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Revealing continuity and sustainability through isotope analysis on the A14 project, Cambridgeshire, UK

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ABSTRACT

The A14 archaeological project was the largest commercial archaeological programme in the UK - spanning a 25 km stretch of rural Cambridgeshire, which included a pioneering and ambitious multi-isotope programme to examine crop, livestock and human remains. The resulting dataset spans the Bronze Age to medieval period, incorporating settlements spread across multiple landscape blocks. Our focus on the Iron Age, Roman and Anglo-Saxon periods reveals a remarkable continuity in agricultural practices, diet and provenance. This isotopic homogeneity suggests a persistence of local traditions despite macro-economic and socio-political shifts. Subtle variations within this pattern, however, offer unique insights into individuals who deviated from the norm, hinting at the growing influence of external connections and market economies on these past communities. This study underscores the value of integrating multi-isotope analysis in large-scale commercial archaeological projects, and the rich narrative that emerges from collaborative efforts between commercial and academic researchers.

1. Introduction

The A14 Road Improvement Scheme between Cambridge and Huntingdon, funded by National Highways, involved one of the largest commercial archaeological projects ever undertaken in the UK. Fieldwork and assessment were completed in 2019, and the analysis programme was finished in early 2024. The scheme encompassed a 25 km stretch of rural Cambridgeshire with excavations by MOLA-Headland Infrastructure (MHI) and partners covering 232 ha. Archaeological remains included two Neolithic monuments, six Bronze Age barrows and two large burial sites, twenty-two Iron Age settlements, thirteen Roman settlements, several Anglo-Saxon settlements, the deserted medieval village of Houghton and scattered post-medieval features (West et al., 2024). The environmental assemblage included the remains of 96 inhumed humans (plus 276 individuals cremated and disarticulated remains), over 4 tonnes of animal bone and over 9000 environmental whole-earth samples.

The analysis programme included provision for the stable light isotope analysis of human, animal and plant remains as well as radiogenic strontium isotope analysis (MHI, 2019). For the archaeobotanical sub-package, the aim was to examine spatial and temporal variation in crop husbandry regimes. For the zooarchaeological sub-package, the work was centred around investigations of long-term foddering/grazing patterns and movement patterns. The human package was designed to investigate mobility and migration, as well as palaeodietary reconstruction that incorporates crop and livestock baselines, and was integrated into a programme of ancient DNA analysis undertaken as part of the Francis Crick Institute 100 Genomes Project (Silva et al., 2022).

1.1. Archaeological and regional setting

Floral, faunal and human samples included in this study derived from Bronze Age through to medieval contexts. The scheme is divided into eight landscape blocks: in the west are Alconbury, Brampton West and

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Brampton South on the gravel terraces of the River Ouse; centrally are West of Ouse and River Great Ouse landscape blocks, on and around the river floodplains; to the east claylands become more prominent, which is where the Fenstanton Gravels, Conington and – in the far east of the scheme – Bar Hill landscape blocks are located (Fig. 1).

The Bronze Age of the A14 is dominated by monumental and burial activity, with only limited settlement evidence and field systems discovered at Conington. Whilst the area was an active, and culturally significant, landscape in the Early and Middle Bronze Age, there is little evidence of domestic or agricultural activity in the Late Bronze Age (Christie, 2024).

The Iron Age of the A14 was marked by a rapid expansion of settlement activity. Early Iron Age settlement expansion was largely restricted to Fenstanton Gravels and Conington, but in the Middle-Late Iron Age settlements became prolific across the scheme, totalling 22 distinct settlements. Many of these settlements were small and did not persist into the Late Iron Age. Evidence of stock enclosures, drove-ways and four-poster structures (likely granaries) were widespread. The Middle-Late Iron Age land grab appears to have given way to aggregation and abandonment in the Late Iron Age - when settlement activity coalesces around fewer locales, especially at Brampton West (Christie and Scholma-Mason, 2024).

The Roman period is a prominent component of the A14 project's archaeological record. Occupation comprised rural settlements scattered between the nucleated settlements outside the scheme boundary at Godmanchester and Cambridge. Thirteen settlements were excavated, comprising mainly complex farmsteads (Allen and Smith, 2016, p. 28), though the periphery of a likely villa at River Great Ouse 2 and parts of two nucleated settlements, Alconbury 4 and Conington 4, were also found. The farmstead of Fenstanton Gravels 4 was notably atypical, and had evidence of a large and diverse population that was engaged in a wide range of economic activities. Fenstanton Gravels 4 may have been linked to a possible roadside settlement recently excavated nearby at Fenstanton Dairy Crest and Cambridge Road (Ingham, 2022). During the Iron Age-Roman transition there had been a period of settlement consolidation. Early Roman settlement locations reflected those of the Late Iron Age, but the size and nature of settlements changed markedly as the Roman period progressed - likely linked to wider socio-economic changes in the post-Conquest period. In the Late Roman period, there was a further phase of consolidation, with smaller sites abandoned, the development of a villa complex near to the River Great Ouse landscape block, and the expansion of Alconbury 4 (Scholma-Mason and Smith, 2024).

The collapse of centralised Roman rule in Britain led to major changes in society and economy, and until recently relatively little was known of Anglo-Saxon settlement patterns in the region. In the early-mid Anglo-Saxon period most settlement activity within the A14 scheme was concentrated at Brampton West and Conington. Significant further contraction occurred in the Late Saxon period, with occupants at Conington likely relocated outside of the scheme boundary to Conington proper. One of the Brampton West settlements was abandoned, whilst another was much reduced. A new, semi-nucleated settlement at Brampton West did emerge, however (West, 2024).

Settlement contraction and nucleation on the A14 reached its zenith in the medieval period. The wider landscape became primarily agricultural with only very occasional, scattered remains. Settlement activity was consolidated at Brampton West at the, later deserted, village of Houghton. Houghton was one of five deserted 'shrunken' villages in the surrounding area (Boxworth, Conington, Fenstanton and Lolworth), and is the only one to have been excavated (Moretti, 2024).

2. Methodology

2.1. Materials

All archaeobotanical samples comprised charred cereal grains, and selection focused on the Iron Age-Roman and Roman-Anglo-Saxon transitions (Table 1). Archaeozoological analysis focused on the Iron

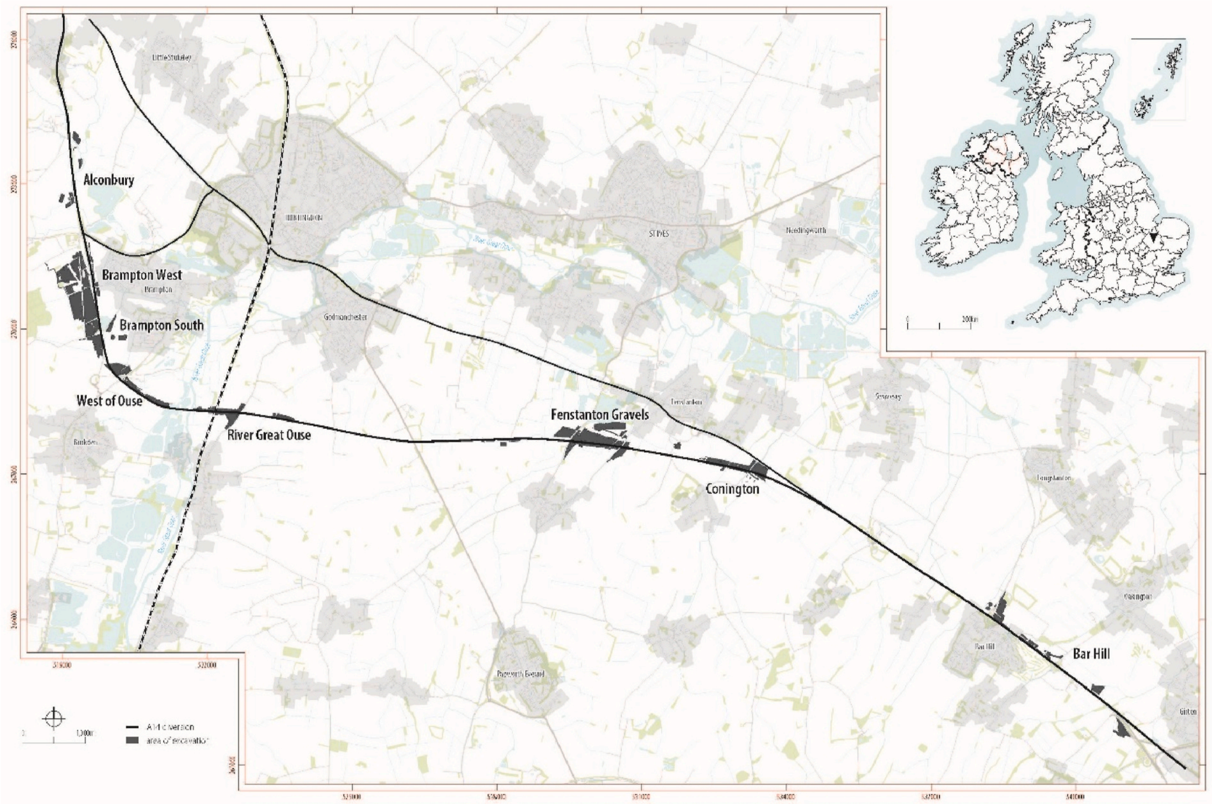


Fig. 1. Map showing the location of the scheme in the UK (inset) and the location of the landscape blocks.

Table 1
Archaeobotanical samples that were included in the isotope analysis.

Landscape block	Iron Age	Roman	Anglo-Saxon	Medieval
Brampton West	19	22	71	20
Fenstanton Gravels	8	43		
Conington			29	

Table 2
Number of samples analysed by period and taxon, and grouped by analytical technique. NB: all samples derive from the Brampton West landscape block.

Period	Cattle	Sheep/Goat	Pig
Bulk bone C & N			
Bronze Age	2	1	
Iron Age	5	10	4
Roman	8	4	
Anglo-Saxon	14		
Medieval	1	4	
Bulk enamel C & O			
Iron Age	20		
Roman	1		
Unphased	2		
Sequential enamel C & O			
Bronze Age	2		
Iron Age	7		
Roman	9		
Anglo-Saxon	16		

Table 3
Number of individuals analysed per period and landscape block (landscape blocks are ordered from west, Alconbury, to east, Bar Hill).

Landscape block	Bronze Age	Iron Age	Roman	Anglo-Saxon
Alconbury	1			
Brampton West	2	2	10	2
River Great Ouse			3	
Fenstanton Gravels	4	1	9	
Conington				1
Bar Hill		3	4	

Table 4
Summary results for stable nitrogen isotope analysis of crop grains.

	No pre-treatment			Pre-treated		
	n	%N	$\delta^{15}N$ (‰)	n	%N	$\delta^{15}N$ (‰)
Wheats						
5.2-Middle-Late Iron Age	2	1.9	6.0	0	–	–
5.3-Late Iron Age	14	1.7	7.4	2	2.8	7.6
6.2-Early Roman	17	1.7	8.1	1	2.1	7.7
6.3-Mid Roman	19	2.0	7.3	1	2.0	7.6
6.4-Late Roman	10	1.7	7.1	3	2.1	5.8
7.2-Early-Middle Saxon	6	2.2	5.2	2	2.9	5.2
7.3-Middle Saxon	13	2.2	5.9	2	3.1	7.1
7.4-Late Saxon	21	1.9	7.6	1	2.9	4.7
7.5-Late Saxon-Early Medieval	21	1.8	8.6	2	2.8	6.7
8.1-High Medieval	14	1.8	10.2	3	2.5	11.8
Barleys						
5.1-Early Iron Age	1	2.3	5.4	0	–	–
5.2-Middle-Late Iron Age	2	1.5	7.5	0	–	–
5.3-Late Iron Age	2	2.0	6.0	3	2.0	7.3
6.2-Early Roman	6	1.5	7.8	0	–	–
6.3-Mid Roman	2	2.3	7.1	1	1.8	9.1
6.4-Late Roman	2	1.5	8.3	1	2.5	4.1
7.2-Early-Middle Saxon	7	2.2	6.9	1	2.5	7.0
7.3-Middle Saxon	6	1.9	5.6	0	–	–
7.4-Late Saxon	4	1.6	7.3	1	2.0	6.5
7.5-Late Saxon-Early Medieval	3	1.4	9.0	1	2.0	9.7
8.1-High Medieval	4	1.4	10.7	0	–	–
Ryes						
6.3-Mid Roman	1	1.6	6.9	0	–	–
7.2-Early-Middle Saxon	4	2.0	6.6	0	–	–
7.3-Middle Saxon	5	1.8	5.7	1	2.3	7.8
7.4-Late Saxon	4	1.8	8.3	2	2.6	7.2
7.5-Late Saxon-Early Medieval	1	1.3	11.7	0	–	–
8.1-High Medieval	2	1.2	8.5	1	1.4	9.9

Age, Roman and Anglo-Saxon, with samples also from Bronze Age and Medieval periods, at Brampton West (Table 2) to maximise the resolution of isotopic study for this archaeologically-rich area (it having comprised c.40% of the entire bone assemblage of the A14 scheme).

Isotope sequences were acquired from the third molar (M_3) of fifteen cattle that could have birth season duration modelled. The maximum duration of birth seasons was calculated (M. Balasse et al., 2012) for each period, except for the medieval because only one tooth was analysed (Table 4). The M_3 forms between approximately 12 and 24 months after birth. Mineralisation can, however, take up to six months, and so there is an imprecise lag (of c. 3–4 months) between tooth formation – which determines isotope ratios – and its mineralisation. Oxygen isotope ratios can be used to estimate the seasonal timing of tooth mineralisation. The minima $\Delta^{18}O$ value represent mid-winter, and the maxima represents peak summer.

2.1.1. *The sampled human osteological remains*

Analysis was conducted on 42 human individuals for strontium, oxygen, carbon, and nitrogen isotopes (Table 3). The individuals spanned the Bronze Age to the Anglo-Saxon period. Most samples were of Roman date, reflecting the predominance of this period in the assemblage, and from the major settlements at Brampton West and Fenstanton Gravels. Amongst the 159 individual humans recovered from Bronze Age contexts, only nine were inhumations. The 42 analyses humans (all from inhumations) thus represent a small subset of people who received atypical funerary practices (Brück et al., 2000).

Relative to the preceding Bronze Age, the Iron Age funerary practices could be described as having been ‘domesticated’ - with a shift from monumental contexts to deposition in and around settlements. The number of cremations and inhumations became equitable, though the small overall number of individuals recovered suggests that the prevailing funerary practices involved deposition away from the settlements and/or by alternative means (e.g. excarnation).

The human population of the Roman period is represented by the remains of 74 individuals, amongst which 61 were inhumations. Again, this is a small subset of the likely much larger living population, and only select individuals were likely inhumed on death (Smith et al., 2018, p. 275). As for earlier periods, the vast majority of the population analysed appears to be individuals who originated and lived locally. Ancient DNA analysis, however, also shows that there was an increased influx of genetic diversity – likely due to immigration from other regions of the Roman empire. Several of these incoming persons are detectable through the isotope data.

The remains of only ten humans were recovered from the A14. Large cemeteries are usual for Anglo-Saxon settlements (Ladd and Mortimer, n.d.; Malim and Hines, 1998; Mortimer et al., 2017), and so it is probable that a burial site that served the scheme’s Anglo-Saxon settlements is located beyond the development boundaries. Three individuals were isotopically analysed, and all appear to have been born-and-bred locals.

2.2. *Isotope analysis*

Isotope analysis was undertaken by the Archaeological Isotope and Peptide Research Laboratory (AIPRL), Durham University. Detailed methodologies are included in the supplementary text, with summary information presented here.

Stable carbon and nitrogen isotope analysis of crop samples was performed on homogenised charred cereal grains using a Thermo

Scientific Delta V Advantage isotope ratio mass spectrometer at the Stable Isotope Geochemistry Laboratory (SIBL), Durham University. Each sample comprised of ten cereal grains from the same context and with the same taxonomic identification. Analytical errors for the standards were ±0.1‰ (one standard deviation, 1σ) for δ^{13}C and δ^{15}N, and for samples were ±0.2‰ (1σ). A subset of 10% of samples were acid-base-acid pre-treated before analysis as per the 'full-gentle' protocol (Vaiglova et al., 2014). Pre-treatment showed a non-significant difference for δ^{15}N values (Supplementary Fig. 1) and a slight, significant increase in δ^{13}C values by 0.6‰ (Supplementary Fig. 2). The C:N ratio for all but one grain sample fell within the normal range (Fraser et al., 2013b). For stable carbon isotope values, Δ^{13}C was calculated according to Ferrio et al. (2005). The Δ^{13}C value represents carbon isotope discrimination during photosynthesis that is independent of the δ^{13}C of atmospheric CO_2, which has changed over time, and is necessary to compare carbon isotope discrimination for samples from different periods.

Animal bone and dentine samples were cleaned and abraded to >100 μm, collagen extracted (O'Connell and Hedges, 1999) and analysed using a Thermo Scientific Delta V Advantage isotope ratio mass spectrometer at SIBL, Durham University. Oxygen isotope analysis was conducted by Iso-Analytical, using Continuous Flow-Isotope Ratio Mass Spectrometry, with helium flushing and conversion of carbonate to CO_2. Analytical errors for the standards were ±0.1‰ (1σ) for δ^{13}C, δ^{15}N and δ^{18}O, and for samples were ±0.2‰ (1σ). The C:N ratio for all but one cattle and one caprine sample fell within the normal range for well-preserved collagen (DeNiro, 1985). Tooth enamel samples were prepared and treated – without an oxidising agent - for carbon and oxygen isotope analysis of carbonate following a modified Sponheimer (1999) protocol.

Carbon and nitrogen stable isotope analysis of human remains followed that used for animal remains, with the exception that dentine samples were of *c.* 200 mg, rather than *c.* 400 mg. Oxygen isotope analysis was conducted by Iso-Analytical, using Continuous Flow-Isotope Ratio Mass Spectrometry, with helium flushing and conversion of carbonate to CO_2. Calibration standard deviations are the same as for animal bone. Additionally, strontium and oxygen isotope analysis was undertaken. Core enamel samples were Sr purified and strontium isotopes were determined by Thermo Neptune plasma ionisation multi-collector mass-spectrometer (MC-ICP-MS) at the Arthur Holmes Isotope Geology Laboratory (AHIGL), Durham University using a static multi-collection routine. The maximum error, based on the internal precision of individual analysis and analytical reproducibility of the reference material, was 0.000013 (2σ). Sr isotope data for samples is normalised to an 'accepted' value for NBS987 of 0.71024. To determine strontium concentrations, samples were analysed via ICP-MS (Thermo Scientific X-series) using an external calibration for the minor elements.

This analytical error, which is shown in figures below, is the reproducibility of the standards or samples. In this case, as is the norm, standards reproduce better than samples. Accordingly, references to analytical error below refer to one standard deviation for sample replicates.

3. Results

Original reporting is available open-access via the Archaeology Data Service. These include three isotope reports – one each for plant, animal and human analysis (Moore et al., 2022, 2023; Moore and Montgomery, 2021), a series of environmental analysis reports – one for each specialism and landscape block, and Environmental remains were separately reported per specialism per landscape block, and the scheme-wide environmental synthesis (Wallace and Ewens, 2024). All of these individual reports have contributed to the following synthesis of the isotope evidence.

3.1. Archaeobotanical stable isotope results

3.1.1. Nitrogen

The mean crop nitrogen isotope value is 7.5‰ (6.3‰–8.8‰ interquartile range) (Table 4). Extreme outliers with δ^{15}N values > 20‰ were recorded. There is no indication of contamination based on pre-treatment data. There is little difference in δ^{15}N values between taxa (Supplementary Fig. 3), and a one-way ANOVA confirms no statistical difference between the three cereal genera – wheat, barley and rye (F (2, 200) = 0.411, p = 0.664).

There were fluctuations in δ^{15}N between phases and period (Fig. 2). There was an initial peak in δ^{15}N values during the Early and Middle Roman periods, after which δ^{15}N values fell in the Late Roman and Early Saxon periods. The highest δ^{15}N values were recorded for the medieval period. This pattern is more apparent in the wheat data, but is also recognisable in the barley data. Rye data is restricted to the latter periods, but these too indicate rising δ^{15}N values through the Anglo-Saxon period.

3.1.2. Carbon

Crop Δ^{13}C values are typical for temperate C_3 crops not under water stress (Wallace et al., 2013, 2015), with a mean of 16.3‰ (interquartile range 15.5‰–16.9‰) (Table 5). Barley Δ^{13}C values are higher than those for wheats by an average of 1.04‰, which is the typical offset between wheat and barley grown in the same conditions (*ibid.*). Rye is largely restricted to the medieval periods, and for these periods the average Δ^{13}C value for ryes was near-identical to those of wheat, which is expected of wheats and ryes grown in the same conditions based on present-day experiments (McKerrcher and Hamerow, 2022).

A chronological trend is apparent (Fig. 3). Higher Δ^{13}C values are recorded for the Iron Age, Roman, Late Saxon and medieval periods, with a dip in Δ^{13}C values during the early Saxon period. Δ^{13}C values increase throughout the Anglo-Saxon period, although this is less pronounced for wheats than it is for barleys and ryes.

There was a subset of spelt wheat grains in the Iron Age that had markedly higher Δ^{13}C values than most of the spelt samples as well as the samples of other wheats (Supplementary Fig. 4). These spelt grains may have been grown in wetter conditions than other crops. During the Roman period, spelt wheat and barley had larger ranges in Δ^{13}C values than other crops, indicating that they may have been grown in more diverse conditions. Inter-taxa differences are not apparent in the Anglo-Saxon period, with all taxa being grown in a similar, narrow range of conditions. In the medieval period, the two rye samples indicate they may have had higher Δ^{13}C values than wheat.

3.2. Archaeozoological stable isotope results

3.2.1. Bone collagen bulk carbon and nitrogen

The δ^{13}C values from mandibular bone collagen are within the typical range for domesticated fauna raised in temperate C_3 environments (Fig. 4) such as Britain (Mulville et al., 2009), and are notably constrained (interquartile range −22.0‰ to −21.5‰) (Table 6). There is no clear diachronic or taxonomic trend in the data, with the only statistically significant difference (Tukey HSD) being that between Anglo-Saxon and medieval caprine samples (p-adj = 0.046), with the latter exhibiting lower δ^{13}C values (see Table 7).

There was greater variation in the δ^{15}N values of mandibular bone (interquartile range of 5.8‰–7.5‰) (Table 6). Caprine results do not split into two groups in any period, indicating the presence of only one taxon – likely sheep based on zooarchaeological analysis (Wallace and Ewens, 2024). Amongst caprine, the only statistically significant differences are between the high δ^{15}N values of the medieval samples and those for the Iron Age (p-adj = 0.02) and Anglo-Saxon (p-adj = 0.02) periods. Cattle δ^{15}N values exhibit a slight increase during the Anglo-Saxon period (Supplementary Fig. 5), particularly the few samples from the later periods, but the difference is not statistically

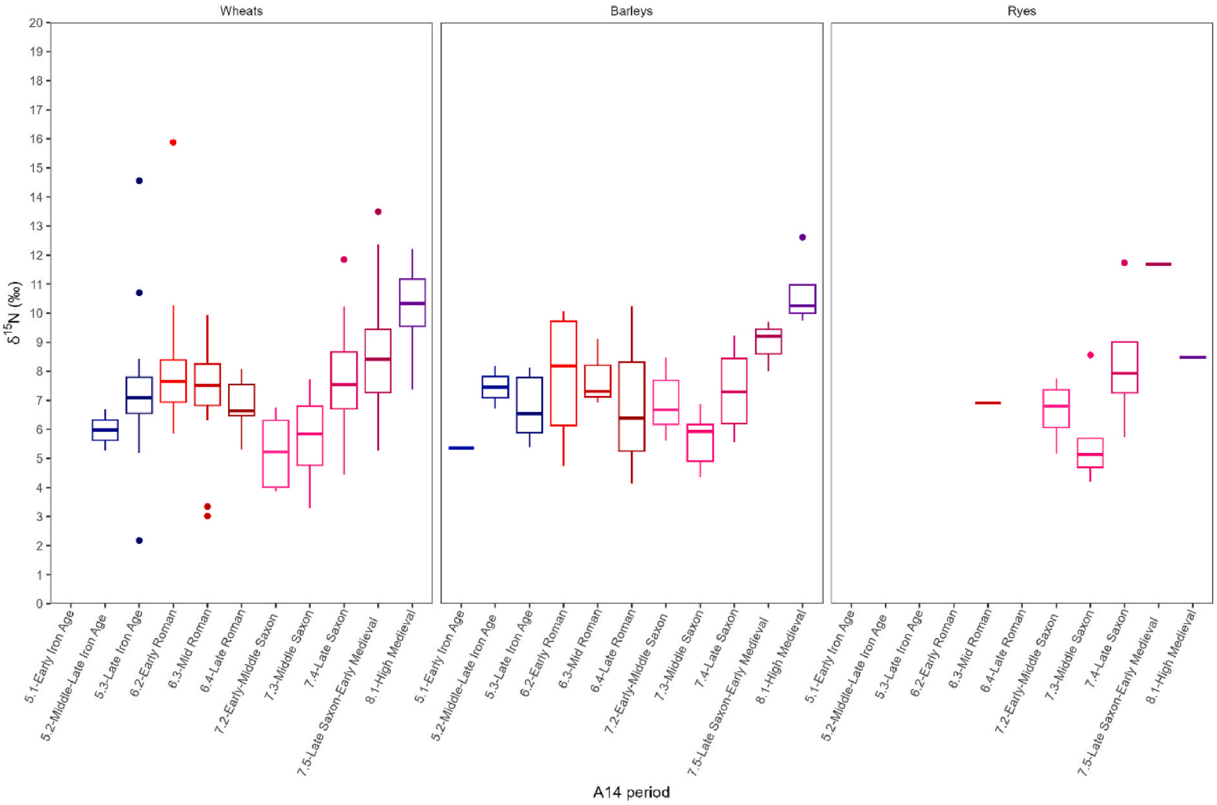


Fig. 2. $\delta^{15}N$ values for cereal grains. The results for cereal grains were pooled by genus (panels) and period (x-axis) and are depicted as conventional box-and-whisker plots with outliers marked as dots. Colours correspond to period, as shown on the x-axis.

significant (Tukey HSD). Cattle and caprine usually have very similar $\delta^{13}C$ (Supplementary Fig. 6) and $\delta^{15}N$ values except in the Roman period, when caprine tend to have higher $\delta^{15}N$ values than their cattle counterparts (mean = +1.6‰).

3.2.2. *Enamel bulk carbon and oxygen*

Apatite from tooth enamel is enriched in ^{13}C compared to bone collagen (Fig. 5) for all samples, which is a typical physiological consequence of fractionation (Cerling and Harris, 1999). The enamel $\delta^{13}C$ values are consistent with a C_3 terrestrial diet. In the case of caprine, however, the offset between enamel and collagen was greater than for other animals, which may imply a taxon-specific factor affecting $\delta^{13}C$ values. As M_3 tooth isotope ratios are fixed upon forming at around one year, unlike bone which is constantly re-modelling, this factor likely relates to the earlier life of the caprine.

Cattle had the lowest $\delta^{18}O$ values (mean = −7.1‰) of the taxa analysed, and a narrow range (1.3‰). $\delta^{18}O$ values for caprine were higher (mean = −6.0‰) and more varied (range = 2.3‰). The difference between cattle and caprine is statistically significant ($t(14) = -3.4$, $p = 0.004$), and was likely due to the physiological differences between the two taxa. Caprines are semi-obligate drinkers and can obtain water from open water sources (lakes, streams, etc.) as well as from foliage, whereas cattle are obligate drinkers and so must remain close to open water sources (Gillis et al., 2021; Makarewicz et al., 2017).

Pig $\delta^{18}O$ values are comparable to those of caprine (mean = −6.3‰) but are constrained similarly to cattle (range = 1.5‰). Although the number of samples is modest, the cattle caprine and pig appear to fall into two groups (Supplementary Fig. 7). One group has lower $\delta^{18}O$ values (i.e. <-6‰) and includes all of the cattle plus about half of the caprines and pigs. A second group has higher $\delta^{18}O$ values (i.e. >-6‰) and includes no cattle and the other half of the caprines and pigs.

3.2.3. *Sequential carbon and oxygen*

Sequential data on the cattle third mandibular molars (M·) reveals individual variations in life history (e.g. Fig. 6), and enhances the general impression of homogeneity in diet and husbandry practices based on bulk collagen analysis. Most of the analysed teeth for the A14 had ten increments taken. The range in $\delta^{13}C$ values for each tooth was consistent at 0.8‰ ±0.3‰, though the range tended to be slightly greater for Iron Age and Roman cattle. The number of increments had a clear impact on the range of $\delta^{13}C$ values, with more increments correlated with more variation (Supplementary Fig. 8).

The two Bronze Age cattle teeth represent varied birth seasons and dietary habits (Supplementary Fig. 9). Individual A14-12-145 shows a $\delta^{18}O$ value indicating a mid-spring to mid-winter cycle, and the peak $\delta^{13}C$ value corresponds with the winter minima. For A14-12-297, the cycle appears to span autumn through to mid-summer and, in this case, the winter minimum was associated with the lowest $\delta^{13}C$ values. With only two specimens, it is not possible to make any generalisations about cattle husbandry in the Bronze Age, but the implication is that the birthing and dietary management differed between these two individuals.

The two Middle-Late Iron Age samples indicate a spring-to-spring sequence, though this may be somewhat curtailed in A14-10-1744 (Supplementary Fig. 10). There is little variation in $\delta^{13}C$ values, though their peak is seemingly associated with the summer maxima. Of the five Late Iron Age sequences (Supplementary Fig. 11), two had few increments and so are difficult to interpret, though both indicate that the $\delta^{13}C$ value minima correspond with $\delta^{18}O$ value minima. For the other three sequences, the seasons represented varies, but winter minima precede summer maxima, indicating tooth formation commenced in the latter half of the year. In all three cases, the maxima/minima of $\delta^{18}O$ and $\delta^{13}C$ values co-occur.

Two Early Roman cattle represent winter to summer/autumn sequences (Supplementary Fig. 12), again with fluctuations in $\delta^{13}C$ values

Table 5
Summary results for stable carbon isotope analysis of crop grains.

	No pre-treatment			Pre-treated		
	n	%C	δ^{13}C (‰)	n	%C	δ^{13}C (‰)
Wheats						
5.2-Middle-Late Iron Age	2	34.5	17.2	0	–	–
5.3-Late Iron Age	14	31.4	16.7	2	55.6	15.3
6.2-Early Roman	17	37.7	17.0	1	39.6	15.2
6.3-Mid Roman	19	38.3	16.4	1	49.2	16.1
6.4-Late Roman	10	34.0	16.5	3	45.3	15.4
7.2-Early-Middle Saxon	6	39.8	15.0	2	56.1	15.3
7.3-Middle Saxon	13	42.8	15.1	2	64.2	14.2
7.4-Late Saxon	21	39.7	15.8	1	64.7	14.1
7.5-Late Saxon-Early Medieval	21	35.6	15.7	2	57.9	15.4
8.1-High Medieval	14	38.7	16.0	3	52.6	15.3
Barleys						
5.1-Early Iron Age	1	35.4	18.5	0	–	–
5.2-Middle-Late Iron Age	2	33.3	18.2	0	–	–
5.3-Late Iron Age	2	34.7	17.2	3	49.9	16.4
6.2-Early Roman	6	38.5	18.4	0	–	–
6.3-Mid Roman	2	51.3	17.2	1	48.5	16.3
6.4-Late Roman	2	34.9	18.0	1	55.1	15.5
7.2-Early-Middle Saxon	7	40.7	15.8	1	59.0	16.0
7.3-Middle Saxon	6	42.3	16.2	0	–	–
7.4-Late Saxon	5	35.6	17.4	2	48.5	16.1
7.5-Late Saxon-Early Medieval	4	34.8	16.8	1	55.4	16.0
8.1-High Medieval	4	33.7	18.0	0	–	–
Ryes						
6.3-Mid Roman	1	34.4	15.3	0	–	–
7.2-Early-Middle Saxon	4	43.2	14.9	0	–	–
7.3-Middle Saxon	5	42.6	15.4	1	55.6	14.8
7.4-Late Saxon	4	40.5	16.2	2	63.3	15.2
7.5-Late Saxon-Early Medieval	1	30.8	16.3	0	–	–
8.1-High Medieval	2	29.2	16.8	1	38.2	16.0

associated with the winter minima. Seven further sequences date to the Late Roman period, two sequences (Supplementary Fig. 13) are difficult to interpret owing to their short increment length and a shallow δ^{18}O value minima preceding the maxima. The remaining sequences (Supplementary Fig. 14) tend to begin around autumn or winter, with one exception (A14-7-1114). Δ^{13}C values are lowest around the minima of δ^{18}O values, and span similar ranges to earlier periods.

Similar patterns to those described above prevail into the Early Saxon (Supplementary Fig. 15) and Early-Middle Saxon (e.g. Fig. 6) periods. The Early-Middle Saxon has the largest sample size, and so greater variation in δ^{13}C values is to be expected. Even so, differences between the δ^{13}C values for some individuals are notably large (i.e. 2-3‰, Supplementary Fig. 16). This may indicate that although generally similar to earlier periods, a greater spectrum of husbandry activities may have been practised in the Anglo-Saxon period.

The only marked deviation occurs In the Late Saxon and Late Saxon-Early Medieval samples (Supplementary Fig. 17). The four samples show M_3 formation commencing at varied points along the curve of δ^{18}O values. In stark contrast with earlier periods, however, in all four cases, it is the summer maxima in δ^{18}O values – rather than the winter minima–- that is associated with the minima of δ^{13}C values. This is the opposite of all earlier periods, and may suggest some substantive change in the diet of these animals through the year.

3.3. *Human osteological isotope results*

3.3.1. *Bulk carbon and nitrogen*

The δ^{13}C values from tooth enamel apatite for the A14 individuals range from −21.0‰ to −4.9‰, with a mean value of 13.8 ± 1.6‰ (n = 41, 1σ) (Table 4). Although the δ^{13}C values are spread over a large range (11.1‰), this is due to an outlier within the Roman population (Inhumation 20.507). When this outlier is removed the data exhibits a smaller spread of 3.8‰, with values consistent with a predominantly C_3, terrestrial diet (Müldner and Richards, 2007). The δ^{13}C values from enamel apatite reflect whole diet, such as proteins, carbohydrates and fats (Ambrose and Norr, 1993; Froehle et al., 2010). A more comprehensive assessment of past diets can be made by comparing δ^{13}C values from enamel apatite with dentine collagen (Kellner and Schoeninger, 2007).

The mean of whole root dentine collagen and enamel apatite δ^{13}C values from the A14 individuals are presented in Fig. 7 alongside the dietary regression lines (Froehle et al., 2010). As both tissues form during early life, the δ^{13}C values represent whole diet during the years of tooth formation. The lower regression line represents C_3 dietary protein. The left of this line reflects the consumption of entirely C_3 resources, and individuals with more C_4 or marine protein incorporated into their diet would plot further along the line towards the right of the plot. The majority of the A14 individuals from all periods plot closely with the C_3 protein line towards the left side of the plot, indicating that the main food groups of fats, carbohydrates and proteins were derived from a predominantly terrestrial C_3 diet. The dentine δ^{13}C values exhibit a smaller range (2.1‰) than the enamel δ^{13}C values, and this could indicate that there was less variation in the protein sources consumed by the A14 individuals than in their sources of carbohydrates and fats.

Comparison of dentine and bone δ^{13}C and δ^{15}N mean values (Fig. 8) shows that the majority of the A14 individuals had long-term diets predominantly based on terrestrial C_3 food sources. This is consistent with British diets in the past (Müldner and Richards, 2007). The δ^{13}C and δ^{15}N values from the dentine represent the dietary protein consumed while the teeth were forming in childhood, and the rib and long bone data represent an average of the diet consumed during approximately the last 5 and 15 years, respectively, before death. A comparison of these tissue types shows a general trend for lower δ^{13}C values in bone collagen relative to dentine collagen (Fig. 8), indicating different dietary protein sources were eaten during childhood and adulthood.

The A14 individuals exhibit a trophic level shift from the faunal and floral comparatives (Fig. 9). Previously it has been assumed that a one trophic level shift (3–5‰) from a faunal baseline indicates a diet with a large component of animal products (Fraser et al., 2013a; Hedges and Reynard, 2007). In the case of the A14, however, the inclusion of crop data demonstrates the dangers of this assumption. The similarity in δ^{13}C and δ^{15}N values for crop and livestock samples means that the human results are one trophic level above both, and so both an animal-rich or crop-rich diet could explain the observed human isotope data.

3.3.2. *Incremental carbon and nitrogen*

Incremental dentine sequences provide information on any dietary change during the formation of a tooth, in childhood. The number of increments varies and the age range depends on the tooth samples and whether the individual died prior to the end of tooth mineralisation. Results of incremental analysis of human teeth are presented in Table 4, Fig. 10 and Supplementary Figs. 18–21.

All of the Bronze Age individuals' incremental dentine profiles (Supplementary Fig. 18) exhibit very little variation in δ^{13}C values with less than 1‰ change in values throughout the formation of the teeth, and are largely around −22‰ to −21‰. The δ^{15}N values in the Bronze Age individuals exhibit slightly more variability with small fluctuations seen in most profiles, and some individuals with >2‰ variation in δ^{15}N values. Whilst the fluctuations with individual's sequences are modest, the difference between individuals could be great. The Bronze Age results for δ^{15}N values include the lowest (8.5‰) and third-highest (13.3‰) across the scheme.

Iron Age individuals (Supplementary Fig. 19) exhibit similar results to those in the Bronze Age, with near-flat profiles of δ^{13}C values and some variation in δ^{15}N values. The two samples from the PM2 have

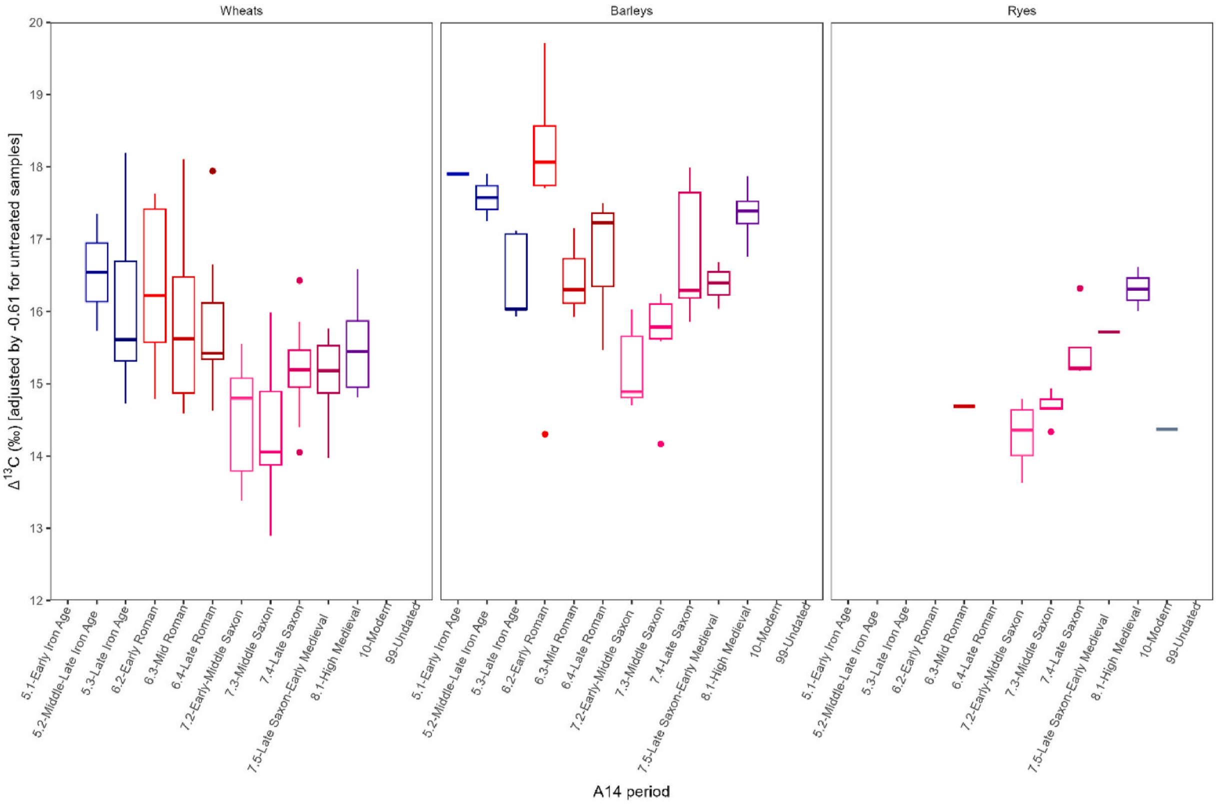


Fig. 3. Δ^{13}C values for cereal grains. The results for cereal grains were pooled by genus (panels) and period (x-axis) and are depicted as conventional box-and-whisker plots with outliers marked as dots. Colours correspond to period, as shown on the x-axis.

slightly higher δ^{13}C values from those two that sampled the M2, and exhibited rising δ^{15}N values over time. All individuals exhibit variation in δ^{15}N values that could be attributed to ‘stress bubbles’ (Beaumont and Montgomery, 2016), particularly 38.135 and 38.319 that have sharp fluctuations spanning c.2‰. Two younger individuals are noteworthy. Both are non-adult skeletons from inhumation 38.74 (381834 and 381833) (Fig. 10). These two individuals provide the only deciduous teeth analysed in this study and offer insights into early infant life. Both individuals have δ^{15}N values averaging at least 2.4‰ above the Iron Age adult mean value (12.0‰), this is consistent with a trophic level shift indicative of breastfeeding (Fuller et al., 2006).

Twenty-five Roman individuals (Supplementary Fig. 20) have incremental dentine profiles. These all, bar one, indicate childhood diets based on predominantly C_3 resources. The δ^{13}C values for Roman individuals are typically flat (variation per individual ≤1.2‰), as seen for earlier periods, with the notable exception of Mid Roman inhumation 20.507 (variation in sequence = 6.8‰). The skeleton from this inhumation exhibits a steep fall in δ^{13}C values from −12‰ at 2–3 years to around −19‰ at around 14 years. For all other profiles, the range of δ^{13}C values was <1.2‰ and values were between −21.0‰ and −18.9‰. The profiles for δ^{15}N values again showed greater fluctuation than those for the δ^{13}C values. During the Early Roman period (6 individuals), δ^{15}N values were between 10.0‰ and 14.1‰, and the average range per individual was <2‰. One Early Roman individual, inhumation 10.340, had a slightly greater range of δ^{15}N values (2.3‰) due to a steep increase at the end of the profile (10–14 years). Others had sharp fluctuations mid-profile which may indicate ‘stress bubbles’; such as in the case of inhumation 10.198 (Fig. 10). The single Mid Roman individual had unusually low δ^{15}N values (6.8‰–9.9‰) and a high within-individual range (3.0‰) owing to fluctuations in earlier (2–6 years) and later childhood (12–14 years). For the Late Roman period (18 individuals), the δ^{15}N values ranged from 9‰ to 15‰ and most had a δ^{15}N range <2‰, including one (inhumation 11.180) with a range of δ^{15}N values of just 0.8‰ (Fig. 10). Greater variation was seen also, including individuals from inhumations 7.305, whose profile is very unstable between 3 and 8 years of age and which may relate partly to the end of weaning, 38.278, whose profile steadily declines until death aged c.5 years, and 27.340, whose profile exhibits both short-term fluctuations and a steady decline over time.

The three Anglo-Saxon individuals (Supplementary Fig. 21) have similar profiles to the rest of the A14 assemblage, showing little variation in δ^{13}C values and fluctuations in δ^{15}N values that could indicate periods of physiological stress. For two individuals the δ^{13}C are typical of other A14 individuals, with values between 20.3‰ and 19.1‰. One individual, from inhumation 7.437, had a slightly greater range: spanning −20.6‰ in earlier years rising to −18.8‰ in later years. This individual, conversely had a narrow range of δ^{15}N values (1.1‰), though there were still variations with peaks bookending the profile. The other two individuals exhibited marked fluctuations in δ^{15}N values through their life. All of the Anglo-Saxon individuals had δ^{15}N values approximately between 9‰ and 13.3‰.

3.3.3. *Strontium*

Strontium isotope ratios were determined for tooth enamel samples for all 42 individuals (Fig. 11). The strontium isotope values range from 0.70884 to 0.71163 with a median of 0.70915 (interquartile range 0.70884–0.70938). The range is consistent with a population sourcing food from the geology of southeastern Britain, and a *t*-test shows that the A14 data do not differ significantly ($p > 0.2$) from other populations from Cambridgeshire (Leggett, 2020; Montgomery et al., 2019; Pellegrini et al., 2019). A Kruskal-Wallis H test shows that there is no significant difference between periods ($H (2) = 0.1617$, $p = 0.92232$). Three statistical outliers exist–- skeletons 28.164, 28.567 and 10.305–- all of which are from the Roman period. Of these, 28.164 lies within the modelled range of bioavailable strontium for individuals who spent their childhood in Cambridgeshire (Evans et al., 2012), whilst the other two

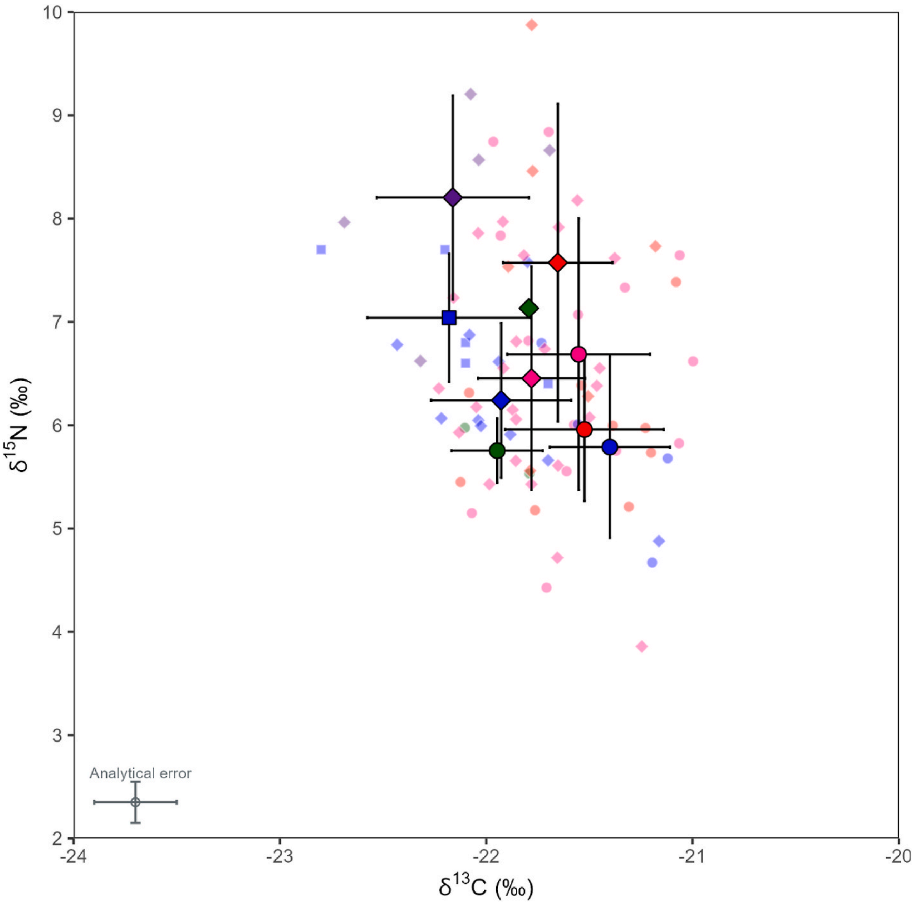


Fig. 4. $\delta^{13}C$ and $\delta^{15}N$ values for faunal remains. Colour denotes the main period (green = Bronze Age, blue = "Iron Age, red = Roman, pink = Anglo-Saxon, and purple = medieval). Shape denotes taxon (circle = cattle, diamond = caprines, square = pig). Large symbols equal means for each period-taxon combination, with error bars representing ± 1σ. Smaller, fainter symbols represent individual samples. The analytical error is ±0.2‰ (1σ).

are above this range. Their higher strontium isotope ratios are typical of regions of Britain with older geology – including western and northern England, Wales and Scotland – as well as in regions across Europe.

Strontium concentration was determined for 41 of the tooth enamel samples (Fig. 11). Strontium concentration ranges from 69.6 to 247.6 ppm with a median of 104.7 ppm (IQR 71.9–119.4 ppm, n = 41). A Kruskal-Wallis H test showed that there was no significant difference in strontium isotope concentrations between periods (H (2) = 2.6535, p = 0.26534). There is, however, some considerable variation in Sr concentration amongst individuals, and three individuals – skeletons 38.278, 38.318 and 38.74 (381834) – are statistical outliers. All three outliers are from the Bar Hill landscape block, and one – an Iron Age skeleton – is outside the range expected for archaeological humans from mainland Britain, but are common (Evans et al., 2012) amongst individuals from Atlantic-facing islands such as the Western and Northern Isles of Scotland (Montgomery et al., 2019). The other two outliers are Roman in date. Modern studies in Britain have recorded tooth enamel concentrations as high as 262 ppm (Brown et al., 2004), and similarly high values have been observed in Roman populations from France and Spain (Moore, 2019). It is worth noting, that archaeological humans in Britain with strontium isotope ratios below rain/seawater and indicative of origins in a region of high-calcium rock such as chalk (such as the two highest outliers in this dataset) tend to have the lowest strontium concentrations, i.e. below 100 ppm (Montgomery et al., 2019), due to high-dietary calcium, adding further weight to the unusual Sr concentrations of skeletons 38.278 and 38.74 (381834).

Table 6
Summary results for bulk stable carbon nitrogen isotope analysis of faunal bone.

		$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)	
Period	n	Mean	1σ	Mean	1σ
Cattle					
4.3-Early-Middle Bronze Age	2	−21.9	0.2	5.8	0.3
5.2-Middle-Late Iron Age	2	−21.2	–	4.7	–
5.3-Late Iron Age	5	−21.5	0.3	6.2	0.6
6.2-Early Roman	2	−21.6	0.7	6.8	0.8
6.4-Late Roman	7	−21.5	0.3	5.7	0.4
7.1-Early Saxon	2	−21.3	0.4	5.9	0.1
7.2-Early-Middle Saxon	10	−21.6	0.3	6.3	1.3
7.4-Late Saxon	1	−21.3	–	7.3	–
7.5-Late Saxon-Early Medieval	3	−21.6	0.4	8.1	0.6
Caprines					
4.3-Early-Middle Bronze Age	1	−21.8	–	7.1	–
5.2-Middle-Late Iron Age	4	−22.2	0.2	6.5	0.4
5.3-Late Iron Age	13	−21.8	0.3	6.1	0.9
6.2-Early Roman	1	−21.8	–	9.9	–
6.3-Mid Roman	1	−21.8	–	5.6	–
6.4-Late Roman	4	−21.6	0.3	7.5	0.9
7.2-Early-Middle Saxon	20	−21.8	0.3	6.3	1.0
7.3-Middle Saxon	3	−21.7	0.2	6.7	1.2
7.5-Late Saxon-Early Medieval	1	−21.6	–	8.2	–
8.1-High Medieval	5	−22.2	0.4	8.2	1.0
Pig					
5.3-Late Iron Age	8	−22.2	0.4	7.0	0.6

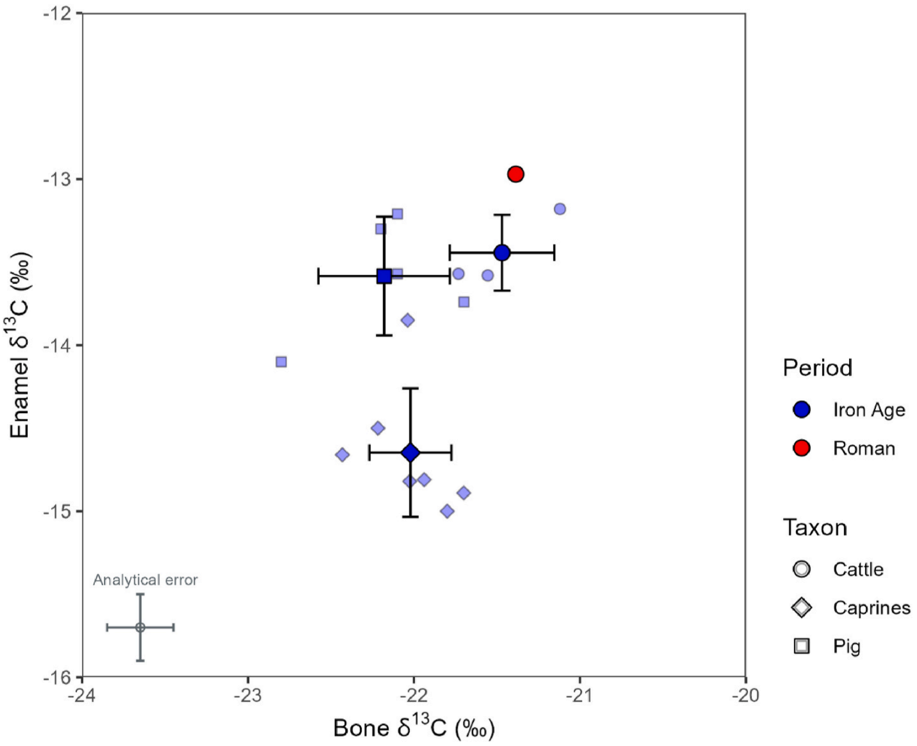


Fig. 5. δ^{13}C values for bone and tooth enamel from the same mandibles. Large symbols are taxon means with 1σ bars. Smaller and fainter samples are values for individual mandibles. Shape denotes taxon (circles = cattle, diamonds = caprine, squares = pig). All samples are dated to the Iron Age (blue) except one Roman sample (red) that was re-phased after isotope analysis. The analytical error is ±0.2‰ (1σ).

3.3.4. *Oxygen*

The $\delta^{18}O_{VSMOW}$ (apatite) values for the A14 individuals range from 23.3‰ to 27.4‰ with a mean of 25.5 ± 0.9‰ (Fig. 12). These values lay within the range of archaeological humans from Britain (Evans et al., 2012), and are comparable with data from contemporaneous sites in Cambridgeshire (Leggett, 2020; Wiseman et al., 2021). The range (3.3‰ excluding the one statistical outlier) is typical for an archaeological cemetery population of 2–3‰ (Evans et al., 2012; Lightfoot and O'Connell, 2016). A one-way ANOVA test shows that there was no significant difference in mean δ^{18}O values between periods (F (3, 37) = 0.3, p = 0.828).

The majority of A14 samples fall within the range of the eastern 'low rainfall' region in Britain, with ten individuals falling within the overlap area with the western 'high rainfall' region (Evans et al., 2012). These results are consistent with a childhood spent in Cambridgeshire. There are no individuals with the high oxygen isotope values that would be expected for warmer regions at lower latitudes such as around the Mediterranean and which have been previously obtained from Roman period individuals buried in Britain (Martiniano et al., 2016). Nine individuals had oxygen isotope ratios lower than the expected range for Britain. All but one of these individuals – skeleton 28.174–- fall within the 2σ range of archaeological humans from Britain. Given the analytical error and large uncertainties associated with oxygen conversion equations, significance is only ascribed to the outlier and the second-lowest value – from skeleton 20.507 – which also had an unusually high δ^{13}C value.

4. Discussion

4.1. *Crop husbandry*

The stable nitrogen isotope ratios of crop remains relate to the capture of nitrogen from soil (Bogaard et al., 2013, 2016; Fraser et al., 2011, 2013b; Styring et al., 2013). The δ^{15}N values for the A14 are high - typically >6‰ – in comparison to data from other UK sites (Bishop et al., 2022; Lightfoot and Stevens, 2012; Lodwick, 2023; Lodwick et al., 2021a; McKerracher, 2019; Stroud, 2022; Treasure et al., 2019; Wallace, 2023). The high values are observed for all crop taxa, with no clear differentiation between any taxa within a period apart from spelt grains having slightly higher values than barley grains in the Roman period. This indicates there was no systematic difference between taxa in aspects of crop husbandry that affect nitrogen fixation.

There are multiple possible causes for elevated δ^{15}N values. One explanation is that soils in the area have naturally high δ^{15}N values, which are inherited by the crops growing on the soils. The baseline δ^{15}N values for the region are unknown, but anthropogenically unaltered soils may be expected to produce plants with δ^{15}N values in the region of 0–4‰ (Bakels, 2019). Given these indicative values it is unlikely that crops from the A14 directly reflect natural soil conditions. Further, by subtracting one trophic level (3–5‰) from the δ^{15}N value of herbivore livestock it is possible to estimate the δ^{15}N values of the vegetation they consumed. The A14 livestock δ^{15}N values are very slightly lower than those of crops, and are suggestive of consumed vegetation with δ^{15}N values in the region of ~1–3‰. Even though we are unable to directly evaluate the δ^{15}N values of arable soils, the comparatively high crop δ^{15}N values and the herbivore data indicate that crop δ^{15}N were raised due to human action.

The human actions that could have led to high δ^{15}N values in crops are varied. The application of manure to arable fields is known to increase the δ^{15}N value of crops (Bogaard et al., 2007, 2013, 2016; Fraser et al., 2011). Experimental studies by Fraser et al. (2011, p. 2802) indicated that δ^{15}N values between ~2.5‰ and ~6.0‰ might indicate low-level long-term manuring, the residual effects of intensive manuring or the early years of a new cultivation regime, and many of the A14 grains fall in this band or even higher for which long-term and/or high-intensity manuring may be indicated. Manuring or other introduction of marine products (e.g. seaweed fertiliser) to arable soils can also substantially increase crop δ^{15}N values (Blanz et al., 2019), as can

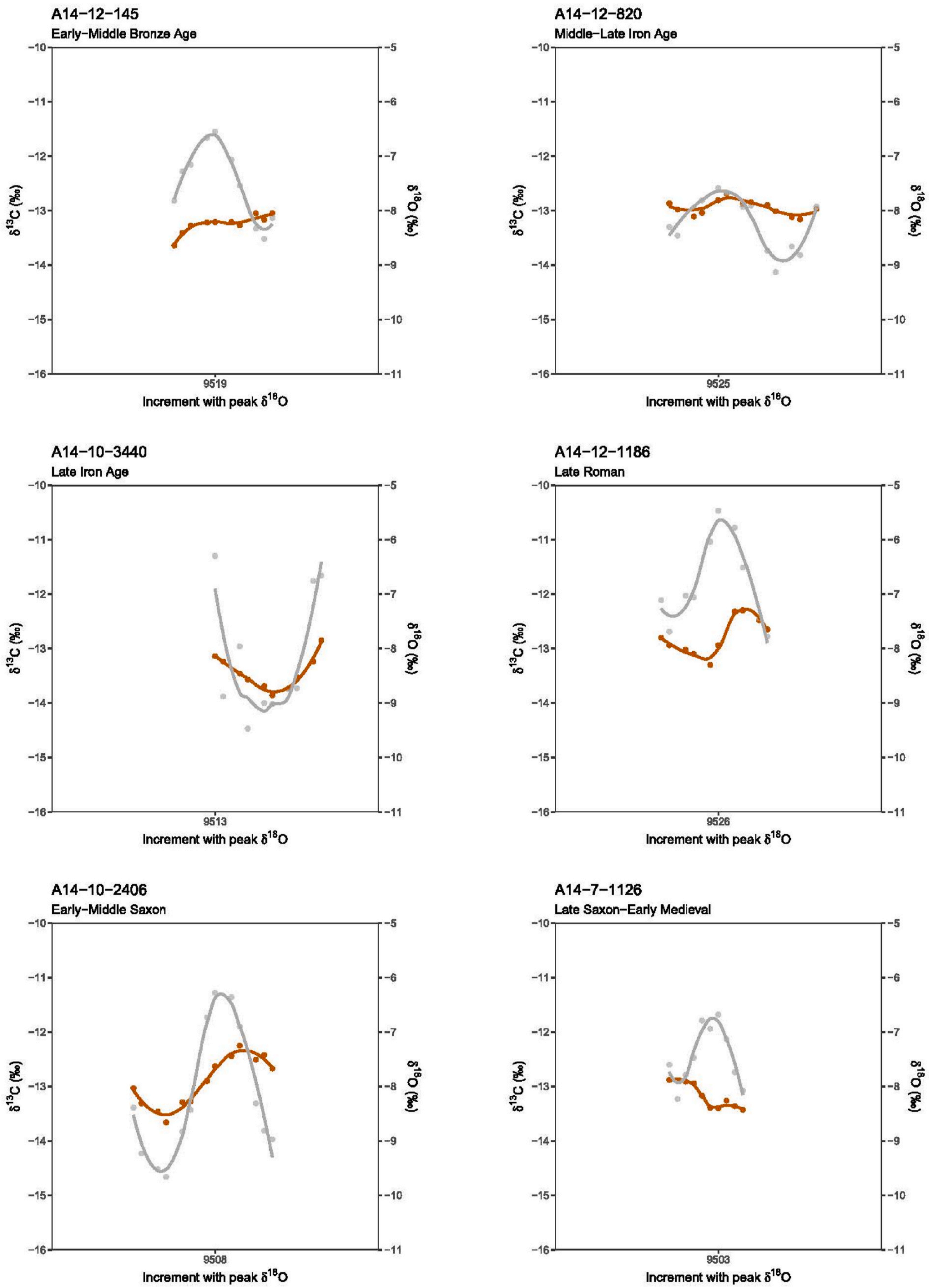


Fig. 6. Selected examples of δ^{13}C and δ^{18}O values from incremental tooth sequences.

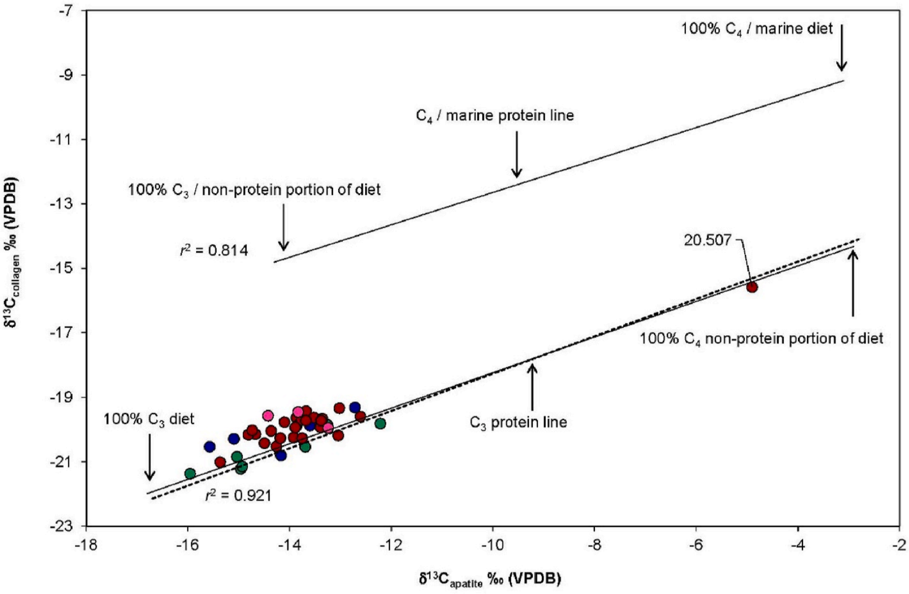


Fig. 7. Mean dentine collagen and enamel apatite δ^{13}C values from the A14 individuals plotted against dietary regressions lines from Froehle et al. (2010). Colour denotes the main period (green = Bronze Age, blue = "Iron Age, red = Roman, and pink = Anglo-Saxon).

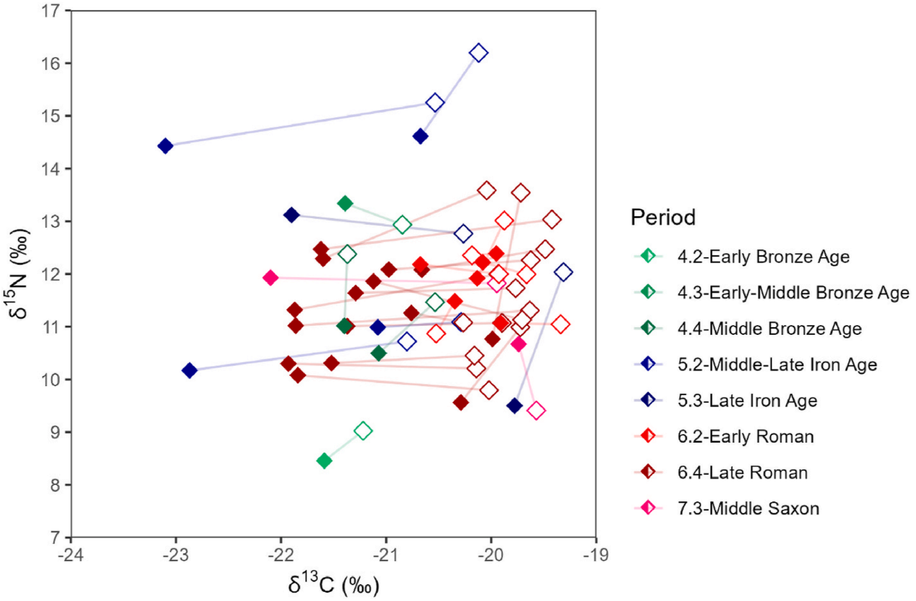


Fig. 8. δ^{13}C and δ^{15}N values for human dentine (hollow symbols) and human bone (filled symbols). Dentine and bone samples from the same individual are joined by a line. Colour denotes the period: Bronze Age = greens, Iron Age = blues, Roman = reds, and Anglo-Saxon = pinks.

the placement of crop fields. The production of crops on waterlogged fields are known to have higher δ^{15}N values due to bacterial activity in the soils (Handley et al., 1999). It is entirely plausible that multiple factors influenced the crop δ^{15}N values simultaneously. Indeed, the subset of Iron Age spelt grains with very high δ^{15}N values may be explained, for example, by their production on both waterlogged soils – which spelt is tolerant to – and under intensive manuring – which spelt responds to favourably.

The crop δ^{15}N values show variation over time with a twin-peak pattern - this is clearest for wheat. Crop δ^{15}N values increased from the Iron Age to the Mid-Roman period, before falling in the Late Roman and earlier Anglo-Saxon periods, before then rising steeply in the Late Saxon and medieval periods. This trend is apparent, though less clear, for barley. Rye samples are only available from the later Roman periods, but these too show steep rises through the later periods.

The Iron Age – Mid-Roman rise can more probably be explained by manuring practices rather than an increased targeting of waterlogged soils. Wetter fenland areas could only be accessed from the most of the A14 settlements by crossing the River Ouse, and given the abundance of suitable soils for arable farming on the settlement-side of the Ouse it seems unlikely farmers were going so far to access wetter soils. Furthermore, vegetation reconstruction (Bunting et al., n.d.) indicates that alder carr survived along river banks, which would further restrict the availability of wetter soils in and around the settlements. The rarity of marine resources on A14 settlements from this period (Wallace and Ewens, 2024) makes the use of these types of products unlikely too. Accordingly, the most likely scenario would seem that the δ^{15}N values are being influenced by the application of livestock manure, which

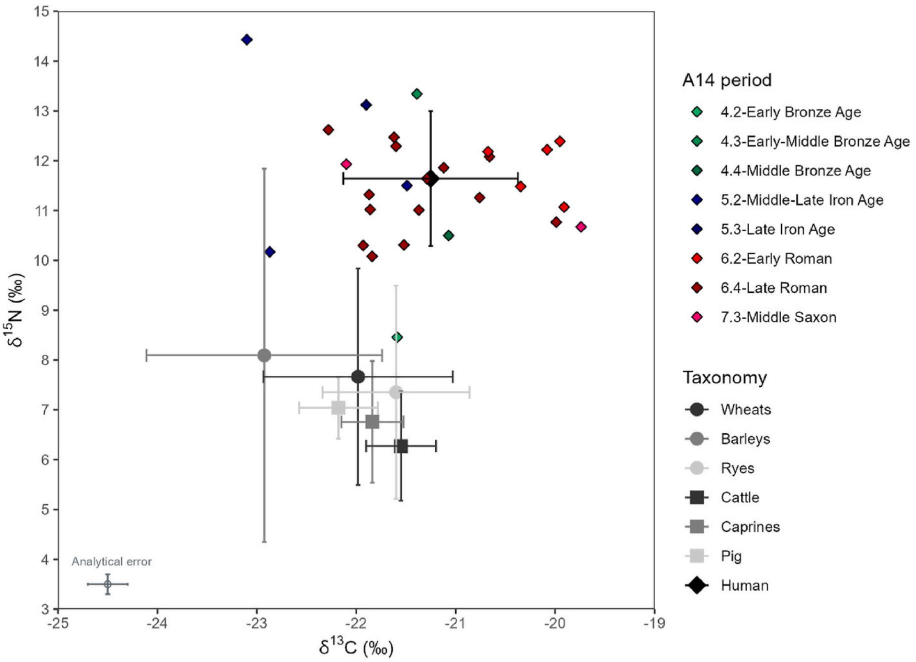


Fig. 9. Human bone $\delta^{13}C$ and $\delta^{15}N$ values compared to cereal grain and animal bone data. Smaller diamond symbols denote individual humans, colour-coded by period. Larger, greyscale symbols denote means for crops (circles), livestock (squares) and all humans (diamond), with error bars representing 1σ. The analytical error is ±0.2‰ (1σ).

indicates a persistence of intensive agriculture through the Iron Age, where comparably high $\delta^{15}N$ values have been reported (Gaunt et al., 2023), and into the Early and Mid Roman periods.

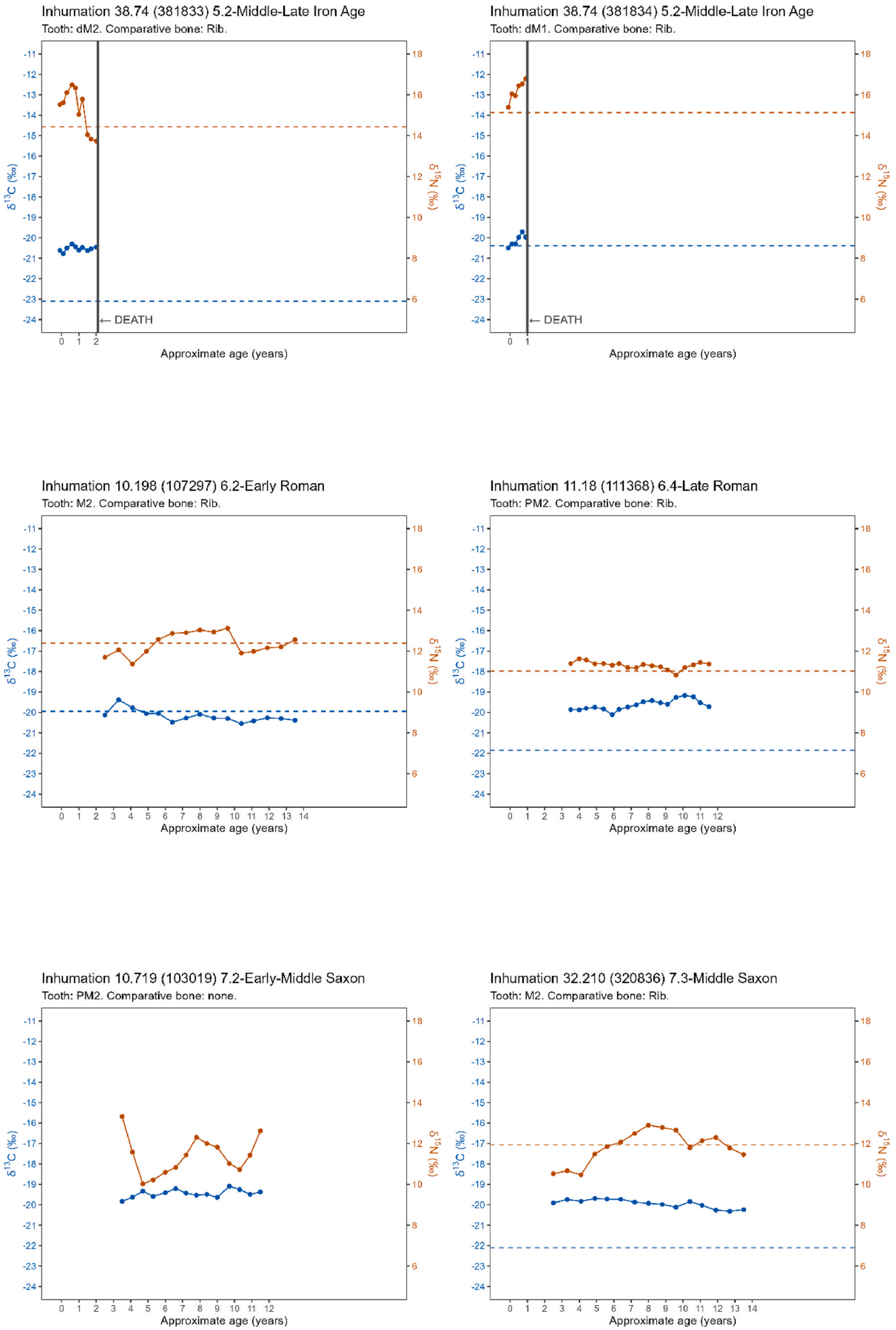
Crop stable isotope studies of the Iron Age to Roman transition have been undertaken for Stanwick in the Nene Valley (Lodwick et al., 2021b) and Danebury on the Hampshire Downs (Lodwick, 2023). In both cases, there were high $\delta^{15}N$ values reported, though not quite as high as for the A14, and, like the A14, there was no clear differential treatment of crop taxa. In contrast to the A14, though, both Stanwick and Danebury exhibit a fall in $\delta^{15}N$ values with the onset of the Roman period. This has been linked to a general extensification of agriculture under Roman rule (Allen and Lodwick, 2017). On the A14, high $\delta^{15}N$ values appear to have persisted until the Mid Roman period. The difference may be explained by settlement patterns. For the early and middle Roman periods on the A14, settlements were mostly small, farmsteads. At these places, prevailing Iron Age traditions of intensive agriculture may have survived the Roman transition. Alternatively, the Early Roman archaeology of the A14 has a very high number of bedding trenches, which are not typically found outside the east of England and are especially prolific on the A14. These bedding trenches may attest to high fertility arable strategy. In the Late Roman period, there was settlement nucleation on the A14, with a farmstead at Brampton West, a possible trading post at Fenstanton Gravels and a villa complex near to the River Great Ouse landscape block. The centralisation of settlement activity and economic influence may have led to an extensification of arable farming. This would entail the use of cattle (which were abundant at these sites) to plough larger areas in a low-input system, likely as a strategy to increase production without a major increase in human labour demand.

The initial fall and a subsequent dramatic rise in $\delta^{15}N$ values through the Anglo-Saxon period and into the medieval was unexpected. At Lyminge in Kent, comprising mainly eight-ninth century (middle-late Saxon) samples, $\delta^{15}N$ values of crops were around 4‰ (Stroud, 2022), equivalent to the earlier Saxon samples from the A14. The Lyminge crops were also notable for very high variation in $\delta^{15}N$ values within each crop taxon tested. At eight-ninth century Stratton, Bedfordshire, $\delta^{15}N$ values were higher (mostly >6‰) and rye rose to >7‰ in the fifteenth-sixteenth centuries (late medieval) (Stroud, 2022). High levels of variability were noted in the isotope data for Lyminge and Stratton, which was also apparent for the A14. Though the available evidence is limited, there may be an emerging trend of earlier periods showing evidence of lower manuring and a lack of systematic regulation of agricultural practices. In later periods, there was a substantial rise in crop $\delta^{15}N$ values, suggestive of yet more intensive management of crops. The A14 is located at the edge of the Fens area, and so peat-fen (Guiry et al., 2021; Kohzu et al., 2003; Nehlich et al., 2011; Peterson and Fry, 1987) or marine (Gröcke et al., 2021; Szpak et al., 2012, 2014) input into the agricultural systems are other plausible explanation of high $\delta^{15}N$ values.

4.2. *Crop variability*

Crop $\Delta^{13}C$ values are determined by stomatal conductance. In regions where water is the main limiting factor on growth, $\Delta^{13}C$ values may be strongly related to crop water status (Wallace et al., 2013, 2015). In temperate regions, such as Britain, where other environmental variables contribute to stomatal conductance the interpretation of $\Delta^{13}C$ values is more complex. For the A14, wheat and barley grains have a c.1‰ offset, which has been widely recorded in experimental studies, and is considered a physiological offset (Araus et al., 1997; Ferrio et al., 2005; Wallace et al., 2013). This implies that, at least in terms of factors that affect stomatal conductance, wheat and barley were grown in comparable conditions.

In both the Iron Age and Roman periods wheats have a broad range of $\Delta^{13}C$ values, spanning 15‰–18‰, though in the Roman period there was a greater emphasis on higher values. This range spans the entirety of the poorly to well-watered crops based on experimental models in semi-arid areas, though the applicablility of these models to a UK context is uncertain. For barley, the range of $\Delta^{13}C$ values was narrower in the Iron Age, and of a similar span as the wheat in the Roman period. Archaeobotanical evidence points to increased use of heavier, wetter soils in the later Roman period, but as a mixed arable model that continued to utilise higher and drier land. These isotope values support this interpretation in that the higher values may well be caused by increased use of wet soils, but the large range indicates drier soils continued to be



Inhumation 38.74 (381833) 5.2-Middle-Late Iron Age
Tooth: dM2. Comparative bone: Rib.

Inhumation 38.74 (381834) 5.2-Middle-Late Iron Age
Tooth: dM1. Comparative bone: Rib.

Inhumation 10.198 (107297) 6.2-Early Roman
Tooth: M2. Comparative bone: Rib.

Inhumation 11.18 (111368) 6.4-Late Roman
Tooth: PM2. Comparative bone: Rib.

Inhumation 10.719 (103019) 7.2-Early-Middle Saxon
Tooth: PM2. Comparative bone: none.

Inhumation 32.210 (320836) 7.3-Middle Saxon
Tooth: M2. Comparative bone: Rib.

Fig. 10. Selected examples of δ^{13}C and δ^{15}N values from incremental sampling of human remains. The dashed blue and red lines indicate the individual's rib or femur δ^{13}C and δ^{15}N values.

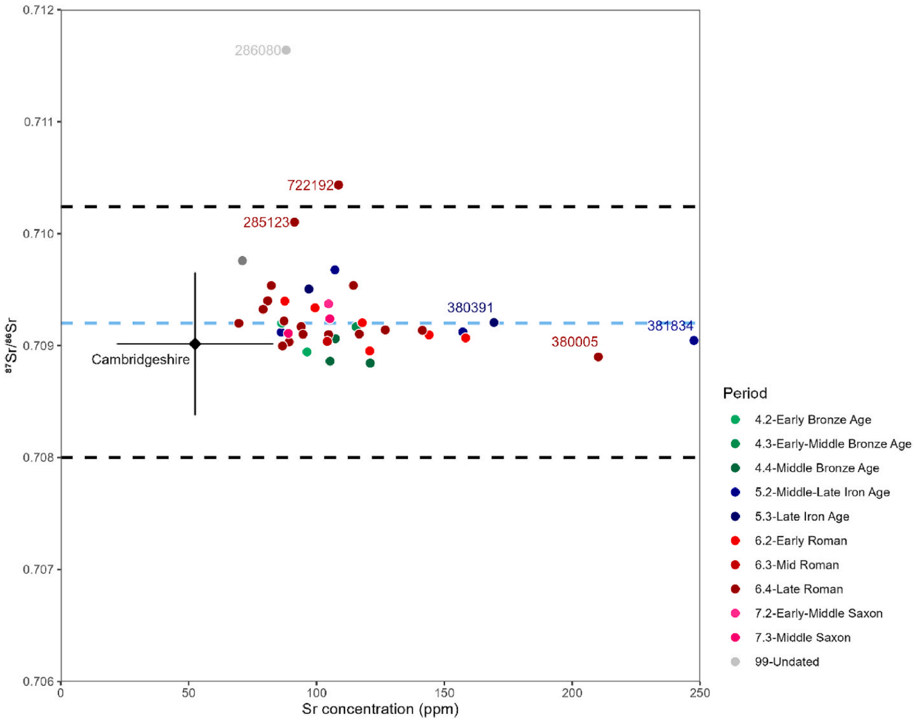


Fig. 11. Tooth enamel strontium isotope data alongside mean (±1σ) regional comparative data (Montgomery et al., 2019). The black dashed lines represent the bioavailable strontium isotope range for Cambridgeshire, and the blue dashed line represents seawater (Evans et al., 2012). Analytical error is within the symbol size.

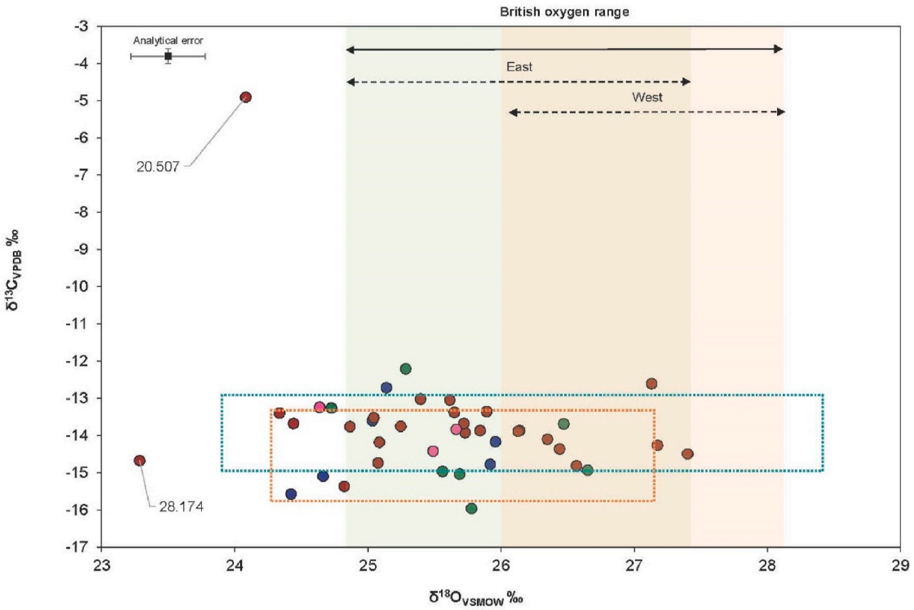


Fig. 12. Tooth enamel carbon and oxygen isotope data alongside mean (±1σ) regional comparative data represented by dotted boxes (Wiseman et al., 2021; Leggett, 2020). The shaded green and orange boxes represent the 2σ oxygen isotope range expected for archaeological human bone from Britain (Evans et al., 2012). The standard error is shown to 1σ. Colour denotes the main period (green = Bronze Age, blue = Iron Age, red = Roman, and pink = Anglo-Saxon). The analytical error is ±0.2‰ (1σ).

utilised. Other environmental factors may have influenced Δ^{13}C values, but the point remains that a diversity of field conditions existed.

In the Anglo-Saxon and medieval periods, there was a marked drop in Δ^{13}C values compared to the preceding periods. This decline is followed by an increase in Δ^{13}C values, reaching values comparable to the Iron Age and Roman periods by the Late Saxon period. For wheats this is a modest rise, whilst for barley and rye there appears to be a steep increase in Δ^{13}C values over time. The early Anglo-Saxon decline in Δ^{13}C values coincides with the aforementioned decline in δ^{15}N values and suggests a marked change in agricultural conditions following the end of the Roman period. One possible explanation may be a decline in the use of manure – as suggested by the δ^{15}N values – and this could also detrimentally affect water availability, as organic-rich soils have greater moisture-holding capacity. Indeed, there was a positive correlation between δ^{15}N and Δ^{13}C values ($r (184) = 0.333$, $p = <0.001$). The decline in Δ^{13}C values could also be an indicator of the Medieval Climatic

Anomaly – a period of warming with increased precipitation in cool seasons (Lamb, 1965). As the $\Delta^{13}C$ value of grain is determined in the summer months, during grain filling, the dry summers of the MCA may have had an impact on crop $\Delta^{13}C$ values, and therefore could have had a tangible impact on agricultural production for populations local to the A14.

4.3. Animal husbandry

The $\delta^{13}C$ and $\delta^{15}N$ values for livestock bone largely show evidence for a constrained C_3 terrestrial diet. The values for livestock are generally comparable to those of crops. If livestock had been consuming crop matter (through stubble grazing or foddering, for example), then their $\delta^{15}N$ values would have been a trophic level higher than those of the crops – and so we can largely exclude the inclusion of arable inputs in animal diet. All three tested taxa (cattle, caprine and pig) exhibit constrained ranges of $\delta^{13}C$ values of $\leq$1.4‰. This narrow range is comparable to the $\delta^{13}C$ value range seen in the modern Chillingham cattle (range = 1.3‰, n = 5). The Chillingham cattle represent a single herd living within a tightly restricted geographical area (Towers, 2013); therefore, the constrained values exhibited by the A14 fauna may be a result of similarly constrained grazing habitats or common husbandry regimes. The A14 pigs have similar $\delta^{13}C$ values to the cattle (mean = −13.6‰ and −13.1‰ respectively). Although pigs are omnivorous, the similarity between their $\delta^{13}C$ values and the cattle suggests that these pigs were consuming a predominantly plant-based diet.

There is a slight increase in $\delta^{15}N$ values over time for cattle and caprine. In the case of cattle (sample numbers are too small for caprine) there is also a hint of a drop in $\delta^{15}N$ values in the Late Roman and Early Saxon periods, which coincides with a drop in the $\delta^{15}N$ values of crops. This may indicate either the cause of the $\delta^{15}N$ values was environment-wide, or that livestock had a small input of crop vegetation in their diet. This must, however, have been a small input given that livestock $\delta^{15}N$ values are below those of crops, and not the one trophic level higher that would be expected if the livestock had been predominately eating crops. Isotopic evidence for differential treatment of livestock taxa is also limited. During the Roman period, however, caprines had higher $\delta^{15}N$ values than cattle. This may indicate that the Roman caprine had greater access to either manured crops or wild plants growing on heavy soils. Given that the Roman period saw an expansion of agriculture onto heavy soils, and that caprines fare better on damp ground than cattle, the offset between the two livestock taxa in the Roman period may be related to caprine access onto damp agricultural lands.

A further possible difference in the management of caprines is also detectable in the enamel $\delta^{13}C$ values from the Iron Age. Compared to collagen, tooth enamel is ^{13}C-enriched (Cerling and Harris, 1999). Whilst the enamel and bone collagen $\delta^{13}C$ values are consistent with a C_3 terrestrial diet, the caprines show greater ^{13}C-depletion than expected (Balasse et al., 2012; Towers, 2013). The two most likely causes of greater discrimination are the canopy effect (van der Merwe and Medina, 1991) and the consumption of plants growing on the wetter ground during the earlier years of the caprines' life. Both of these areas existed near the Brampton West landscape block, including wetland and alder carr along the River Ouse and the mature oak woodland of Brampton Woods (Milton et al., 2024). Younger caprines may have been restricted to these nearby non-agricultural environs, before being permitted to roam more freely at older ages in the predominately open landscape around the A14. The low $\delta^{13}C$ values of Iron Age sheep is perhaps less likely to have been a consequence of the canopy effect because sheep prefer to graze in open areas, rather than in woodlands or forests, and so the grazing of marshy habitats would seem a more likely explanation of the isotope data (Lynch et al., 2008).

4.4. Animal seasonality

Variation in $\delta^{13}C$ values through a tooth sequence can indicate dietary changes through the approximately one-year period over which the M_3 tooth develops, from around 12 to 24 months. Direct comparison between teeth is problematic because teeth are more likely to reflect year-to-year fluctuation in the $\delta^{13}C$ value of consumed plants to a greater extent than bone, which is prone to more pronounced dietary averaging. Further, tooth wear can reduce the period of tooth formation preserved in the tooth, typically resulting in there being fewer increments that can be sampled.

The maximum spread of births was calculated for each period with more than one individual (Table 9). The Iron Age witnessed the broadest spread of births, over nine months between individuals whilst the most restricted birth season was during the Roman period wherein the spread was under three months duration. During the Bronze Age and Saxon periods, the spread was intermediate. Manipulation of birth season can be indicative of the purpose for which cattle are raised, with beef cattle typically giving birth in a restricted spring birth season, whilst dairy cattle are manipulated for a larger spread of births to ensure ongoing lactation for the production of milk (Gron et al., 2015; Henriksen and O'Rourke, 2005; Nöremark et al., 2009). The Bronze Age and Saxon data could be indicative of either system, whilst the Iron Age system is more consistent with a dairy production economy and the Roman cattle more consistent with husbandry for meat (see Table 8).

The season of birth can be estimated from when the M_3 began to mineralise (at around 12 months after birth). Saxon cow A14-10-2406 appears to show that the M_3 started mineralising in the autumn (profile is falling towards winter minima) and completing the following autumn when it was c. 24 months of age. Several other cattle profiles exhibit a similar seasonal profile and possibly autumn births with a small number, e.g. A14-12-820 (Fig. 6), conversely showing a rising profile at the start, which may be indicative of a spring birth. However, caution is required when considering these birth season estimations because enamel at any point on the tooth takes up to 6 months to fully mineralise and is incorporating carbon and oxygen throughout this time (Balasse, 2002; Towers, 2013). As a result, for example, profiles that show an autumn birth (i.e. shortly before the winter minima) may have started mineralising in spring or summer. This makes it difficult to predict the season of birth for individuals from the profiles alone, but there are some animals that are highly likely to have been born in the same season, e.g. compare A14-10-3873 and A14-7-1124 and in contrast, others who were not, e.g. compare A14-12-297 and A14-12-820.

One of the clearest seasonal curves comes from a Saxon cow (A14-10-2406) (Fig. 6). In this instance, $\delta^{18}O$ and $\delta^{13}C$ values co-vary, with summer maxima ($\delta^{18}O$ = −6.5‰) and winter minima ($\delta^{18}O$ = −9.5‰) roughly coincident. This could reflect seasonal variation in the isotope values of the food being consumed but could also alternatively reflect a seasonal shift between foddering and grazing. It could also stem from the seasonal movement of animals from one location to another (Towers et al., 2017). While this pattern is not evident in all animals sequentially sampled here, its clear presence in some individuals points to the likelihood that the dietary history of these animals is more complex than the collagen data imply.

4.5. Human population trends

The diets of almost all of the analysed A14 individuals are very similar, regardless of location on the scheme or chronological period. This is especially the case for dentine $\delta^{13}C$ values, which indicates that protein dietary variation was narrower than for fats and carbohydrates. Comparison with long bone collagen shows that $\delta^{13}C$ values typically fell in later years, indicating a shift from dietary protein sources eaten during childhood. This fall in $\delta^{13}C$ values from dentine to bone was most pronounced in the Iron Age and Late Roman periods. The Roman period also shows increased variation in $\delta^{13}C$ values for the bone compared to dentine data (Fig. 8 and Figure S 18). For $\delta^{15}N$ values, there is little change from dentine to bone, though values were less varied in bone

Table 7
Summary of bulk $\delta^{13}C$ and $\delta^{15}N$ values for human samples. * The value shown for longbones is from either a femur or rib sample, and for instances where both were sampled the value shown is the mean of the two.

	Enamel apatite $\delta^{13}C$		Dentine collagen $\delta^{13}C$		Dentine collagen $\delta^{15}N$		Longbone* collagen $\delta^{13}C$		Longbone* Collagen $\delta^{15}N$	
Main period	Mean (‰)	1σ (‰)	Mean (‰)	1σ (‰)	Mean (‰)	1σ (‰)	Mean (‰)	1σ (‰)	Mean (‰)	1σ (‰)
Bronze Age	−14.3	1.3	−20.7	0.6	11.1	1.6	−21.4	0.2	10.8	2.0
Iron Age	−14.4	1.0	−20.2	0.5	13.0	2.2	−21.6	1.3	12.1	2.2
Roman	−13.4	1.9	−19.7	0.9	11.7	1.2	−20.9	0.7	11.4	0.8
Anglo-Saxon	−13.8	0.6	−19.7	0.3	10.9	1.3	−20.9	1.7	11.3	0.9

than dentine in the Roman period (Fig. 8 and Figure S 19). The diet is predominantly terrestrial but there are indications in the incremental dentine profiles for periods where a small amount of protein of marine or estuarine origin may have been consumed if $\delta^{13}C$ values approach or exceed −19‰. The Late Iron Age individual 10.152 is a clear example of this with both $\delta^{13}C$ and $\delta^{15}N$ values rising at the end of the profile.

Generally, there is an expected trophic level increase in $\delta^{15}N$ values of 3–5‰ and of 1–2‰ in $\delta^{13}C$ values between diet and bone collagen (Bocherens and Drucker, 2003; DeNiro and Epstein, 1981; Robbins et al., 2005; Van der Merwe, 1989). The trophic level increase is the same regardless of consumption of plant or animal products. If plant and animal foods have distinct isotopic values, it is then possible to infer their relative contribution to diet. For the A14 crops and livestock $\delta^{15}N$ and $\delta^{13}C$ values are very similar. Indeed, crop $\delta^{15}N$ values are a little higher, which is the opposite of what would normally be expected. In the case of the A14, then, a person consuming a diet comprising purely of crop products might be expected to have $\delta^{15}N$ value of approximately 9.7–12.7‰ (crop mean + 3–5‰), and for livestock-based diet $\delta^{15}N$ values between 8.6 and 11.6‰ (livestock mean + 3–5‰). The mean human $\delta^{15}N$ value is 11.6‰. This is very slightly above the expected range of a pure animal-based diet, but almost any contribution of crops could raise $\delta^{15}N$ values sufficient to reach the average. For example, a 90% livestock diet and 10% crop diet, would produce a likely range of $\delta^{15}N$ values for humans of 9.7–11.7‰.

Stable carbon isotope ratios are more challenging to use for palaeodietary reconstruction as the trophic level increase is smaller, and crops and livestock on the A14 have near-identical $\delta^{13}C$ values. Notably, however, barley has lower $\delta^{13}C$ values (a physiological offset discussed above), and the difference between the $\delta^{13}C$ values for livestock and humans is less than the expected trophic at +0.5‰. This may indicate that crops, and barley in particular, were an important part of human diets. This contrasts with cereal-based food analysis that found wheat to be the main component of preserved food remains, though the extent to which rarely found remains accurately represent overall dietary trends is unclear (Carretero, 2023). Taken as a whole, the stable isotope data for the A14 indicates that both crops and livestock could have been important parts of human diet. Perhaps the less likely scenario, is that humans consumed predominately meat-based diets (as to do so would likely have resulted in slightly lower $\delta^{15}N$ values and higher $\delta^{13}C$ values). Nevertheless, animal products may well have been an important source of sustenance alongside crops.

Across stable carbon, nitrogen, oxygen and strontium isotope ratios the results indicate that the people of the A14 area largely lived local and similar lives across the chronological range of the study. Overall $\delta^{13}C$ and $\delta^{15}N$ values for A14 individuals indicate no significant difference seen in values from bone or enamel between the different periods. This trend is consistent with evidence from previously published studies from Cambridgeshire (Hannah et al., 2018; Kulick, 2010; Leggett, 2020; Lucy, 2009; Mays and Beavan, 2012; Scheib et al., 2019). In the round, these people appear to have consumed similar, terrestrial diets. This dietary similarity is likely related to the strontium evidence that indicates most persons were born-and-bred locally. Strontium isotope ratios were constrained between individuals, which is also consistent with other populations from Cambridgeshire (Evans et al., 2012; Montgomery et al., 2019) and within the range expected for Britain (Evans et al., 2012; Leggett, 2020; Montgomery et al., 2019), as well as consistent with the region's Cretaceous and Cretaceous chalk, Jurassic limestone and Gault formation mudstone, and nearby Oxford and Ampthill clay formations (Evans et al., 2012). Likewise, strontium isotope concentrations fall within the range expected for British populations (Evans et al., 2012). Strontium concentrations can be influenced by several factors such as calcium intake, geology, atmospheric deposition (dust, sea spray, precipitation etc.), anthropogenic influences (e.g. fertilizer) and trophic level (Burton and Wright, 1995; Lazzerini et al., 2021; Maurer et al., 2012; Montgomery, 2002). Therefore, unusually high strontium concentrations may indicate a predominantly plant-based diet, low dietary calcium intake or residency in a region with unusual geology or high aridity. All but one of these individuals can be considered local and have similar values to other individuals from Cambridgeshire (Leggett, 2020; Wiseman et al., 2021).

An isotopically homogenous population is further indicated by oxygen isotope ratios. The range (excluding one outlier) in $\delta^{18}O$ values is just 3.3‰, which is consistent with a single archaeological cemetery population (Evans et al., 2012; Lightfoot and O'Connell, 2016). The Roman population exhibits the most variability, though there was no statistically significant difference between periods. The analysis of $\delta^{18}O$ values for individuals residing in Britain can be split into an eastern 'low rainfall' range and a western 'high rainfall' range, with some overlap between these ranges (Evans et al., 2012). Ten individuals fall within the overlap area indicative of a general value expected for Britain, while the majority of the A14 individuals fall within the eastern 'low rainfall' region of the plot. Late Roman individual 28.174 was, however, likely not local to Cambridgeshire given that this individual's $\delta^{18}O$ values was below that for rainfall. All of these values are common within Britain and not particularly diagnostic with regards to refining the childhood origins of this population; they are, however, entirely consistent with most of the A14 individuals having lived locally around the Cambridgeshire area with the exceptions of 28.174 and 20.507.

4.6. Human life histories

Although many of the people of the A14, regardless of period or settlement location, can be characterised as having lived similar life experiences, there are certain individuals with outlier isotope results that point to deviation from the norm. Three individuals stand out from the rest of the population with high $\delta^{13}C$ or $\delta^{15}N$ values. These include the high $\delta^{15}N$ values from the deciduous teeth of two Iron Age children from a double inhumation (38.74, skeletons 381833 and 381834), and Roman individual 20.507, exhibits a high $\delta^{13}C$ value of −15.6‰, which is consistent with a diet containing a large portion of C_4/marine protein. The relatively low $\delta^{15}N$ value observed in the individual from inhumation 20.507 (8.7‰), suggests that marine resources were not a major component of their diet, therefore the high $\delta^{13}C$ values could be due to eating C_4 crops such as millet or sorghum. Furthermore, two Roman individuals (28.567, which is only tentatively dated to the Roman period, and 7.305) have strontium isotope ratios that indicate a

Table 8
Summary results for incremental analysis of human teeth samples.

Sampling				δ^{13}C (‰)			δ^{15}N (‰)		
Inhumation	Context	Increments	Age range (years)	Mean	Min.	Max.	Mean	Min.	Max.
4.2-Early Bronze Age									
10.545	100586	14	11.0	−21.2	−21.4	−20.9	9.0	8.7	9.4
28.505	280285	9	8.0	−19.8	−20.1	−19.6	10.8	9.6	12.7
4.3-Early-Middle Bronze Age									
12.7	122219	15	11.0	−20.8	−21.2	−20.4	12.9	12.4	13.6
4.4-Middle Bronze Age									
28.46	280488	15	11.0	−20.5	−20.9	−20.4	11.5	10.8	12.1
28.41	280494	9	11.0	−21.4	−21.5	−21.3	12.4	11.5	13.1
4.6-Late Bronze Age-Early Iron Age									
5.276	51018	12	8.0	−19.8	−20.2	−19.4	8.9	8.4	9.6
5.2-Middle-Late Iron Age									
38.74	381833	10	2.1	−20.5	−20.8	−20.3	15.3	13.7	16.5
38.74	381834	6	1.0	−20.1	−20.5	−19.7	16.2	15.4	16.8
38.135	383075	15	8.0	−20.3	−20.8	−19.9	11.1	9.8	12.1
7.3	720506	6	5.5	−20.8	−21.0	−20.6	10.7	10.1	11.3
5.3-Late Iron Age									
38.318	380391	15	11.0	−20.3	−20.6	−19.7	12.8	11.8	13.7
10.152	604553	15	8.0	−19.3	−20.0	−18.8	12.0	11.4	12.9
6.2-Early Roman									
10.198	107297	15	11.0	−20.2	−20.6	−19.4	12.4	11.4	13.1
10.192	107389	7	8.0	−20.5	−21.0	−20.2	10.9	10.5	11.4
11.55	112202	11	8.0	−19.7	−20.0	−19.3	12.0	11.4	12.4
28.328	281771	18	8.0	−19.9	−20.5	−19.4	13.0	12.7	14.1
10.34	604282	10	11.0	−19.3	−19.9	−18.9	11.0	10.1	12.4
10.132	604319	14	10.0	−19.9	−20.2	−19.8	12.0	11.2	13.2
6.3-Mid Roman									
20.507	203645	15	11.0	−15.6	−18.8	−12.0	8.7	6.9	9.9
6.4-Late Roman									
11.18	111368	18	8.0	−19.6	−20.1	−19.2	11.3	10.8	11.6
11.19	111370	15	11.0	−19.9	−20.1	−19.7	11.1	10.2	11.5
19.21	190172	15	11.0	−19.8	−20.0	−19.6	11.7	11.4	12.7
20.179	204136	15	12.0	−19.7	−20.0	−19.5	13.5	12.4	14.3
27.34	271107	16	12.0	−19.9	−20.3	−19.4	12.0	10.5	14.8
27.32	271109	20	12.0	−19.5	−19.8	−19.2	12.5	11.6	13.6
28.173	285008	17	8.0	−19.4	−20.1	−19.1	13.0	12.5	13.6
28.174	285034	13	11.0	−20.1	−20.4	−19.5	10.2	9.3	11.1
28.168	285093	15	9.0	−19.7	−20.1	−19.5	11.0	10.1	11.5
28.162	285098	15	9.0	−20.4	−20.9	−20.2	11.7	11.2	12.4
28.164	285123	15	8.0	−20.2	−20.8	−19.8	12.4	11.9	13.0
28.167	286100	15	8.0	−19.6	−19.9	−19.3	13.0	12.5	13.7
38.278	380005	8	4.0	−20.0	−20.3	−19.9	13.6	12.0	15.1
38.129	380615	16	11.0	−19.7	−20.2	−19.4	11.1	10.5	11.7
38.45	381111	15	11.0	−19.6	−20.2	−19.3	12.3	11.7	13.0
7.305	722192	15	8.0	−20.3	−20.6	−19.6	11.1	10.1	12.9
7.63	723735	14	11.0	−20.2	−20.8	−19.6	10.5	9.5	11.2
7.64	723739	13	11.0	−20.0	−20.4	−19.5	9.8	9.1	10.4
7.2-Early-Middle Saxon									
10.719	103019	14	8.0	−19.4	−19.8	−19.1	11.4	10.0	13.3
7.3-Middle Saxon									
32.210	320836	15	11.0	−19.9	−20.3	−19.7	11.8	10.5	12.9
7.437	767165	15	8.0	−19.6	−20.6	−18.8	9.4	8.9	10.0

Table 9
Calculated maximum duration of birth season for cattle by period.

Period	Maximum birth season duration (months)	Number of teeth
Bronze Age	5.1	2
Iron Age	9.1	3
Roman	2.8	2
Anglo-Saxon	4.4	6

childhood spent elsewhere than Cambridgeshire. One Iron Age individual (38.74, 381834) and two Roman individuals (38.278 and 38.318) have higher than expected strontium concentrations. Only the Roman individual from inhumation 28.174 has a sufficient low δ^{18}O value to indicate a non-local origin. There are no individuals with the high oxygen values that would be expected for warmer regions at lower latitudes such as around the Mediterranean and which have been previously obtained from Roman period individuals buried in Britain (Martiniano et al., 2016). The results for these atypical individuals are discussed in more detail in the following account of individuals' life histories.

4.6.1. *Bronze Age individuals*

Reconstruction of diet for the Bronze Age is problematic given the lack of suitable crop samples for stable isotope analysis and the scarcity of livestock samples. Despite the lack of comparative data for the Bronze Age, human individuals are striking for the narrowness of their range of δ^{13}C values and high variation in δ^{15}N values. Indeed, though the sample size is small, Bronze Age individuals might be assigned to two groups based on δ^{15}N values. Inhumations 10.545 (EBA, likely female) and 5.276 (EBA, likely female) have δ^{15}N values consistently below 10‰, whilst individuals 12.7 (EMBA, male), 28.41 280494 (MBA, likely female) and 28.46 (MBA, likely male) have δ^{15}N values around 12‰. The δ^{15}N values for the individual of inhumation 28.505 (EBA, female, discussed below) vary between these two groups. These dietary groups could have a chronological dimension, with high δ^{15}N values associated with mid Bronze Age individuals, or a sex dimension, with the two low δ^{15}N value individuals both being females and all high δ^{15}N values individuals being males except one – who was a double inhumation (28.41) with a male.

Early Bronze Age inhumation 28.505 (280285), an adult (genetically consistent with a female) found in a crouched position from Fenstanton Gravels, experienced a substantial decrease in δ^{15}N values. The decrease began at an age of *c*.3.5 years, ending at *c*.7.5 years of age. This fall may have begun even earlier in infancy, and could signify the weaning period. Alternatively, the fall in the results at the start of the profile could represent a stress event in early childhood (Beaumont et al., 2018; Beaumont and Montgomery, 2016). The continued decrease in δ^{15}N values, however, suggests a significant change in diet with a shift away from the consumption of the prevailing diet, that likely comprised manured crops (though not confirmed as present in the Bronze Age) or terrestrial meat. The diet of individual 28.505 was at a lower trophic level, and is comparable to that of inhumed individuals from inhumations 5.276 and 10.545.

The lowest δ^{15}N value is for Early Bronze Age inhumation 10.545 (100586), of Brampton West Cemetery 103, a genetically female adult of 18–25 years with evidence of significant healed trauma to the right clavicle. Though isotopic analysis is consistent with a local childhood, genetically this individual had a greater input of Steppe-related ancestries (Silva et al., 2022). Her δ^{15}N value was below the minimum expected for one trophic level rise for livestock from all periods, indicating her diet comprised mainly (i) unmanured crops, (ii) wild plants or (iii) non-local plants. The latter may seem most likely given her genetic non-local ancestry, however, her strontium isotope ratios are consistent with life in Cambridgeshire. The individual's ancestry could have been expressed as a culturally-mediated deviation from the typical diet, and may have also been a reason for funerary inhumation rather than the more usual cremation.

Middle Bronze Age Inhumation 28.41, from Cemetery 3 at Fenstanton Gravels, comprised two individuals: an 18–25 year old of undetermined sex (280494) and a male of 26–35 years (280495). The former had two periods (between 2.5 – 7 years and 7–13.5 years), where their δ^{15}N values significantly increase, stabilise, and then fall back towards their average adult value (see Fig. 4b). As the δ^{13}C values remain stable during these times the rises in δ^{15}N values may be due to periods of physiological stress such as childhood disease, rather than a change in diet (Beaumont and Montgomery, 2016).

4.6.2. *Iron Age individuals*

Except for inhumation 38.135, which shows signs of 'stress bubbles' (Beaumont and Montgomery, 2016) in their profile of δ^{15}N values, the most notable inhumation is 38.74. Inhumation 38.74 contained two children, one of approximately 3 years of age (381833) and another of 7–11 months (381834). Ancient DNA analysis indicates these children were half-siblings, with different fathers. The two individuals provide the only deciduous teeth analysed in this study, and so uniquely offer insights into early infant life. The deciduous first molar, from 381834, begins forming at 30 weeks in utero, and the δ^{15}N values rise until death around 11 months (AlQahtani et al., 2010). This contrasts with the older child's deciduous second molar, which provides a profile up until death at *c*.2 years of age. Both individuals have δ^{15}N values averaging at least 2.4‰ above the Iron Age adult mean value, this is consistent with a trophic level shift indicative of breastfeeding, although values approaching 16–17‰ are very high and may also be recording stress as the consumption of breast milk has been shown to result in a trophic shift of approximately only 2‰ above the δ^{15}N values of the mother (Dupras and Tocheri, 2007; Fogel et al., 1997; Fuller et al., 2006; Herrscher et al., 2017). For the younger child, the profile of δ^{15}N values suggests weaning had not begun, whilst the fall in δ^{15}N values for the older child could be an indication that this child was being weaned (Jay et al., 2008; Redfern et al., 2012). The rib bone values for the two children likely represent the diet of their shared mother whilst she was pregnant. Whilst δ^{15}N values are higher than typical for A14 adults, most notable is the extremely low δ^{13}C value (very uncommon for Iron Age populations in Britain) and high δ^{15}N value of the younger child. This indicates that between the two births either the mother's diet was markedly different to that of other A14 individuals or the mother or foetus experienced stress during pregnancy (Beaumont et al., 2018; Beaumont and Montgomery, 2016). The former scenario may be more likely given that the younger child's high strontium concentration, which is unusual for archaeological humans from England, which may indicate a vegetarian diet deficient in calcium, though the isotopic dynamics and interaction between the mother and foetus are still largely unknown and the subject of current research.

4.6.3. *Roman individuals*

Mid-Roman inhumation 20.507 (203645), an adult of unknown sex inhumed at River Great Ouse 2, had a non-native C_4 diet and an oxygen isotope ratio inconsistent with Britain. The δ^{18}O value is indicative of an origin at high latitudes, altitudes or in continental eastern Europe (Crowder et al., 2020). Ancient DNA analysis indicates that genetic ancestry derives from the Caucuses (Silva et al., 2022, 2024). The middle Roman date of this burial suggests a possible connection with Marcus Aurelius' Sarmatian cavalrymen brought to Britain following the Marcomannic War (AD169–175). In this individual's childhood, at c.5 years of age, they experienced a rapid shift to a mixed C_3/C_4 diet, and then a further more gradual shift, aged c.9 years, to a diet based predominantly on C_3 resources. The combined isotope and DNA evidence supports the theory that this person migrated from the eastern provinces as a child (Damgaard et al., 2018; Silva et al., 2022). The two shifts in diet may have revealed a hiatus in the journey westward: the first dietary change – an introduction of C3 foods - being abrupt and the second – a more gradual removal of C4 foods from the diet - possibly as a result of a migration west through Europe to Britain. The presence of enamel hypoplasia on the crowns of nine teeth may reflect periods of arrested growth during episodes of malnutrition or illness (Aufderheide and Rodríguez-Martín, 1998, p. 405; Hillson, 1996, p. 165). The location of these defects suggests they occurred around the age of 5 years.

Late Roman Inhumation 72.305 (722192) of a male aged 26–35 years from Brampton West 100 was deposited in the backfill of a well. The lower body was missing, apparently cut off at the thoracic/lumbar border and was not identified in any of the other fills, whilst a semi-articulated cattle skeleton was also present in the deposit. The individual had severe dental malformities and evidence of healed porotic hyperostosis. The individual's strontium isotope ratio was indicative of a non-Cambridgeshire origin, but it can be widely obtained from regions of clay sedimentary sandstones in central and southern England. Although the strontium isotope ratios observed in these A14 individuals are common in burials from England, they are also common in regions across Europe. These data, therefore, do not provide a conclusive indication of local origins. A further individual (Supplementary Fig. 22) had a similar strontium isotope ratio (inhumation 28.567), but it has not been possible to securely date the individual.

Inhumation 28.174, an adult male of 36–45 years from Cemetery 4 at Fenstanton Gravels had an oxygen isotope ratio well below the range expected for Britain, which is even lower than that of the other Roman period immigrant, 20.507, discussed above. As with 20.507, such a value indicates that this individual spent their childhood (2.5–8.5 years) in a cooler province; for example, the Alps or continental Eastern Europe. Similarly low δ^{18}O values have been observed in Roman populations from Alpine regions of the Roman Empire such as northern Italy and southeast France and regions of Eastern Europe such as Romania (Crowder et al., 2020; Milella et al., 2019).

4.6.4. Anglo-Saxon individuals

Two (10.719 and 7.437) of the individuals from Brampton West display the trophic level drop in δ^{15}N values at the start of the profile before the age of *c.*5 years, which is seen in other individuals from earlier periods. This could indicate an extended breast feeding period, but the profile of δ^{13}C values are rising, suggesting a post-weaning dietary change overlain by physiological stress (Beaumont et al., 2018), which, for 10.719 seems to be a recurring pattern. The profiles for 7.437 and 10.719 may show the ending of weaning between the ages of 3.5 years and 4.5 years (Fig. 10), however, this is rather land and other studies have demonstrated that weaning had occurred by the age of 3 years in Anglo-Saxon populations (Privat et al., 2002). The slightly later weaning pattern seen in the A14 individuals may be due to regional variation in feeding practices (Macpherson et al., 2007). However, if the profiles are recording the trophic level shift that occurs after the cessation of breastfeeding both profiles should fall (Beaumont et al., 2018) – such a weaning profile is clearly shown in the Roman individual 27.34. There is a difference in when the analysed teeth formed. For the Roman individual, a canine was analysed, which starts to form c. 6 months of age. The three Anglo-Saxon individuals had second molars and premolars analysed, which do not start to form until after the age of two, and so these teeth may have missed the period of breastfeeding entirely.

The falling δ^{15}N values accompanied by rising δ^{13}C values as seen in 10.719 may be recording an earlier stress event (Beaumont and Montgomery, 2016). Individuals 32.210 and 10.719 have very similar profiles after the age of c. 4 years when both profiles show a rise in δ^{15}N values possibly accompanied by a small fall in δ^{13}C values, after which the profiles decrease until the age of 10 years and then rise again (Fig. 10). It is unusual that this pattern is seen in both individuals and could signify a cultural change in diet during the periods of life or be due to environmental factors such as limited availability of animal products or a period of physiological or nutritional stress.

The Anglo-Saxon period female of inhumation 32.210 did at around fifteen years of age. This individual was buried in a highly unusual position (West et al., 2024) which is consistent with ‘deviant’ burials of persons classed as having ‘otherness’ and/or being dangerous to the living (Harman et al., 1981; Reynolds, 2009). The young woman also appears to have been of eastern descent, possibly from Scandinavia, North-Eastern or North-Central Europe, based on ancient DNA analysis (Silva et al., 2022). Her diet underwent a significant tropic shift (*c.*3‰) between the ages of 4 and 8 years, and similar shifts occur twice in the profile of 10.719. Despite these deviations, the isotopic analysis is entirely consistent with a local origin and diet.

5. Conclusion

The A14 project stands as a landmark in UK commercial archaeology. The endeavour to integrate isotope analysis of crops, livestock, and human remains with a rich archaeological record, has yielded insights into past lives across various periods. It showcases the transformative power of isotope analysis in commercial archaeology, unlocking novel narratives at both assemblage and individual levels. Furthermore, this project highlights the immense research potential of large datasets generated by commercial infrastructure projects, as well as the effectiveness of partnerships between researchers in the commercial sector and those based in academia. By working together, the result is a richer narrative than would have been possible by separate groups working in isolation.

Agricultural practices from the Iron Age through to the Anglo-Saxon period along the A14 reveal remarkable stability. The isotope record suggests a largely homogenous life history for crops and livestock, with no dramatic changes following the Roman invasion. This indicates the persistence of well-established Iron Age agricultural traditions in this rural landscape. Subtle shifts emerged in the Late Roman period, possibly reflecting extensification of agriculture, utilisation of heavier soils, and changes in cattle birthing seasons. These gradual adjustments in agricultural decision-making may be linked to the encroachment of nucleated settlements, slowly bringing the A14 area into alignment with the regional Romano-British trends that are more apparent at large and high-status sites.

The Anglo-Saxon period marks the first dramatic shift in agriculture, evident in a sharp decline in crop δ^{15}N values and an inversion of maxima/minima in δ^{13}C and δ^{18}O values for cattle. These sudden changes at the start of the Anglo-Saxon period might have stemmed from climatic or regional factors. Significant contraction of settlement organisation and the introduction of new agricultural technologies and methods during this period point to a more substantial transformation over time, though one that took the entire early medieval period to become fully established.

The human isotope data further reflects a pattern of stability and continuity. The sampled population originated primarily from the Cambridgeshire area, with little evidence of dietary variations between periods. Albeit with the relative contribution of plants and meat to dietary protein masked by the isotopic similarity of the crops and livestock from the A14; this highlights the importance of using site-specific baseline data for accurate dietary reconstructions. Evidence of malnutrition and physiological stress was found throughout the studied period, corroborating osteological analysis. Thes prevailing homogeneity does not, however, negate the presence of fascinating outliers. Isotope signatures reveal rare migrants from other parts of Britain and Europe, alongside unusual burial practices. These exceptions highlight the power of multi-isotope analysis, especially when combined with traditional osteological analysis and ancient DNA analysis, to build rich life stories for individuals.

The observed homogeneity in agriculture, diet and provenance is particularly striking given the backdrop of changing socio-economic models and settlement contraction. This stability suggests a community identity built on shared practices. Even during the Iron Age, when there was perhaps more capacity for individual variations amongst small, dispersed rural settlements, the overall picture remains one of remarkable consistency. Indeed, the trend for settlement nucleation seen throughout the A14 was perhaps facilitated by these shared traditions.

The A14 isotope record paints a picture of resilient traditions that were slow to develop into new models. While earlier periods demonstrate a degree of individual variation within a framework of consistent practices, later phases exhibit more pronounced extremes in the isotope data. This shift suggests the growing influence of external factors, potentially reflecting increased connectivity and adaptation to a more market-driven economy. The A14 project serves as a powerful example of how isotope analysis can illuminate the complex interplay between local traditions and broader cultural shifts.

Author contributions

Wallace, M. design of sampling strategy, data analysis, interpretation, manuscript preparation, editing Montgomery, J.[2]* design of sampling strategy, interpretation, manuscript preparation, editing Rogers, B.[2] sample preparation, data analysis, interpretation, manuscript preparation Moore, J.[2] design of sampling strategy, sample preparation and mass spectrometry, data analysis, illustration and interpretation, manuscript preparation, editing Nowell, G.[2] sample measurement, mass spectrometry and data analysis and interpretation Bowsher, D.[3] interpretation, editing, project management Smith, A.[1] interpretation, editing, project management.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT and Google Gemini in order to improve the readability of the manuscript text. After using these services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.109059.

Data availability

Data available in supplementary information and at https://doi.org/10.5281/zenodo.7189337.

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