araus JL, Febrero A, Buxó R et al (1997) Identification of ancient irrigation practices based on the carbon isotope discrimination of plant seeds: a case study from the south-east iberian Peninsula. J Archaeol Sci 24:729–740

Araus JL, Ferrio JP, Voltas J, Aguilera M, Buxó R (2014) Agronomic conditions and crop evolution in ancient Near East agriculture. Nat Commun 5:3953

Austad I, Sørli S, Domaas ST (2012) Den før-industrielle garden—Havrå i Hordaland. Heimen 49:277–290

Bakels CC (1997) The beginnings of manuring in western Europe. Antiquity 71:442–445

Bakkevig S (1992) Prehistoric cereal raising at Forsandmoen, southwestern Norway: changes between the Bronze Age and the Iron Age. Laborativ Arkeologi 6:49–55

Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci Data 5:180214

Bergsvik KA, Hjelle KL, Halvorsen LS, Olsen AB, Zinsli C (2020) Low-level agriculture in Neolithic western Norway. In: Gron KJ, Sørensen L, Rowley-Conwy P (eds) Farmers at the frontier: A pan European perspective on Neolithisation. Oxbow Books, Oxford, pp 339–362

Bergsvik KA, Darmark K, Hjelle KL, Aksdal J, Åstveit LI (2021) Demographic developments in Stone Age coastal western Norway by proxy of radiocarbon dates, stray finds and palynological data. Quat Sci Rev 259:106898

Blanz M, Ascough P, Mainland I et al (2019) Seaweed fertilisation impacts the chemical and isotopic composition of barley: implications for analyses of archaeological skeletal remains. J Archaeol Sci 104:34–44

Blume H-P, Leinweber P (2004) Plaggen Soils: landscape history, properties, and classification. J Plant Nutr Soil Sci 167:319–327

Bogaard A, Heaton THE, Poulton P, Merbach I (2007) The impact of manuring on nitrogen isotope ratios in cereals: archaeological implications for reconstruction of diet and crop management practices. J Archaeol Sci 34:335–343

Bogaard A, Fraser R, Heaton THE et al (2013) Crop manuring and intensive land management by Europe's first farmers. Proc Natl Acad Sci USA 110:12589–12594

Bogaard A, Hodgson J, Nitsch E et al (2016) Combining functional weed ecology and crop stable isotope ratios to identify cultivation intensity: a comparison of cereal production regimes in Haute Provence, France and Asturias, Spain. Veget Hist Archaeobot 25:57–73

Britton K, Müldner G, Bell M (2008) Stable isotope evidence for salt-marsh grazing in the Bronze Age Severn Estuary, UK: implications for palaeodietary analysis at coastal sites. J Archaeol Sci 35:2111–2118

Coplen TB (2011) Guidelines and recommended terms for expression of stable-isotope-ratio and gas-ratio measurement results. Rapid Commun Mass Spectrom 25:2538–2560

De Jong R, Hammarlund D, Nesje A (2009) Late Holocene effective precipitation variations in the maritime regions of south-west Scandinavia. Quat Sci Rev 28:54–64

DeNiro MJ (1987) Stable isotopy and archaeology. Am. Scientist 75:182–191

Diinhoff S (1999) Træk af det Vestlandske jordbrugs historie fra sen stenalder til tidlig middelalder (Features of the western Norwegian agricultural history from the late Stone Age to the Early Middle Ages). Arkeo 1:14–28

Diinhoff S (2004) Tidlige jordbrugsbosætninger på Vestlandet med spor efter toskibede langhuse (Early agrarian settlements in Vestlandet with two-aisled longhouses). Primitive Tider 7:41–48

Diinhoff S, Slinning T (2013) Langhuset på Gjøsund og dateringsproblematikken (The longhouse at Gjøsund and the dating issues). In: Diinhoff S, Ramstad M, Slinning T (eds) Jordbruksbosetningens utvilking på Vestlandet (The development of the agrarian settlement in Vestlandet) UBAS—Universitetet i Bergen Arkeologiske Skrifter 7. Universitetet i Bergen, Bergen, pp 65–76

Ferrio JP, Araus JL, Buxó R, Voltas J, Bort J (2005) Water management practices and climate in ancient agriculture: inferences from the stable isotope composition of archaeobotanical remains. Veget Hist Archaeobot 14:510–517

Flohr P, Jenkins E, Williams HRS, Jamjoum K, Nuimat S, Müldner G (2019) What can crop stable isotopes ever do for us? an experimental perspective on using cereal carbon stable isotope values for reconstructing water availability in semi-arid and arid environments. Veget Hist Archaeobot 28:497–512

Fraser RA, Bogaard A, Heaton T et al (2011) Manuring and stable nitrogen isotope ratios in cereals and pulses: towards a new archaeobotanical approach to the inference of land use and dietary practices. J Archaeol Sci 38:2790–2804

Fraser RA, Bogaard A, Charles M et al (2013) Assessing natural variation and the effects of charring, burial and pre-treatment on the stable carbon and nitrogen isotope values of archaeobotanical cereals and pulses. J Archaeol Sci 40:4754–4766

Fraser RA, Bogaard A, Schäfer M, Arbogast R, Heaton THE (2013b) Integrating botanical, faunal and human stable carbon and nitrogen isotope values to reconstruct land use and palaeodiet at LBK Vaihingen an der Enz, Baden-Württemberg. World Archaeol 45:492–517

Grabowski R (2011) Changes in cereal cultivation during the Iron Age in southern Sweden: a compilation and interpretation of the archaeobotanical material. Veget Hist Archaeobot 20:479–494

Gröcke DR, Treasure ER, Lester JJ, Gron KJ, Church MJ (2021) Effects of marine biofertilisation on Celtic bean carbon, nitrogen and sulphur isotopes: Implications for reconstructing past diet and farming practices. Rapid Commun Mass Spectrom 35:e8985

Gron KJ, Gröcke DR, Larsson M, Sørensen L, Larsson L, Rowley-Conwy P, Church MJ (2017) Nitrogen isotope evidence for manuring of early Neolithic Funnel Beaker Culture cereals from Stensborg, Sweden. J Archaeol Sci Rep 14:575–579

Gustafsson S (1998) The farming economy in South and Central Sweden during the Bronze Age. A study based on carbonised botanical evidence. Curr Swedish Archaeol 6:63–71

Guttmann EB, Simpson IA, Davidson DA (2005) Manuring practices in antiquity: A review of the evidence. In: Smith DN, Brickley MB, Smith W (eds) Fertile ground. Papers in honour of Susan Limbrey. Symposia of the Association for Environmental Archaeology 22. Oxbow books, Oxford, pp 68–76

Halvorsen LS, Hjelle KL (2017) Prehistoric agriculture in western Norway—Evidence for shifting and permanent cultivation based

on botanical investigations from archaeological sites. J Archaeol Sci Rep 13:682–696
Handley LL, Austin AT, Robinson D et al (1999) The ^{15}N natural abundance (δ^{15}N) of ecosystem samples reflects measures of water availability. Aust J Plant Physiol 26:185–199
Heaton THE (1987) The ^{15}N/^{14}N ratios of plants in South Africa and Namibia: relationship to climate and coastal/saline environments. Oecologia 74:236–246
Heaton THE, Jones G, Halstead P, Tsipropoulos T (2009) Variations in the ^{13}C/^{12}C ratios of modern wheat grain, and implications for interpreting data from Bronze Age Assiros Toumba, Greece. J Archaeol Sci 36:2224–2233
Hjelle KL (1999) Use of modern pollen samples and estimated pollen representation factors as aids in the interpretation of cultural activity in local pollen diagrams. Norw Archaeol Rev 32:19–39
Hjelle KL, Hufthammer AK, Bergsvik KA (2006) Hesitant hunters: a review of the introduction of agriculture in western Norway. Environ Archaeol 11:147–170
Hjelle KL, Prøsch-Danielsen L, Soltvedt E-C (2016) Potential and recommendations: Agrarian botanical data from Western Norway. In: Iversen F, Petersson H (eds) The agrarian life of the north 2000 BC-AD 1000: Studies in rural settlement and farming in Norway. Portal Academic, Kristiansand, pp 293–342
Hjelle KL, Halvorsen LS, Prøsch-Danielsen L et al (2018) Long-term changes in regional vegetation cover along the west coast of southern Norway: The importance of human impact. J Veg Sci 29:404–415
Hjelle KL, Halvorsen LS (2013) Makrofossilanalyser av prøver fra dyrkingslag, Osnes gnr. 7, bnr. 775/776, Ulstein kommune, Møre og Romsdal (Macrofossil analyses of samples from agricultural layers). 10/2013, Unpublished report
Jensen MA, Monstad K, Kvamme M (2012) Kulturlandskap på museum—er det mulig i praksis? utfordringer og erfaringer fra det freda kulturmiljøet Havrå (Cultural landscapes at the museum—is it possible in practice? Challenges and experiences from the protected cultural environment Havrå). Heimen 49:319–332
Jones G (2002) Weed ecology as a method for the archaeobotanical recognition of crop husbandry practices. Acta Palaeobot 42:185–193
Kaland SH (1979) Lurekalven, en lyngheigård fra vikingtid/middelalder. En økonomisk studie. In: Fladby R, Sandnes J (eds) På leiting etter den eldste garden. Nye metoder i studie av tidlig norsk bosettingshistorie. Skrifter fra Norsk lokalihistorisk institutt 6. Universitetsforlaget, Oslo, pp 71–86
Kanstrup M, Thomsen IK, Andersen AJ, Bogaard A, Christensen BT (2011) Abundance of ^{13}C and ^{15}N in emmer, spelt and naked barley grown on differently manured soils: towards a method for identifying past manuring practice. Rapid Commun Mass Spectrom 25:2879–2887
Kanstrup M, Holst MK, Jensen PM, Thomsen IK, Christensen BT (2014) Searching for long-term trends in prehistoric manuring practice. δ^{15}N analyses of charred cereal grains from the 4th to the 1st millennium BC. J Archaeol Sci 51:115–125
Kolmanič A, Sinkovič L, Nečemer M, Ogrinc N, Meglič V (2022) The effect of cultivation practices on agronomic performance, elemental composition and isotopic signature of Spring Oat (*Avena sativa* L.). Plants 11:169
Kreuz A, Schäfer E (2011) Weed finds as indicators for the cultivation regime of the early Neolithic Bandkeramik culture? Veget Hist Archaeobot 20:333–348
Kvamme M (1982) En vegetasjonshistorisk undersøkelse av kulturlandskapets utvikling på Lurekalven. Lindås hd., Hordaland. Unpublished Cand. Real Thesis. University of Bergen, Bergen
Mathias JM, Hudiburg TW (2022) *isocalcR*: An R package to streamline and standardize stable isotope calculations in ecological research. Glob Chang Biol 28:7428–7436
Moen A, Odland A (1993) Vegetasjonsseksjoner i Norge (The vegetational sections of Norway). In: Krovoll A, Moen A (eds) Fagmøte i vegetasjonsøkologi på Kongsvold i 1993 (Symposium on vegetation ecology at Kongsvold 1993). Universitetet i Trondheim, Vitenskapsmuseet, Trondheim, pp 37–53
Moen A, Lillethun A, Odland A (1999) National Atlas of Norway: Vegetation. Norwegian Mapping Authority, Hønefoss
Myhre B (2004) Agriculture, landscape and society ca. 4000 BC–AD 800. In: Almås R (ed) Norwegian agricultural history. Tapir Academic Press, Trondheim, pp 14–77
Naumann E, Krzewińska M, Götherström A, Eriksson G (2014) Slaves as burial gifts in Viking Age Norway? evidence from stable isotope and ancient DNA analyses. J Archaeol Sci 41:533–540
Nitsch EK, Charles M, Bogaard A (2015) Calculating a statistically robust δ^{13}C and δ^{15}N offset for charred cereal and pulse seeds. STAR: Sci Technol Archaeol Res 1:1–8
Olausson M (1998) "Sig mig hur många djur du har…" Om arkeologi och stallning ("Tell me how much livestock you have…" About archaeology and stalling). In: Viklund K, Engelmark R, Linderholm J (eds) Fähus från bronsålder till i dag. Stallning och utegångsdrift i långtidsperspektiv (Cattle houses from the Bronze Age to the present Stalling and grazing in the long perspective). Skrifter om skogs–och lantbrukshistoria. Nordiska museet, Stockholm, pp 28–56
Olsen AB (2013) Jordbrukskulturens pionertid på Vestlandet. Hus, åker og territorialitet. In: Diinhoff S, Ramstad M, Slinning T (eds) Jordbruksbosetningens utvikling på Vestlandet. UBAS—Universitetet i Bergen Arkeologiske Skrifter 7. Universitetet i Bergen, Bergen, pp 129–148
Øye I, Julshamn L, Bade RL, Valvik KA, Larsen J (2002) Vestlandsgården-fire arkeologiske undersøkelser (The western Norwegian farm—four archaeological surveys) Arkeologisk institutt. Universitetet i Bergen, Bergen
Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci Discuss 4:439–473
Prøsch-Danielsen L, Soltvedt E-C (2011) From saddle to rotary. Hand querns in South-Western Norway and the corresponding crop plant assemblages. Acta Archaeol 82:129–162
Prøsch-Danielsen L, Prescott C, Holst MK (2018) Economic and social zones during the Late Neolithic/Early Bronze Age in Jaeren, Southwest Norway reconstructing Large-scale land-use patterns. Praehist Z 93:48–88
R Core Team (2015) R version 3.2.2
Rognstad O, Løvberget AI, Steinset TA (2016) Landbruket i Norge 2015. Jordbruk—Skogbruk—Jakt (Agriculture in Norway 2015. Farming—Forestry—Hunting). Statistisk sentralbyrå Statistics Norway, Norway
Rosvold J, Halley DJ, Hufthammer AK, Minagawa M, Andersen R (2010) The rise and fall of wild boar in a northern environment: Evidence from stable isotopes and subfossil finds. Holocene 20:1113–1121
Sageidet BM (2009) Late Holocene land use at Orstad, Jæren, southwestern Norway, evidence from pollen analysis and soil micromorphology. Catena 78:198–217
Schulting RJ, Vaiglova P, Crozier R, Reimer PJ (2017) Further isotopic evidence for seaweed-eating sheep from Neolithic Orkney. J Archaeol Sci Rep 11:463–470
Sharp Z (2017) Principles of stable isotope geochemistry, 2nd edn. https://doi.org/10.25844/h9q1-0p82
Skre BG (1994) Havråboka: soga om ein gammal gard på Osterøy. Stiftinga Havråtunet, Osterøy
Solberg B (2000) Jernalderen i Norge 500. før Kristus til 1030 etter Kristus. Cappelen Akademisk Forlag, Oslo

Solemdal L, Frøseth RB, Grønmyr F (2021) Bygg og havre til mat—resultat fra feltforsøk i Surnadal (Barley and oats for food—results from field trials in Surnadal). NORSØK Rapport 6:4–32
Styring AK, Fraser RA, Bogaard A, Evershed RP (2014) Cereal grain, rachis and pulse seed amino acid $\delta^{15}N$ values as indicators of plant nitrogen metabolism. Phytochemistry 97:20–29
Styring AK, Ater M, Hmimsa Y et al (2016) Disentangling the effect of farming practice from aridity on crop stable isotope values: a present-day model from Morocco and its application to early farming sites in the eastern Mediterranean. Anthropocene Rev 3:2–22
Styring AK, Charles M, Fantone F et al (2017) Isotope evidence for agricultural extensification reveals how the world's first cities were fed. Nat Plants 3:17076
Szpak P (2014) Complexities of nitrogen isotope biogeochemistry in plant-soil systems: implications for the study of ancient agricultural and animal management practices. Front Plant Sci 5:288
Treasure ER, Gröcke DR, Caseldine AE, Church MJ (2019) Neolithic farming and wild plant exploitation in Western Britain: archaeobotanical and crop stable isotope evidence from wales (c. 4000–2200 cal BC). Proc Prehist Soc 85:193–222
Van der Sluis LG, Hollund HI, Kars H, Sandvik PU, Denham SD (2016) A palaeodietary investigation of a multi-period churchyard in Stavanger, Norway, using stable isotope analysis (C, N, H, S) on bone collagen. J Archaeol Sci Rep 9:120–133
Viklund K (1998) Cereals, weeds and crop processing in Iron Age Sweden: methodological and interpretive aspects of archaeobotanical evidence. University of Umeå, Umeå
Viklund K, Linderholm J, Macphail RI (2013) Integrated palaeoenvironmental study: micro- and macrofossil analysis and geoarchaeology (soil chemistry, magnetic susceptibility and micromorphology). In: Gjerpe LE (ed) E18-prosjektet Gulli-Langåker, Oppsumering og arkeometriske analyser (E18-Project Gulli-Langåker, Summary and archaeometrical analyses). Fagbokforlaget Vigmostad & Bjørke, Oslo, pp 25–83
Virginia RA, Delwiche CC (1982) Natural ^{15}N abundance of presumed N_2-fixing and non-N_2-fixing plants from selected ecosystems. Oecologia 54:317–325
Wallace M, Jones G, Charles M, Fraser R, Halstead P, Heaton THE, Bogaard A (2013) Stable carbon isotope analysis as a direct means of inferring crop water status and water management practices. World Archaeol 45:388–409