3 Understanding Early Medieval Crop and Animal Husbandry through Isotopic Analysis

Elizabeth Stroud

Introduction

The early medieval period saw changes in both animal and crop husbandry methods in some regions, from the introduction of crop rotation and the mouldboard plough to the possible reduction in animal pasture (Hamerow, this volume). This paper explores the nature of animal and crop husbandry during this period using stable carbon and nitrogen isotope analysis. The stable isotopes of carbon and nitrogen provide direct information relating to the diet of animals and the soil conditions in which crops were cultivated. For the first time, the isotopic values of early medieval English crop remains are used to investigate whether cereals could have been regularly consumed by domestic animals: for example, through grazing on stubble or fallow fields. Two case study sites – Lyminge in Kent and Stratton in Bedfordshire (Figure 4) – had both plant and animal remains available for isotopic sampling, providing the unique opportunity to explore changes in crop and animal husbandry over time and between different species.

As crop and animal husbandry are interlinked, understanding one can provide information regarding the other. Arable expansion could have reduced the availability of pasture, thus restricting the grazing locations of animals. Conversely, grazing on stubble or fallow fields may have increased as arable cultivation expanded. Grazing of the fallow by livestock is thought to be a method of increasing the fertility of the soil, with sheep manure and urine providing nitrogen and phosphate (O'Connor, 2011, 372). It has been suggested that the expansion of arable farming in the early medieval period is linked to a widespread increase in sheep rearing (Holmes et al., forthcoming), potentially associated with the use of sheep to manure stubble and fallow fields (Campbell, 2000, 154).

Historical documents pertaining to fully developed open-field systems indicate that sheep spent significant amounts of time on fallow fields. In fourteenth-century France, for example, textual evidence indicates that sheep grazed on fallow fields for four months of the year (Carroll and Wilson, 2012). In seventeenth-century Laxton in Nottinghamshire, sheep could spend most of their lives grazing on stubble and fallow: grazing the autumn field after the harvest until October, when that field was ploughed in preparation for the sowing of the spring crop (Haigh, 2016, 80). The sheep would then be moved to the newly harvested spring field and could graze there until the following October (Haigh, 2016, 81). Other livestock, such as cattle and horses, would be removed from the fields by 23 November and kept inside for winter (Haigh, 2016, 81). The reliance on fallow grazing is thought to have increased over time – with the Laxton example probably a consequence of rigid regulations and the lack of alternative grazing locations – but exactly what occurred during the early medieval period is unclear. Isotopic analysis of animal and plant remains offers one way of understanding developments in the consumption patterns of livestock during this poorly documented period.

While zooarchaeological studies have provided crucial information regarding the relative proportions and regional variations of domestic animals (e.g., Holmes, 2014; 2016; Sykes, 2007), understanding the animals' diet is more difficult and requires the use of other methods. Some studies have used tooth wear and related pathologies to investigate dietary inputs (Wilkie et al., 2007; Holmes et al., 2021b), but stable isotope analysis offers a more direct method of investigating diet: as demonstrated, for example, by isotopic research on medieval pigs (Hamilton and Thomas, 2012; Hammond and O'Connor, 2013) and herbivores (Evans et al., 2007; Müldner et al., 2014).

Background to the sites

Lyminge

Lyminge is located on chalk bedrock at the head of the Nailbourne river valley, eight kilometres from the Kent coast (Figure 4). The site has access to different soils: while it is surrounded by silty soils, areas of deep loam and clay, as well as seasonally wet deep clay, are accessible to the south and east of the site. Palaeoenvironmental reconstruction as well as historical records indicate wooded areas in the vicinity during the early medieval period (Maslin, 2017).

Excavations by the University of Reading (2007–14) have revealed a long occupation sequence including a seventh-century hall complex, a mid-seventh- to late ninth-century monastic centre, and a tenth- to twelfth-century archepiscopal estate (Thomas and Knox, 2012; Thomas, 2013). A seventh-century plough coulter excavated here represents the earliest archaeological evidence for the mouldboard plough in early medieval England, making this a key site in the history of early medieval farming (Thomas et al., 2016; Bogaard et al. and Hamerow, this volume).

Bioarchaeological research into early medieval agriculture at Lyminge has been extensive. Archaeobotanical research indicates that a range of crops was cultivated throughout the occupation sequence, with a particularly diverse range of crops and weeds represented in the eighth- to ninth-century phase (McKerracher, 2017; Bogaard et al., this volume). Zooarchaeological and isotopic research has also been conducted at the site (Knapp, 2018). Zooarchaeological analysis reveals that cattle, the dominant animal between the fifth and seventh centuries, was superseded by sheep in the eighth- to ninth-century phase. This shift could indicate a change in the provisioning of the site or in the wider animal economy, or perhaps an increase in the importance of arable agriculture, given the mobility of sheep and their potential use in grazing and manuring the fallow (Knapp, 2018).

Stratton

Stratton lies in the Ivel valley in east Bedfordshire (Figure 4). The soils surrounding the site comprise easily worked, free-draining loams; deep clays which are prone to waterlogging; and seasonally wet alluvium. Local pollen evidence indicates that the area was a relatively cleared landscape throughout the early to late medieval periods, with some wooded areas available for use by the inhabitants (Shotliff and Ingham, 2022).

Large-scale excavations by Albion Archaeology (1990–2003) revealed an occupation sequence spanning the fifth to seventeenth centuries, with extensive, formal settlement planning evident from the seventh to ninth centuries onwards – perhaps indicating some ecclesiastical oversight (Blair, 2013, 33). Research into the agricultural activities at the site has indicated that a wide range of crops were consumed throughout its occupation history, including both bread and rivet wheat, barley, oat and rye (Moffett and Smith in Shotliff and Ingham, 2022). Documentary evidence suggests that Stratton may not have produced its own barley, but rather received it from Biggleswade, the manorial centre of the parish, at least by the thirteenth century: the local rolls of assess from 1297 indicate that barley was cultivated at Biggleswade but not at Stratton (Shotliff and Ingham, 2022). Zooarchaeological research highlights a heavy reliance on cattle, supplemented by sheep and pigs, to provide meat for consumption. Cattle appear to have been slaughtered at an older age over time, and a rise in the proportion of female cattle indicates a possible increase in the importance of secondary products such as milk (Maltby in Shotliff and Ingham, 2022; Holmes in McKerracher et al., forthcoming).

Stable carbon and nitrogen isotopes

The analysis of cereal grains' stable carbon isotopic ratio ($\delta^{13}C$) allows information about the growing conditions of the plant to be gained, particularly how wet or dry the environment was during cultivation. This is due to the fact that wheat, barley, oat and rye use the C_3 photosynthetic pathway which preferentially selects the lighter isotope of carbon over the heavier one. The plant, when absorbing the CO_2 required for photosynthesis, can also lose water via its stomata. Thus, there is a trade-off between the absorbance of CO_2 and the conservation of water. In times of water limitation, that plant will close its pores to reduce water loss; the plant has to use any of the intercellular CO_2 present, including the heavier isotope of carbon, and therefore the ratio changes in a more positive direction.

The isotopic ratio of the absorbed CO_2 also has an impact on the $\delta^{13}C$ value of the plant. In locations where the CO_2 stable carbon isotopic ratio has been depleted – i.e., closed canopy forest and woodlands – the plant's isotopic value will also be depleted. Consequently, plants within closed environments will have a more negative $\delta^{13}C$ value compared with those in open environments (Bonafini et al., 2013). The consumption of plants from such environments by animals will be reflected in their isotopic values which will be more depleted in ^{13}C.

There is, however, a fractionation which occurs between diet and consumer. A 4.8‰ difference between the consumed plant matter and the animal's collagen carbon isotopic value has been found (Fernandes et al., 2012). There are also differences in isotopic values between stems, seeds and leaves in both carbon and nitrogen. Experiments indicate that there is a difference between cereal grains and chaff (rachis): −2.4‰ for $\delta^{15}N$ (Fraser et al., 2011) and −2‰ for $\delta^{13}C$ (Wallace et al., 2013).

The ratio of the stable isotopes of nitrogen ($\delta^{15}N$) provides information regarding the soil ^{15}N enrichment. The proportion of the heavier isotope (^{15}N) within the soil, compared to the lighter isotope (^{14}N), provides information about the modes by which nitrogen found its way into the soil, and the processes which may have changed the nitrogen into different compounds in the soil. Different environmental processes affect soil ^{15}N enrichment. Factors such as seasonal wetting and drying, salinity, waterlogging and aridity can all change the ratio of ^{14}N to ^{15}N in the soil (Handley et al., 1999; Hartman and Danin, 2010; Heaton, 1986; Yousfi et al., 2010). The addition of manure to the soil also changes its isotopic ratio (Senbayram et al., 2008; Fraser et al., 2011). Manuring in agriculture to increase the fertility of the soil enriches the soil in ^{15}N as a large proportion of the lighter isotope (^{14}N) is released as ammonia gas. The remaining nitrogen in the soil (in the form of ammonium) is therefore enriched in ^{15}N.

Stable nitrogen isotopes can also provide information regarding the trophic position of a species. As plants absorb their nitrogen from the soil, their ^{15}N values are some of the lowest in the food web. Herbivores consume, and thus take their nitrogen from, the plants. It is believed that the fractionation of that nitrogen occurs during amino acid synthesis, with the heavier ^{15}N retained and the light ^{14}N excreted (DeNiro and Epstein, 1981). There is about a 3–5‰ increase between each trophic level, with researchers commonly using an average as an estimate of the diet-to-tissue discrimination factor (Minawaga and Wada, 1984; Steele and Daniel, 1978). Thus, it is possible to infer the relative position of different animals within a food web, understanding the different dietary positions of herbivores, omnivores and carnivores. The $\delta^{13}C$ values of consumed plants vary, according to different ecosystems and photosynthetic pathways (Chisholm et al., 1982; Schoeninger et al., 1983; van der Merwe and Vogel, 1978). Due to dietary routing, there is about a 4.8‰ difference between the $\delta^{13}C$ value of the consumed food compared to the consumer (Fernandes et al., 2012).

Methods

The plant material from Lyminge and Stratton derived predominantly from mixed archaeological deposits where it is possible that the grains originated from multiple depositional events; grains were therefore analysed individually, rather than as bulk samples. Grains from mixed deposits are more likely to be from different years/harvests, so bulk samples, which average those grain together, would have been providing an average of multiple years' harvests and thus obscuring any variations between harvests. In total, 50 charred grains from Lyminge were analysed, representing four species – free-threshing wheat (*Triticum* L. free-threshing type), rye (*Secale cereale* L.), oat (*Avena* L.) and hulled barley (*Hordeum vulgare* L.). The grains came from four different periods (sixth-century, eighth- to ninth-century, ninth- to tenth-century, and eleventh- to twelfth-century), with the majority coming from the well-preserved eighth- to ninth-century phase. For Stratton, the plant material suitable for isotopic analysis was limited because of the high temperatures at which most of the grains had been charred. In total, thirteen grains of rye and barley were analysed from two phases: the eighth to ninth centuries, and the fifteenth to sixteenth centuries.

The selected grains were those whose internal and external morphology indicated a charring temperature in the range of 230–300°C. This was necessary because an understanding of the offset between charred and uncharred material would be required to reconstruct diet, with current research only conducted up to 300°C (Nitsch et al., 2015; Stroud et al., in prep.). Three grains per site were analysed using FTIR (Fourier-transform infrared spectroscopy) to determine the presence of contaminants (as per Vaiglova et al., 2014). No peaks associated with carbonate, humics or nitrates were detected in the Stratton material and so no pre-treatment was conducted. However, the Lyminge FTIR analysis detected a large peak at 870 cm^{-1}, with a second smaller peak at 720 cm^{-1}. These peaks correlate with carbonate contamination and so the samples were pre-treated. The grains were placed in 0.5M HCL, which was heated at 70°C for 40 minutes or until any effervescence stopped. The acid was decanted and the samples washed in water until they reached a neutral pH. The samples were then frozen, then freeze-dried.

The collagen samples from animal bones were selected so as to prevent multiple measurements of the same individual: elements determined to be from only one specific side of the body were used. Forty-three bone samples from sheep, pig and cattle were chosen from Stratton covering four phases: fifth- to sixth-century, seventh- to ninth-century, tenth- to twelfth-century, and thirteenth- to fourteenth-century. Thirteen bone samples from two species (cattle and sheep) were selected from Lyminge, most samples dating to the later phases of the site. The bones were cleaned of adhering soil using a sandblaster and *c.*300 milligrams of bone was removed. The material was crushed and then demineralized in 0.5 M HCL for 24–48 hours, until the mineral phase of the bone had dissolved. The acid was decanted and the samples rinsed three times before being heated in acidic water (pH 3) at around 70°C for 48 hours. The solution was filtered using Ezee Filters, the liquid then frozen, and then freeze-dried for 48 hours.

The samples from Stratton, both plant and collagen, and the collagen samples from Lyminge, were analysed at the Research Laboratory for Archaeology and the History of Art at the University of Oxford on a SerCon EA-GSL mass spectrometer. The plant samples from Lyminge were sent to Iso-Analytical Ltd for simultaneous carbon and nitrogen determination using a Europa Scientific 20-20 IRMS.

The samples analysed at Oxford used a combination of internal standards of Cow ($\delta^{13}C$ −24.28‰, $\delta^{15}N$ 7.76‰), Seal ($\delta^{13}C$ −12.6‰, $\delta^{15}N$ 16.3‰), Alanine ($\delta^{13}C$ −26.91‰, $\delta^{15}N$ −1.57‰) and Leucine ($\delta^{13}C$ −28.23 ± 0.07‰, $\delta^{15}N$ 6.35 ± 0.19‰), in addition to EMA-P2 ($\delta^{13}C$ −28.19 ± 0.14‰, $\delta^{15}N$ −1.57 ± 0.19‰) (see project archive for full details: McKerracher et al., forthcoming). Every tenth sample was duplicated to understand precision. For the plant samples analysed at Iso-Analytical, four IAEA standards (N1, N2, CH6 and CH7) were included, along with EMA-P2. Iso-Analytical also included their in-house standards of IA-R045, IA-R045, IA-R046, IA-R005, and IA-R006. In total, four standards were used for calibration per isotope (CH6, CH7, IA-R005 and IA-R006 for carbon and N1, N2, IA-R045 and IA-R046 for nitrogen), while P2 and IA-R001 were used as check standards.

Precision, accuracy and overall uncertainty were calculated as per Szpak et al. (2017) and are recorded in the project database for the different sites and materials (McKerracher et al., forthcoming). All plant results were adjusted by 0.16‰ for $\delta^{13}C$ values and 0.34‰ for $\delta^{15}N$ values to account for charring and to allow comparison with uncharred materials (as per Stroud et al., in prep.). Reliability of the plant isotope values was assessed on the basis of correlation between %N and $\delta^{15}N$ values or %C and $\delta^{13}C$ values; if any strong correlation was found, the specific samples were removed.[1] The C:N ratio of the collagen samples was used to determine if they fell within the acceptable ranges of 2.9 and 3.6 (DeNiro, 1985; Ambrose, 1990).

In addition to the new isotopic measurements of animal collagen, the isotopic values of 85 previously analysed samples were included from Knapp (2018). The additional 13 samples analysed in the FeedSax project extended the overall temporal range of the samples into the later phases (spanning the tenth to twelfth centuries). All published and new data from Lyminge's sheep, cattle and pig samples were combined for this publication (original data in Knapp, 2018 and McKerracher et al., forthcoming). Sheep and sheep/goat data have been considered together as sheep. Although sheep and goat are seldom zooarchaeologically distinguishable, it is assumed that most of the samples analysed here represent sheep, since previous research has indicated that goats are genuinely rare in medieval bone assemblages in England (Salvagno and Albarella, 2019).

1 One sample from Stratton and two from Lyminge were removed due to a correlation between high $\delta^{15}N$ values and high %N.

Diet reconstruction was modelled on Styring et al. (2017), using ellipses to understand the theoretical isotopic signature of different dietary inputs. The theoretical isotope range of an animal consuming 100 per cent cereal grain was calculated as the mean of the cereal values for the phase in question plus 4‰ for $\delta^{15}N$ trophic offset, and plus 4.8‰ for the $\delta^{13}C$ dietary offset. The theoretical isotope range of an animal consuming 100 per cent cereal rachis was calculated as cereal grain minus the offset between grain and chaff (−2.4‰ for $\delta^{15}N$, as per Fraser et al., 2011; −2‰ for $\delta^{13}C$, as per Wallace et al., 2013), with the result then adjusted to account for the dietary offsets. The isotopic ratio of wild vegetation is difficult to calculate because of the lack of wild herbivores within the early medieval assemblages: wild herbivore collagen values minus the dietary offsets are commonly used as a proxy for wild vegetation (e.g., Styring et al., 2017). Roman deer values from Kent were used as a potential 'natural' vegetation baseline for the site of Lyminge (data from Madgwick et al., 2013) as they will have occupied geologically similar landscapes. The use of deer data from the Roman period assumes that the fallow deer were not consuming agricultural products, an assumption which in other periods would be questionable, given the propensity of fallow deer to graze in agricultural fields. However, research by Madgwick et al. (2013) indicates that, in Roman Britain, the deer were most likely enclosed in an area for display, preventing them from grazing within the agricultural fields. The use of deer isotope values from Kent provides an estimation of the 'natural' vegetation's $\delta^{15}N$ and $\delta^{13}C$ values for the region and can be applied, with some caveats relating to different time periods and differing locations, to the Lyminge data. For Stratton, no isotopic results from wild herbivores in the region (or local geology) exist, making it difficult to estimate the isotopic value of 'natural' vegetation. The use of the deer values from Kent would be highly problematic in this case because of the geological difference between the two regions; consequently, the interpretation of the Stratton dataset has been conducted without an understanding of the 'natural' vegetation's isotopic value.

Results

Lyminge: plants

The results of the isotopic analysis of plant remains from Lyminge show variable ranges in $\delta^{13}C$ and $\delta^{15}N$ values depending on the crop examined. The overall mean $\delta^{13}C$ values of the crops reflect the physiological differences expected if the crops were cultivated in similar soil moisture availability: barley (−23 ± 1‰) and oat (−23.9 ± 1‰) are lower than wheat (−22.2 ± 0.8‰) and rye (−21.5 ±

0.85‰) (Plate IIa). However, when separated into phases (Plate IIb), the physiological separation of the species is not as consistent. The sixth-century samples show no statistical difference between the mean barley and free-threshing wheat values (–23.5 ± 1.3‰ and –23 ± 0.6‰). The eighth- to ninth-century phase has samples of all four crop species, and the means of the samples reflect some of the physiological differences expected if the crops were cultivated in the same soil moisture availability. As expected, oat (–23.9 ± 1‰) is significantly lower than the other crops, though barley and wheat are highly variable, with barley's mean (–22.7 ± 0.8‰) not 1–2‰ lower than wheat's (–22 ± 0.9‰). Rye's mean (–21.5 ± 0.85‰) is higher than the wheat and barley mean. Statistically, oat's mean is different from wheat and rye ($p < 0.001$ Tukey post hoc), while the other three species are not statistically different from each other; such results are expected of oat, wheat and rye when grown in the same soil moisture, but the similarity of barley to wheat and rye is not as expected, with less than a 1‰ difference between them. The high variability seen in wheat and barley is most likely the reason for the lack of statistical difference; the rye and oat values are less variable. The lack of multiple species in the other two phases limits any interspecies comparison.

The $\delta^{15}N$ values, like the $\delta^{13}C$ values, show high variability, especially in the barley and wheat values. Overall, the means of the four species are within 2.5‰ of each other, with oat the lowest (2.3 ± 0.9‰); wheat (3.9 ± 2.1‰), barley (4.2 ± 2.2‰) and rye (4.6 ± 0.3‰) are within 1‰ of each other (Plate IIc). The highly variable ranges of wheat and barley are noticeable, having standard deviations of greater than ± 2‰. Comparison of the samples by phase shows a similarity in means for the sixth-century samples; the difference between means is ~1‰. The eighth- to ninth-century phase has similar values for oat and free-threshing wheat (2.4 ± 0.9‰ and 2.3 ± 2.1‰), and similar means for rye and barley (4.6 ± 0.3‰ and 4.9 ± 2.2‰). Statistically, oat's mean is different from those of barley ($p = 0.01$) and rye ($p = 0.007$), while wheat's mean is different from that of rye ($p = 0.02$)[2] (Plate IId).

Lyminge: animals

The $\delta^{13}C$ values of sheep, cattle and pig, regardless of phase, range from –23.1 to –20.4‰ (Plate III). Cattle and sheep means are similar (–21.8 ± 0.4‰, –21.7 ± 0.5‰) while pig is more positive (–21.1 ± 0.4‰) and statistically different from both cattle and sheep ($p < 0.001$)[3].

2 Kruskal Wallis rank sum test with post hoc Dunn test.

3 Anova with a Tukey post hoc test.

Within the fifth- to seventh-century phase, pig (−21.1 ± 0.5‰) has a more positive $\delta^{13}C$ mean value than cattle (−21.8 ± 0.5‰) and sheep (−21.5 ± 0.4‰). Post-hoc testing shows that the pig mean is different from cattle ($p < 0.001$) and to a lesser extent, sheep ($p = 0.055$), while the sheep and cattle means also differ from each other ($p = 0.056$)[4] (Plate IIIa). Similar trends are seen in the eighth- to ninth-century phase, with pig (−21.2 ± 0.3‰) significantly different from both sheep (−21.9 ± 0.5‰) and cattle (−21.7 ± 0.3‰) in terms of $\delta^{13}C$ values, due to a more positive mean $\delta^{13}C$ value (Plate IIIc) ($p < 0.001$ and $p = 0.008$ respectively). In the tenth- to twelfth-century phase, only cattle and sheep were sampled, with no significant difference between their mean $\delta^{13}C$ values (−21.5 ± 0.4‰ and −22.1 ± 0.6‰) (Plate IIIe).

Examining each species through time reveals limited changes in $\delta^{13}C$ values. Cattle show no significant differences between phases, with the means from each phase falling within 0.4‰ of each other (Plate III). Sheep display rather more change over time: there is a slight trend towards more negative $\delta^{13}C$ values, with a decrease from the more positive mean of -21.2 ± 0.5‰ in the fifth to seventh centuries, to a low of −22.1 ± 0.6‰ in the tenth to twelfth centuries (Plate III). However, statistical testing suggests no significant difference between the phase means ($p = 0.07$). Pig samples are only available from the first two phases, and the means for these phases show limited differences.

The $\delta^{15}N$ values of the animals examined range from 1.3 to 11.8‰. The mean values of sheep (5.9 ± 1.3‰), cattle (5.7 ± 1.5‰) and pig (5.9 ± 1.3‰) are very similar. In the fifth- to seventh-century phase, the same trends are seen with sheep (6 ± 1.1‰), cattle (5.8 ± 1.6‰) and pig (6.2 ± 1.6‰) falling within 0.4‰ of each other. The eighth- to ninth-century and tenth- to twelfth-century phases follow very similar patterns, with the species means not significantly different from each other (Plate III).

Comparing the species through time shows limited differences between phases. Pigs are only represented in the first two phases and, while their $\delta^{15}N$ means are lower in the second phase than in the first, the difference is not significant. Cattle means are relatively consistent over time, with a slight enrichment in ^{15}N during the tenth- to twelfth-century phase. Sheep $\delta^{15}N$ means are also consistent over time with just a slight depletion in the eighth- to ninth-century phase.

4 Anova with a Tukey post hoc test. Note that sheep vs cattle is just insignificant at the arbitrary 0.05 level with a p-value of 0.056. Sheep compared to pig also has a similar p-value of 0.055.

The potential diet of the animals can be investigated using the plant values from the site. Plotting the animal data against the theoretical isotopic range of an animal consuming 100 per cent cereal rachis or 100 per cent cereal grain indicates that the animals could have been consuming cereal rachis/straw in both the sixth-century and the eighth- to ninth-century phases, and/or stubble and fallow vegetation (there appears to be limited offset between leaf and rachis) (Plate IV). Evidence that the cattle, sheep or pigs were consuming a high proportion of cereal grain is limited. The lack of wild herbivore remains from the site prevents us from using their data as a proxy for natural vegetation, but there are isotopic values for Roman fallow deer from Kent which provide a general impression of the natural vegetation (see Methods section above for justification and caveats). The overlap between the hypothetical range of animals consuming 'natural' vegetation and that of animals grazing on arable fields indicates that the livestock at Lyminge were possibly consuming a combination of the two vegetation types, and that manuring levels were low.

Stratton: plants

Barley and rye samples from Stratton have similar overall mean $\delta^{13}C$ values (barley: −24 ± 1.3‰, rye: −23.7 ± 1.7‰); there is no evidence of the species-specific offset expected if they were grown in the same water availability conditions (Plate Va). Comparing samples from the eighth- to ninth-century phase reveals a similar pattern. There is a ~1‰ difference in the expected direction between the means (barley: −24 ± 1.3‰, rye: −23 ± 1.1‰), but the high variability means that there is no statistical difference between the two groups. Looking at rye over time indicates that there is a difference in means, but statistical testing does not indicate a significant difference between the means, most likely because of the wide standard deviation (−23 ± 1.1‰ in the eighth to ninth centuries, and −25 ± 2.2‰ in the fifteenth to sixteenth centuries) (Plate Vb).

A student t-test indicates that there is a difference between the two species' $\delta^{15}N$ means (barley: 8.2 ± 0.7‰, rye: 6.3 ± 1.7‰) ($p = 0.03$) (Plate Vc). The eighth- to ninth-century data also indicate a difference of ~2‰ between the two species' means (t-test $p = 0.04$) (Plate Vd). Statistical comparison of the rye samples by phase shows no significant difference between the means, even though the means differ by over 1‰ (5.8 ± 1.79‰ for the eighth to ninth centuries, 7.1 ± 1.5‰ for the fifteenth to sixteenth centuries).

Stratton: animals

The $\delta^{13}C$ values from the Stratton animal collagen, examined without regard to phase, range from –21.2 to –19.7‰. Cattle and sheep have similar $\delta^{13}C$ values (–21.6 ± 0.4‰ and –21.9 ± 0.5‰ respectively), while the pigs' values are more positive (–20.9 ± 0.7‰). Post hoc testing[5] indicates a difference between the pig and sheep means ($p < 0.001$) and pig and cattle means ($p = 0.01$).

Dividing the samples by phase shows that cattle and sheep have similar $\delta^{13}C$ values in the fifth to sixth centuries (Plate VIa–b). By the seventh- to ninth-century phase, the number of pig samples allows comparison between the three species; there is limited difference in $\delta^{13}C$ values but the trend for pig to have more positive $\delta^{13}C$ values is apparent (Plate VIc–d). During the tenth- to twelfth-century phase there is a more species-specific separation in carbon values; the sheep $\delta^{13}C$ mean is more negative (–22.3 ± 0.3‰) than that of pig (–21.2 ± 0.6‰) and cattle (–21.5 ± 0.6‰), with post hoc testing indicating a difference between sheep and pig means ($p = 0.023$) (Plate VIe–f). In the thirteenth- to fourteenth-century phase, due to limited cattle samples, only sheep and pig can be compared; there is limited difference between their means because in this phase the sheep have more positive values than in the other phases (–21.5 ± 0.5‰) (Plate VIg–h).

Comparison of the species' $\delta^{13}C$ values through time is possible, although limited samples in some phases prevent all phases being included for all species. Sheep means stay within 1‰ of each phase, but during the tenth- to twelfth-century phase sheep are at their most negative and further from the means of other phases. Statistically, however, there is limited difference between sheep means over the four phases. Cattle only have enough samples in the first three phases to allow for comparison and have very similar means (within 0.5‰) with no statistical difference between them. Pigs can only be examined for the final three phases and have limited differences between them.

The mean $\delta^{15}N$ values of the three species are similar (sheep 7.1 ± 1.2‰, cattle 6.6 ± 0.8‰ and pig 6.9 ± 0.7‰) and, when phasing is disregarded, statistically there is limited difference between the means of the three species (Plate VI). Examining the data by phase shows a consistency in mean $\delta^{15}N$ values, with all species having similar mean values within each phase. One notable detail is the small range of the pig $\delta^{15}N$ values in the thirteenth- to fourteenth-century phase.

5 Anova with a Tukey post hoc test.

While this is only based on three individuals, the pig $\delta^{15}N$ values are very similar but their $\delta^{13}C$ values are variable, especially compared to the tenth- to twelfth-century data which sees the opposite trend. Consideration of the individual species through time also reveals no difference between the phases in either $\delta^{13}C$ or $\delta^{15}N$ mean values.

The diet of the animals at Stratton was investigated by projecting the theoretical isotopic values of animals consuming 100 per cent cereal grain and 100 per cent cereal rachis (Plate VII). The limited number of plant samples suitable for isotopic analysis from multiple phases of the site restricts our ability to trace change over time. However, the high variability in the cereal grain isotopic values is consistent with the animals consuming cereal chaff in the seventh- to ninth-century phase, and this trend is also seen when all data are combined irrespective of phase. Interpreting the diet of the animals further via the plant isotope data is difficult because we have limited understanding of the isotopic value of the natural vegetation at Stratton: it is possible that the natural vegetation and arable fields had indistinguishable isotopic signatures.

Discussion

Crop husbandry: rotation and fertility

The crop isotope results from Lyminge and Stratton provide an indication of cultivation conditions and support an assessment of the likelihood that crops were cultivated in rotation. At Stratton, the nitrogen isotope results indicate that some crops were cultivated in slightly different soil conditions, with a statistical difference between rye and barley. The lack of difference between the rye and barley $\delta^{13}C$ values also suggests that the two crops were cultivated in slightly different conditions: either a difference in annual precipitation or cultivation on different soils resulted in different water availability. Such evidence correlates with historical documents which record, by the thirteenth century, the cultivation of barley at Biggleswade – the centre of the parish – and the cultivation of rye at Stratton (Shotliff and Ingham, 2022). This in turn suggests that Biggleswade provided barley for the smaller settlement of Stratton, and the isotopic evidence now indicates that this may already have been the case prior to the thirteenth century. Whether the difference between the $\delta^{15}N$ values is due to different crop husbandry methods, such as the addition of manure to the soil, is difficult to ascertain because of our lack of information about the natural soil ^{15}N enrichment at Stratton. The functional ecology of weed species from the site indicates that a trend towards low fertility and extensive cultivation had begun by the eighth to ninth centuries, which suggests that, if manuring was occurring, it was having a limited effect on overall fertility (Hamerow et al., in prep.).

At Lyminge, the cultivation conditions of the four crops varied. During the sixth century, the $\delta^{15}N$ values of wheat and barley are similar, with a ~1‰ difference between them indicating similar levels of ^{15}N enrichment. However, the similarity between barley and wheat $\delta^{13}C$ values may indicate either a difference in soil moisture between the two species or differing annual precipitation. The eighth- to ninth-century samples provide an opportunity to look at all crop species and show some differences due to high variability in wheat and barley. There are some similarities in water availability, suggesting similar soil moisture conditions, with oat offset from the other crops as expected. However, the highly variable barley values produce a mean value similar to those of wheat and oat, something which would not be expected if the crops had been grown in the same soil moisture conditions. Again, theoretically, the difference could be due to differing annual precipitation amounts, or to cultivation in different soils – i.e., free-draining chalk compared to heavier clays which occur around the site. The $\delta^{15}N$ values confirm that differences in soil conditions are a contributory factor, with the barley and rye from this phase cultivated in a more enriched location than oat. The high variability seen in wheat and barley (in both $\delta^{13}C$ and $\delta^{15}N$) compared to the other crops could indicate that these crops were cultivated across a variable landscape of different soil types and water retention, or else were imported from different locations. The different ^{15}N enrichments of the soils could be due to different natural properties of the soil, or to the variable addition of manure in different fields. However, natural variability seems more likely for two reasons. The first is that a study of functional weed ecology at the site indicates low fertility, which implies that manuring was either limited or ineffectual (see Bogaard et al., this volume). Second, when the $\delta^{15}N$ values of the crops are compared to the adjusted values of the Kent deer (which act as a proxy for the natural ^{15}N enrichment), there are strong similarities. This suggests that the arable fields have similar ^{15}N enrichment to the 'natural' vegetation, indicating limited manuring.

The plant isotope results highlight the variability of the arable landscape in terms of ^{15}N enrichment and water availability. The two sites examined do not reveal evidence that species were systematically cultivated in rotation; similar $\delta^{15}N$ means and the expected $\delta^{13}C$ offsets are not present. The lack of additional species, especially at Stratton, limits our conclusions. If barley was cultivated elsewhere, it is possible that a different crop such as wheat or oat (both present in the archaeobotanical record at the site) was grown in rotation with rye. It is also possible that the high plant isotopic variability seen for some species, for example barley and wheat at Lyminge, may suggest different growing conditions were being maintained by different farmers. Hence, it is possible that no *systematic* rotation occurred during the phases with isotopic data from multiple species, but this does not rule out *individual* farmers cultivating crops in rotation, or the use of two-course rotation (the weed ecological data from Lyminge are plausibly consistent with two-course rotation: see Bogaard et al., this volume).

Animal husbandry: grazing locations and diet

One of the main aims of this research is to investigate whether the grazing of stubble and/or fallow fields can be detected isotopically. The impact that such grazing would have on the isotopic ratio of animal collagen is dependent on two things: the proportion of the animal's diet provided by stubble and/or fallow field grazing, and how different the isotopic ratio of such a diet is compared to the consumption of other vegetation – i.e., pasture or 'natural' grazing. It is hypothesized that a change in the isotopic ratio of animals over time might indicate a change in diet. It is thought that the grazing of stubble may have increased as the availability of pasture declined over the course of the early medieval period; if so, changes in animal diet indicated isotopically may reflect an increased dependence on stubble grazing. It is possible that such a change would be represented by an increase in $\delta^{15}N$ values, as stubble contributed increasingly to the animals' diet – provided that there is an isotopic difference between the arable fields and pasture/natural vegetation due to a higher input of manure on the arable fields.

Looking for the two possible indicators of increased stubble grazing in the Lyminge data is facilitated by both the high number of samples compared to Stratton and the use of the Kent fallow deer values as a proxy for 'natural' vegetation. While caution is required when using the fallow deer values – minus dietary offsets – as a representation of the natural vegetation, this approach provides a possible guide as to what the isotopic value of natural vegetation might be. It is possible that the animals at Lyminge consumed cereal rachis, since the animal values fall within the cereal rachis ellipse (Plate IV); but the limited difference between the 'natural' vegetation and the cereal rachis ellipses indicates there is high similarity between these two environments' isotopic signatures, making it extremely difficult to distinguish between them. The lack of any statistically significant change within the Lyminge animals' isotopic values over time (in either $\delta^{13}C$ or $\delta^{15}N$) suggests four possibilities: (i) that there was no switch to stubble grazing over time, (ii) that stubble grazing was part of the animal husbandry regime from the beginning, (iii) that consumption of stubble was occurring, but is 'masked' by similar isotopic values representing the surrounding pasture, or (iv) that stubble constituted only a small proportion of the animals' diet.

Turning to the two possible indicators of increased stubble grazing at Stratton, it can be seen that there is no change over time in either $\delta^{13}C$ nor $\delta^{15}N$ values. The reconstructed ellipses of animals consuming cereal grain or rachis at Stratton have very large ranges, due to the high variability seen in the crop plant isotopic values, and the limited number of plant isotopic samples (compare Plate VII with Styring et al., 2017, Appendix 6). Due to the limited quantity of cereal remains available from this site, only the seventh- to ninth-century phase can be examined in this way; this restriction precludes any investigation of trends through time, something which would be crucial for identifying a general increase in stubble grazing. The dietary reconstructions do not rule out animals consuming cereal rachis – and therefore stubble – as the animal values do fall within the potential rachis consumption ellipse (Plate VII). However, the highly variable nature of the plant isotope values suggests a landscape with variable ^{15}N enrichment, which results in the ellipses encompassing the majority of possible isotopic values. If the theory that barley was cultivated elsewhere than Stratton is correct, then this species must be removed from the ellipse calculation. Removing barley has a limited effect on reducing the resultant ellipse, however. Until another way of understanding the isotopic value of pasture/natural grazing is developed which does not rely on wild herbivore isotopic values, it is difficult to determine whether stubble and natural pasture had similar isotopic values at this site.

There is evidence of an environmental difference in nitrogen enrichment between the two sites, with Stratton significantly more enriched than Lyminge (Stratton averaging around 8‰, Lyminge 6‰). The elevated nature of the Stratton samples in terms of ^{15}N is also noticeable when the values are compared to other early medieval data (Mallet, 2016; Mallet and Stansbie, 2021). These results could suggest that the land surrounding Stratton had a higher $\delta^{15}N$ baseline than other locations. Given the difference between the sites' local geologies – Lyminge located on chalk, Stratton in a valley with deep clays which are prone to waterlogging – it is unsurprising that there is a difference between the results from the two sites, and this highlights the importance of using baseline data from the same geology/environment. The lack of wild herbivores from Stratton precludes a detailed understanding of the whole landscape enrichment in ^{15}N, although locations within the landscape which experienced seasonal flooding, waterlogging, salinity or high amounts of animal/human waste could explain the trend towards higher enrichment at Stratton.

It is possible to use the animal isotope results to understand similarities and differences in diet between the different species. The sheep and cattle from the two sites show limited statistical differences, which potentially suggests that they consumed similar diets. At Stratton, however, the more negative sheep $\delta^{13}C$ values in the tenth to twelfth centuries, although they are not significant within the broader sheep values, potentially indicate that the sheep during this phase consumed plants from wetter or more closed canopy environments within the landscape in comparison with Stratton's cattle. The sheep and cattle from Lyminge also show limited differences from one another isotopically, especially in the eighth- to ninth-century phase where the isotopic values are very similar, thus suggesting very similar diets. There is some difference in the sheep values in the tenth- to twelfth-century phase and, as at Stratton, more negative $\delta^{13}C$ values. Such findings are limited by the small number of samples, but they do raise the possibility that the sheep grazed on slightly different areas of the landscape or were foddered in a different way compared to the cattle during this period, at both sites. Factors which may cause sheep to have more negative $\delta^{13}C$ values than cattle are either the consumption of forage from wetter locations or the consumption of forage from more closed environments (i.e., woodlands). It therefore seems strange that sheep – commonly perceived as grazing in dry and open landscapes – have more negative values. The small difference between the animals' values limits any further speculation as to the significance of this difference in terms of animal management practices; an increased sample size would help us to understand if the pattern is just an artefact of low sample numbers.

The $\delta^{13}C$ values of the pigs are consistently higher than those of the other animals at both Lyminge and Stratton. The isotopic difference between pig and the other ruminants is not gut-related, as the differences in digestive systems should show the *opposite* trend, with the ruminants enriched in ^{13}C due to methane production (Hamilton and Thomas, 2012, 251). The difference could be related to the pigs consuming plants from relatively drier locations compared to the wetter locations of the ruminants, or the consumption of fungi by pigs. The consumption of fungi has been shown to have the opposite effect to shade on the $\delta^{13}C$ values of its consumer, and this could explain the enriched ^{13}C values of the pigs at Stratton and Lyminge (Hamilton and Thomas, 2012). The pig $\delta^{15}N$ values are also not overly enriched, suggesting that these animals were not consuming a high proportion of ^{15}N enriched food scraps such as meat. Instead, the similarity of the herbivore and pig $\delta^{15}N$ values indicates a similar trophic level: pigs were more herbivorous than omnivorous. It is possible that an omnivorous signal in pigs is being dampened down by the consumption of pulses, but disentangling this possibility is very difficult. Overall, it seems likely that the pigs consumed proportions or types of food different from those consumed by sheep and cattle, and the lack of change over time suggests that this was a long-term practice.

Other isotopic research has found a difference between urban and rural pigs in medieval England, with urban pigs being more omnivorous (Albarella, 2006, 79); this correlates with the isotopic results from Stratton and Lyminge. Historical documents indicate that medieval swine husbandry relied on the exploitation of woodlands: providing areas for the pigs to forage on roots, acorns and beech mast (pannage) (Albarella, 2006, 77). Pannage is thought to have extended as far back as the seventh century (Trow-Smith, 1957, 51). The Domesday Book also provides an indication of the connection between pigs and woodland: woodland was measured in terms of the number of pigs it could support (Albarella, 2006, 77). The results from Stratton and Lyminge may reflect the driving of pigs within woodland for pannage. The more positive $\delta^{13}C$ signal may reflect the higher dietary consumption of fungi (compared to the cattle and sheep), while the limited ^{15}N enrichment indicates a high proportion of plant protein in their diet, potentially from mast and other woodland fruits and nuts. However, fattening of pigs using pannage is traditionally seasonal, occurring in autumn and winter, and therefore the pigs may have had a different diet for the other half of the year (Wiseman, 2000, 33; Albarella, 2006, 77). Other options would include feeding on crops, and possibly pasture or stubble fields, an idea which has been explored above (Kelly, 1997, 83; Arabella, 2006, 77; Trow-Smith, 1957, 53).

Conclusion

The early medieval sites of Lyminge and Stratton provide the opportunity to investigate changes in crop and animal husbandry over time and between different species. At Lyminge, stable isotope analysis of crop remains indicates that the crops were cultivated in a landscape with variable ^{15}N enrichments, potentially representing different soil types. Differences between the crop species suggest that systematic crop rotation was not occurring during the periods for which we have isotope data; however, it is possible that rotation was occurring on a non-systematic basis, practised by individual farmers. The collagen results add additional data points to already published isotopic values from Lyminge and, coupled with the cereal grain results, allow for an attempt at animal dietary reconstruction to investigate stubble/fallow field grazing. The results indicate a high likelihood of similar isotopic values between natural vegetation and arable forage (such as fallow fields and stubble), a consequence of limited manuring due to extensification (see Bogaard et al., this volume). Such conditions make it difficult to differentiate between the two dietary sources. Similar findings at Stratton highlight the problem of distinguishing between pasture and arable fodder isotopically. At both Stratton and Lyminge, however, the isotopic results do highlight differences in the animals' grazing/foraging locations within the landscape. Sheep and cattle had similar diets, grazing on the pastures surrounding the sites and potentially on the fallow fields. Pigs consumed forage which may have included fungi, which suggests extensive foraging in woodlands.

This research for the first time brings together stable carbon and nitrogen isotopic results from both plant and animal remains from early medieval England. The results provide additional information regarding crop and animal husbandry during the period, which, when combined with results from zooarchaeology, archaeobotany and palynology, help to provide a much more detailed picture of early medieval agriculture.