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The ups & Downs of Iron Age animal management on the Oxfordshire Ridgeway, south-central England: a multi-isotope approach

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Abstract

The hillforts of the Oxfordshire Ridgeway in south-central England have been interpreted as central places in the Early/Middle Iron Age, ca. 600–100 BC, serving, among other functions, to integrate the management of animals, particularly sheep, between the upland Chalk downs and the adjacent low-lying Vale of the White Horse. Since these landforms differ geologically and pedologically, they lead to distinct isotopic ratios in the biosphere and so present the potential to investigate animal management practices in some detail. Here, we report the results of a multi-isotope study on domestic fauna (cattle, sheep and pig) within a very constrained study area, with the aim of testing the hypothesis that the Ridgeway's hillforts were placed to control and coordinate the movement of sheep between the Chalk and the Vale. However, the results suggest a different scenario. Bone collagen $\delta^{15}N$ results indicate that cattle and sheep were both kept locally. Strontium isotopes, conversely, indicate that, while sheep and pigs were raised locally, cattle appear to have been mainly kept in the Vale during at least the first year of their lives. The apparent discrepancy between the two isotopes can be reconciled by the different periods of life represented by enamel and bone collagen measurements, with the movement of cattle onto the Ridgeway in their second or third year of life. Sequential measurements of $\delta^{13}C$ and $\delta^{15}N$ in dentine, and of $\delta^{13}C_c$ and $\delta^{18}O_c$ in enamel, provide further detail on the management of cattle, and offer some support for the above scenario. Early/Middle Iron Age stock-keeping in south-central England was complex, being integrated in some respects but distinct in others. The study demonstrates the level of detail it is possible to achieve with a multi-isotope approach to animal management practices in prehistory. The focus on a micro-region contrasts with, or rather complements, studies addressing larger-scale movement of animals in prehistory.

Keywords: stable isotopes; carbon, nitrogen; oxygen; strontium; sequential sampling; animal mobility

Introduction

As in any mixed farming system, the management of animals doubtless played an important part in the Iron Age societies of southern Britain. Economically, they furnished meat, milk and wool, and served as draught animals for transport and tillage. Intersecting with their economic uses, they were also important socially, politically and ritually (Green 2002; Parker Pearson 1996). It is relatively straightforward to determine the proportional representation of the major economic species – sheep/goat, cattle and pig – and their respective kill-off patterns, e.g., whether animals were killed upon reaching their maximum weight, or were retained longer for their secondary products. While this can provide insights into how and why animals were managed, it does not allow the detailed investigation of how individual animals were actually kept, how they were moved around the landscape, and how various nearby communities integrated their animal management practices. Isotopic approaches can offer new insights into just these aspects.

Hillforts are one of the most prominent sites types in the British Iron Age, both in terms of their physical presence on the landscape (Lock and Ralston 2017), and in the amount of research attention they have received. One long-standing and pervasive interpretation has been that they served as central places, as foci for a range of political, economic and ritual activities (Cunliffe 1984; 2001; Harding 2012; though this view has not gone uncontested, not least because the category of 'hillfort' itself is problematic – see Hill 1996). The size and density of occupation at Danebury, for example, would seem to necessitate provisioning from the surrounding communities (Cunliffe 1984). Recent studies have attempted to investigate these connections more specifically for domestic fauna (Stevens et al. 2010; 2013) and cereals (Lightfoot and Stevens 2012). Once elucidated, the nature of the economic relationships between hillforts and contemporary farmsteads would have clear implications for discussions of political power, subordination and control. At present, however, the matter is far from settled.

As with hillforts more generally, those of the Oxfordshire Ridgeway in south-central England have been interpreted in various ways. Segsbury, for example, has been seen as a central place, serving, among other functions, to integrate the management of animals, particularly sheep, between the upland Chalk downs and the adjacent low-lying Vale of the White Horse (Lock et al. 2005). Alfred's Castle, in contrast, seems to been a more self-sufficient community with a mixed farming economy, though again with a special focus on sheep, while, in the neighoubouring Vale of the White Horse, Watchfield shows an emphasis on cattle. This area therefore forms an ideal micro-region to test the hypothesis that Segsbury served as a central place to which sheep were brought, and, more generally, to investigate variability in animal management practices (Figure 1). Firstly, there has been an intensive programme of investigation on both the Ridgeway 'hillforts' and a number of non-hillfort sites in the Vale of the White Horse, complemented by rescue excavations in advance of development (Birbeck 2001; Gosden and Lock 2014; Heawood 2004; Kamash et al. 2010; Lock et al. 2005). All have yielded abundant remains of domestic fauna in a good state of preservation. Secondly, the study area straddles a geological boundary (Norton et al. 2004), facilitating the use of strontium isotope ratios in the identification of animals raised on the Chalk uplands (the Berkshire Downs) vs. those raised in the lowlands (the Vale of the White Horse). In addition, the Chalk grasslands appear to be depleted in ^{15}N (Hamilton 2016; Stevens et al. 2010; 2013), meaning that another isotope system is available to help distinguish animals kept on the Chalk and in the Vale.

Here, we use a multi-isotope approach – combining stable carbon and nitrogen isotope analyses on bone and dentine collagen together with carbon, oxygen and strontium isotope analyses on tooth enamel – to test the hypothesis that some Early/Middle Iron Age (ca. 600–100 BC) hillforts served as central places, to which were brought animals, especially sheep, from both upland and lowland pastures. We compare isotopic results on cattle, sheep and pigs from two Ridgeway hillforts with two unenclosed sites in the adjacent Vale. While a number of studies have used stable isotopes to investigate animal management, this has usually been in the context of long-distance mobility (Minniti et al. 2014; Towers et al. 2010; 2011; Viner et al. 2010). By focussing on a micro-region (ca. 25 by 20km), we are able to address the kinds of animal management practices that would have occurred on a daily and seasonal basis, forming an integral part of the mixed farming economy in the Iron Age of south-central England (cf. Stevens et al. 2013).

Figure 1. Map of the study area showing study sites and plant sample locations.

Isotopic analyses

Stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes are now routinely used in archaeological studies of past human and animal diets (Lee-Thorp 2008). Measurements on bulk bone collagen inform on an average of foods consumed over months to years, depending on the species and the age of the animal. Bone growth is rapid in very young animals, so that measurements will primarily reflect averaged diet over the order of several months, while with older animals, a longer-term average of some years will be represented, particularly in cortical bone (cf. Pearce et al. 2007). Sequential sampling of tooth dentine provides much higher resolution than bone collagen, relating to the period of root growth of the tooth in question (Mainland et al. 2016; Makarewicz 2014). Since primary dentine does not remodel, the analysis of molars in adult animals will reflect their early diet. In a C_3 terrestrial ecosystem such as that of Britain, variation in ^{13}C will be limited, but can nevertheless be informative. Plants – and hence the herbivores consuming them – can vary in their $\delta^{13}C$ values according to species, the part of the plant ingested, season and location (Takahashi and Miyajima 2008; Tieszen 1991). The latter in particular may be relevant even within very small regions, such as that being investigated here, since light levels have been shown to have a significant effect, with lower values seen in more shaded areas (Berry et al. 1997; Bonafini et al. 2013; van der Merwe and Medina 1991). Stable carbon isotopes can be measured both in collagen, where it is biased towards dietary protein, and in the mineral carbonate fraction of bone or enamel, where it reflects whole diet (Ambrose and Norr 1993).

Stable nitrogen isotopes in archaeology are used primarily to infer trophic level (Hedges and Reynard 2007). Since the main species of interest in this paper are herbivores (cattle and sheep), it is necessary to consider other factors potentially impacting on ^{15}N levels in plants within a small micro-region. This would also rule out, for example, aridity effects that could be relevant in a much broader comparative study (Amundson et al. 2003). This leaves two main factors. The first relates to different levels of bacterial activity between the thin soils of the Downs, derived predominantly from the immediately underlying chalk bedrock, and those of the Vale, which are much heavier colluvial and alluvial soils with higher clay content. The second potentially relevant factor relates to the anthropogenic modification of soils, both through the intentional manuring of arable fields (with stock grazing on the stubble or being fed crop waste), and indirectly through higher stocking rates on the best pastures. Both of these practices can lead to quite substantial levels of ^{15}N-enrichment in plants, and hence in the animals consuming those plants (Bogaard et al. 2007; 2013; Fraser et al. 2011; Handley and Raven 1992; Robinson 2001).

Stable oxygen isotopes ($\delta^{18}O$) record sources of ingested water, with the relative contributions of drinking water and food varying with the physiology of the animal (Bowen et al. 2005; Sponheimer and Lee-Thorp 1999). While the distances involved in the study area are not great, $\delta^{18}O$ values for drinking water sources may nonetheless differ between the Ridgeway and Vale, particularly given the scarcity of surface water on the Downs (Levick 2015, 51-53). The combined sequential analysis of $\delta^{18}O$ and $\delta^{13}C$ in enamel can track seasonal variation in the sources of water and food (Balasse et al. 2002; 2009; 2012; Towers et al. 2011).

Strontium isotope analysis is being increasingly used to investigate the mobility of both humans and animals in prehistory (Bentley et al. 2003; Chenery et al. 2010; Minniti et al. 2014; Stevens et al. 2013; Towers et al. 2010; 2011; Viner et al. 2010). Briefly (for more detailed overviews see Bentley 2006; Montgomery 2010), ^{87}Sr is a radiogenic decay product of ^{87}Rb, and so will become more abundant the older the rock, assuming the same starting concentration of rubidium. Measurements are made of the ratio of ^{87}Sr and ^{86}Sr, with geologically recent values ranging around 0.707-0.709 for most calcareous formations, while older rock typically has values >0.710. Recent volcanic rock will exhibit even lower $^{87}Sr/^{86}Sr$ ratios, but does not feature in the study area. The Chalk is a very homogeneous calcareous formation dating to the Cretaceous, and has highly constrained $^{87}Sr/^{86}Sr$ ratios of ca. 0.708, reflecting those of the ocean of that time (McArthur et al. 1993). The Vale is considerably more varied geologically, with a greater contribution of more radiogenic Greensands and Gault Clays (Norton et al. 2004), such that the two geologies are isotopically distinct (Evans et al. 2010, fig. 1b). The preferred skeletal tissue for $^{87}Sr/^{86}Sr$ analysis is dental enamel, to minimise issues of contamination from the burial environment (Hoppe et al. 2003; Sealy et al. 1991). Moreover, because of the incremental deposition of enamel during growth, there is the possibility of tracking animal movements between lowlands and uplands in considerable detail (Balasse et al. 2002; Bentley and Knipper 2005).

The sites

Segsbury is a large hillfort of 11 ha, adjoining the Ridgeway near the edge of the chalk Downs and overlooking the Vale. Excavation places the site within the Early (7th – 4th c. BC) and Middle Iron Age (4th – 2nd c. BC) and suggests that it was not permanently or densely occupied but was, perhaps, a communal meeting place for the surrounding population (Lock et al. 2005). The primarily EIA faunal remains derive largely from a series of internal pits, dated mainly by pottery associations. Sheep dominate the faunal assemblage, including lambs but no neonates, while there is evidence for on-site cattle breeding (Mulville and Powell 2005) (Table S1; Figure 2).

Alfred's Castle is a small 'hillfort' of 1.2 ha, located some 5km south of the north edge of the Downs, and not in a locally elevated position. A series of radiocarbon dates place the site in the MIA (4th – 3rd c. BC), though the pottery assemblage suggests the possiblity of an earlier Iron Age presence. Excavation has shown that it was fairly densely occupied, with the usual range of domestic activities represented, especially those associated with sheep, together with evidence for ritual deposition (Gosden and Lock 2013). The presence of neonatal animals of all three main domestic species suggests they were reared on or near the site (Lange 2013). Evidence for metalworking together with the substantial enclosing earthwork suggests that this was a high status settlement.

Watchfield is one of a number of unenclosed Iron Age settlements in the Vale (Birbeck 2001; Heawood 2004). Part of an excavated field system featured a complex funnel-type entrance that must relate to the management of large numbers of animals (Birbeck 2001, fig. 3; Lambrick and Robinson 2009, 386), presumably cattle as these dominated the faunal assemblage to an unusual degree (Figure 2). The Early and Middle Iron Age faunal remains were recovered from a series of pits and ditches, dated primarily through pottery associations.

Marcham is an unusual site and probably not a 'normal' settlement but rather consisted of a series of pit groups and circular enclosures defined by banks and ditches, possibly demarcating a ritual space. The animal bone analysed here derived from a series of MIA pits, again dated mainly by pottery. The site became the focus of more overtly ritual activity in the Romano-British period, with the construction of a temple complex including an amphitheatre (Kamash et al. 2010).

Figure 2. Bar chart of the three main domestic species at the Ridgeway (Segsbury and Alfred's Castle) and the Vale (Marcham and Watchfield) sites (sources: Birbeck 2001; Lange 2013; Mulville and Powell 2005; P. Levick pers. comm.).

Materials and Methods

Materials

Samples of dental enamel of sheep, cattle and pig were taken for strontium isotope analysis from the Ridgeway 'hillforts' of Alfred's Castle and Segsbury Camp, and from the unenclosed Vale sites of Marcham and Watchfield (Figure 1). It is possible that some goats were included in the analysis, but since very few of their remains were positively identified in any of the sites we assume that most if not all were sheep. The comparison between the three species addresses the question of whether or not their patterns of movement are similar. One might expect, for example, that pigs would tend to be more local to the immediate area, as they are more difficult to drive (Grigson 1982; though see Madgwick et al. 2012). The contexts sampled date to the Early and Middle Iron Age (600–300 BC), though some Late Iron Age material may also be included. We selected 61 archaeological tooth enamel samples from 55 distinct individuals for $^{87}Sr/^{86}Sr$ analysis, comprising 21 sheep, 26 cattle and 14 pig teeth from Segsbury Camp and Alfred's Castle on the Ridgeway, and Marcham and Watchfield in the Vale (Birbeck 2001; Gosden and Lock 2013; Heawood 2004; Lock et al. 2005). Adhering sediments were sampled for $^{87}Sr/^{86}Sr$ analysis from five teeth, two from the Ridgeway and three from the Vale.

Twenty-nine plant samples were taken from 11 Ridgeway and Vale locations, targeting the various geologies represented (Figure S1). Two or three plant samples were collected from each location, with one being grass and the others either hazel, hawthorn and/or oak. These represent different rooting depths, and hence ptentially tap into difference water sources, which can in turn influence strontium isotope ratios (Reynolds et al. 2012). Locations were recorded by GPS.

Fifty-one mandibular or maxillary bone samples from the same individuals as selected for $^{87}Sr/^{86}Sr$ analysis were analysed for $\delta^{13}C$ and $\delta^{15}N$ to compare Chalk and Vale values. Four cattle molars from Alfred's Castle and Marcham were analysed sequentially for $\delta^{18}O_c$ and $\delta^{13}C_c$; the dentine of three of the same teeth were analysed sequentially for $\delta^{13}C$ and $\delta^{15}N$.

Bone collagen carbon and nitrogen isotope analysis

Bone collagen samples were prepared using the modified Longin (1971) method in place in the Research Laboratory for Archaeology and the History of Art, University of Oxford. Samples were analysed on a SerCon Callisto CF-IRMS system, together with an alanine standard to correct for machine drift, and two internal standards (cow and seal bone collagen) used to calibrate the values (see Coplen et al. 2006). Reported values are the averages of duplicate measurements of standards, with errors of ca. ±0.2‰ for both $\delta^{13}C$ and $\delta^{15}N$. In a small number of cases (three) where the difference between the two runs exceeded 0.5‰ in either isotope, the measurements were repeated in duplicate. In one case a clear outlier emerged and was removed, with the remaining three results averaged. In the other two cases the final reported result is the average of all four measurements.

Enamel carbonate oxygen and carbon isotope analysis

Intra-tooth enamel samples were taken using a diamond-tipped dental burr, horizontally along the crown in order to produce a series of samples parallel to the direction of tooth growth. Samples were prepared following the methods outlined in Sponheimer and Lee-Thorp (1999).
Approximately 5 mg of powdered enamel was placed into a 2 ml micro-centrifuge tube, to which

1.8 ml of sodium hypochlorite (NaOCl) solution (1.5% v/v) was added and left for 30 minutes to remove any organic matter. The samples were then rinsed three times with distilled water and centrifuged to ensure that all NaOCl solution was removed. Then 1.8 ml of 0.1 M of acetic acid (CH_3COOH) was added and centrifuged to remove exogenous carbonate. The samples were rinsed again with distilled water and then freeze-dried.

Samples of pre-treated enamel powder weighing ca. 0.5 mg were loaded into a microCAPS carbonate analysis preparation unit, directly connected to a Sercon Geo 20-22 dual-inlet gas IRMS. The enamel carbonate of each sample was reacted with 100% phosphoric acid at 90°C. CO_2 released by the reaction was analysed by mass spectrometry along with CO_2 from a reference supply. The resulting $\delta^{13}C_c$ and $\delta^{18}O_c$ ratios were calibrated against internal laboratory (mammoth and wildebeest enamel) and international standards (CO-1, a Carrara marble prepared by the International Atomic Energy Agency) and are reported relative to VPDB. Analytical precision based on repeat measurement of standards is ca. ±0.1‰ for both isotopes.

Strontium isotope analysis

Plant samples for strontium isotope analysis were dried naturally and crushed in a coffee grinder. To remove all organic matter, the samples were then ashed in a muffle furnace by step-heating from 200 to 650-700°C. A subset of 10 samples were analysed at both the University of Cape Town and at the Université Libre de Bruxelles (Suppl Appendix 1).

Enamel surfaces were shotblasted and abraded with a clean diamond-tipped burr, prior to sampling with another burr. Unless otherwise noted, all samples were taken vertically down the tooth, and so reflect an averaged signal over the period the specific tooth formed. Four horizontal samples were taken at ca. 10mm intervals from one cattle tooth to explore intra-tooth variability. Samples underwent no further pre-treatment, following a comparison by Chenery et al. (2012) suggesting minimal difference when using an acetic acid wash as recommended by Hoppe et al. (2003). The main drawback to the acetic acid wash is the loss of approximately half the sample that this entails.

All enamel strontium isotope measurements were undertaken at the MC-ICP-MS facility in the Department of Geological Sciences, University of Cape Town. After dissolution of enamel in HNO_3, routine facility procedures for strontium separation chemistry (Pin et al., 1994) and analysis on a NuPlasma HR MC-ICP-MS were followed (Copeland et al., 2008; Radloff et al., 2010). Analyses are referenced to a $^{87}Sr/^{86}Sr$ value of 0.710255 for the NIST international standard SRM987. An inhouse carbonate standard, NM95 (0.708907 ± 23, n = 56), measured alongside the samples on two separate occasions returned values of 0.708907 ± 28 (n = 5) and 0.708909 ± 26 (n = 7), respectively.

Strontium isoscape

An updated version of the map of biosphere $^{87}Sr/^{86}Sr$ variation across Britain (Evans et al. 2010, fig. 1b) was generated using British Geological Survey 1:625,000 bedrock geology digital mapping (DiGMapGB-625). The Evans et al. (2010) dataset was supplemented with data for plants growing on key rock types relevant to the study area from Gloucester (Chenery et al. 2010) and with new results from the Ridgeway (see below). Mean values and standard deviations were calculated for samples corresponding to each polygon in the DiGMapGB-625 dataset. Where possible, only values from plant samples were used to calculate the mean values and standard deviations for each polygon. Where no plant data were available, mean values and standard deviations were calculated, in order of preference, as follows: 1) other samples – using values from bone, dentine, soil and water samples; 2) rock types – using values from other polygons of the same rock type, and; 3) isotope packages – using values for other polygons of the same isotope package.

Statistical analysis

The data were assessed for departures from normality using Shapiro-Wilk tests, with parametric (Student's t-tests, ANOVA) or non-parametric (Mann-Whitney, Kruskal-Wallis) statistical tests applied as appropriate. All tests are two-tailed, with $\alpha = 0.05$.

Results

Bone collagen stable carbon and nitrogen isotope results

Bone collagen $\delta^{13}C$ and $\delta^{15}N$ measurements (Tables 1, S2; Figure 3a) all met the criteria for well-preserved collagen in terms of collagen yield, C:N ratios, and %C and %N (DeNiro 1985; van Klinken 1999). C:N ratios were between 3.1 and 3.5 (averaging 3.3. ± 0.06), within the more conservative range proposed by van Klinken (1999). Fauna from Alfred's Castle previously analysed by one of the present authors (Hamilton 2013) have been included in the summary statistics and discussion. Stable carbon isotope values exhibit remarkably little variation by site or species, averaging -21.6 ± 0.4‰ overall (Kruskal-Wallis ANOVA, $p = 0.487$, n = 51). Stable nitrogen isotopes however, demonstrate clear differences between species ($p = 0.000$); as might be expected in an Iron Age context, it is the pigs that have higher $\delta^{15}N$ values (Hamilton et al. 2009). But this global picture glosses over distinct differences between the Ridgeway and Vale. Pigs from the Vale sites of Marcham and Watchfield do not differ from cattle and sheep in their $\delta^{15}N$ values ($p = 0.210$), while those from the Ridgeway sites do ($p = 0.000$). It is the latter, then, that are driving the significant species difference seen in the combined sample. No difference is seen in the values of pigs from the Ridgeway and Vale (Mann-Whitney U-test, $p = 0.923$).

Cattle and ovicaprids from the Ridgeway sites are not statistically distinguishable in $\delta^{15}N$ ($p = 0.186$), nor do they differ from one another in the Vale sites ($p = 0.534$). However, the combined Ridgeway herbivores are clearly depleted in ^{15}N compared to those of the Vale ($p = 0.000$) (Figure 3b). This is part of a wider pattern that has been noted for the Upper Thames (Hamilton 2016; Stevens et al. 2010; 2013). It can be related to natural ^{15}N differences in the soils (Robinson 2001), but also perhaps to more intensive agricultural practices in the Vale, involving higher stocking rates, and/or foddering of animals with chaff grown on manured fields (Bogaard et al. 2007; 2013; Fraser et al. 2011). This difference in bone collagen results, which represents an averaged diet over some years (depending on the age of the animal), implies the existence of separate cattle herds and sheep flocks on the Ridgeway and in the Vale. This does not mean that no animals were moving between the two areas, but it does indicate that any such movements were limited, with most animals spending much of their time grazing in one place or the other.

Table 1. Summary faunal bone collagen $\delta^{13}C$ and $\delta^{15}N$ values from the Ridgeway and Vale. Alfred's Castle includes data previously published by Hamilton (2013). Individual measurements are provided in Table S2.

Figure 3a, b. $\delta^{13}C$ and $\delta^{15}N$ isotope results on faunal bone collagen from the Ridgeway (Segsbury and Alfred's Castle) and the Vale (Marcham and Watchfield).

Sequential dentine stable carbon and nitrogen isotope results

There is relatively limited variation in the sequential samples taken from three cattle second molars, two from Alfred's Castle and one from Marcham. The range of values in each tooth is less than 1‰ for $\delta^{13}C$ (only 0.2‰ in the case of M09), and 0.8 to 1.1‰ for $\delta^{15}N$ (Tables 2, S3, Figure 4a-c). The only hint of covariation between the two isotopes is seen in the molar (AC08) from Alfred's Castle.

In two cases (AC06, M09) the bone collagen $\delta^{15}N$ values are more than three standard deviations lower than the dentine average for the same individual, while in the third case (AC08) it is one SD lower. It may not be a coincidence that this animal is the youngest of the three at 18-30 months, while the others are adult (4+ years) and 30-36 months, respectively.

Table 2. Summary of sequential dentine $\delta^{13}C$ and $\delta^{15}N$ results from Alfred's Castle and Marcham. Individual measurements are provided in Table S3.

The high $\delta^{15}N$ values for second molars cannot be due to nursing. Instead, it may be that young animals of less than two years of age were preferentially kept on the richer pastures of the Vale. The bone collagen isotope results discussed above, together with other studies on Iron Age fauna from sites on the Chalk, convincingly demonstrate that soils there are significantly ^{15}N-depleted compared to the Vale. Why this pattern is seen at both Alfred's Castle and Marcham is unclear, but here we run up against the limitations of the small sample size.

Figure 4. Sequential dentine collagen $\delta^{13}C$ and $\delta^{15}N$ results from: a) AC06, b) AC08, and c) M09.

Sequential enamel carbonate stable oxygen and carbon isotope results

The expected sinusoidal pattern in $\delta^{18}O_c$ values can be seen in three of the four cattle molars (Tables 3, S4, Figure 5b-d). This captures seasonal variation in drinking water, with the troughs indicative of the colder winter months, and the peaks of the summer months. The curve for the remaining molar, from Alfred's Castle (AC06), exhibits a surprisingly dampened signal, with less than half the range seen in the other teeth; specifically, it lacks the expected ^{18}O-enriched warm season values (Figure 5a). This may relate to the use of drinking water from the spring-lines at the foot of the Downs some 4km to the north of the site, which served this purpose in historic times. Indeed, many villages along the foot of the Downs are known as 'spring-line settlements' because they formed around these dependable, year-round sources of water. Because of residence time, the Chalk aquifer is thought to include a substantial contribution of Pleistocene precipitation, and so is slightly depleted in ^{18}O (Darling et al. 1997; Edmunds et al. 1987). As early as the 1930s, Sir Cyril Fox surmised that people in the Bronze Age 'tended to live at the spring-line below the Downs, driving [their] herds and flocks on to the plateaux and hill-tops for pasture; while in the [Iron] Age that followed he moved his actual dwelling sites on to the uplands, using them both for arable and for pasture and driving his flocks down to the spring-line for watering' (Fox 1932, 69).

While by no means a perfect relationship, the $\delta^{18}O_c$ and $\delta^{13}C_c$ results generally covary positively (Figure 5), so that the colder months of the year are associated with lower $\delta^{13}C$ values. This is a common trend seen in other studies in mid- to high-latitude environments (Balasse et al. 2009; 2012). There is a notable departure from this relationship in the lower crown of a molar from Alfred's Castle (AC08) (Figure 4b), which sees increasing $\delta^{13}C_c$ values at the same time as sharply decreasing $\delta^{18}O_c$ values, possibly reflecting winter foddering with summer hay.

Table 3. Summary of sequential enamel $\delta^{18}O_c$ and $\delta^{13}C_c$ results. Individual measurements are provided in Table S4.

Figure 5. Sequential enamel carbonate $\delta^{18}O_c$ and $\delta^{13}C_c$ results from Alfred's Castle and Marcham

$^{87}Sr/^{86}Sr$ results

Modern plants

Measurements on modern plants (grass and trees) confirm the expected difference in biologically available strontium in the Chalk and the Vale (Figure 6; Table S5). The Chalk is relatively homogeneous, with eight plant samples from three locations (Segsbury, White Horse bottom and Alfred's Castle) averaging 0.7080 ± 0.0004 (n = 8), consistent with the ratio expected for Cretaceous marine deposits (McArthur et al. 1993). This includes one sample (an oak from the vicinity of Alfred's Castle) with an unexpectedly high value of 0.7088, the removal of which lowers the Chalk mean to 0.7079 ± 0.0002. The Vale shows greater heterogeneity, reflecting its more complex and varied geology, but its overall average of 0.7089 ± 0.0008 (n = 21) is significantly higher than that of the Chalk (Mann-Whitney U, $p = 0.002$). There are three outliers (>1.5 times the interquartile range) with higher $^{87}Sr/^{86}Sr$ values from two locations (Longcot and the road to Woolstone); one of these samples was re-analysed in a second run of samples, producing a very similar result (averaging 0.7101). Longcot is located on the West Walton, Ampthill and Kimmeridge Clay Formations, and Woolstone is on the Gault and Upper Greensand Formations (Figure S1).

Figure 6. Plant $^{87}Sr/^{86}Sr$ isoscape for the study area (a) with associated prediction error map (b).

A small number of sediment samples found adhering to specific teeth were also analysed (Table S5). Calcium carbonate adhering to two *Bos* teeth (SC97, samples 2 and 5) from Segsbury Camp yielded $^{87}Sr/^{86}Sr$ values of 0.707854 and 0.708027, in keeping with the plant values for the Chalk. In both cases the corresponding tooth enamel samples were enriched above this, 0.708468 and 0.708871, respectively. Adhering sediment from three teeth at Watchfield gave a mean value of 0.709167 ± 15, consistent with Vale plants (though no plant values were available specifically from Watchfield).

Table 4. Average $^{87}Sr/^{86}Sr$ values for tooth enamel and plants from Ridgeway and Vale sites.

Pigs

In traditional subsistence farming, pigs tend not to be moved over more than very short distances, generally staying close to the settlement (Grigson 1982). They are therefore often seen as good proxies for the local $^{87}Sr/^{86}Sr$ signal (Bentley and Knipper 2005). This is supported here, with pigs from the Ridgeway and Vale differing significantly (Mann-Whitney U-test, $p = 0.004$), and closely matching their find locations (Tables 4, S6; Figure 7). There are no significant differences between the pig enamel and plant strontium isotope results for either the Ridgeway (Mann-Whitney U, $p = 0.298$) or Vale sites ($p = 0.353$). And, although the Vale as a whole is quite variable in $^{87}Sr/^{86}Sr$, it can be noted that the Marcham pigs (0.7087 ± 0.0005; n = 3) closely match the values of modern plant samples collected from the site itself (0.7085 ± 0.0004; n = 4). This does not in itself necessarily mean that they were raised locally, since this isotopic range is shared with other locations in the Vale.

Figure 7. Boxplots of $^{87}Sr/^{86}Sr$ results for Ridgeway and Vale plants and fauna (created using BoxPlotR, http://shiny.chemgrid.org/boxplotr/)

Sheep

What was less expected, and contrary to the hypothesis set out in the beginning of this paper, is that sheep show a very similar pattern to that seen for pigs (Figure 7). That is, the $^{87}Sr/^{86}Sr$ values for sheep from the Ridgeway sites are clearly distinct from those from the Vale (Mann-Whitney U-test, $p = 0.001$), and do not differ significantly from the modern plant values of the Chalk ($p = 0.142$). The ten Vale sheep analysed, on the other hand, are on average more radiogenic than that zone's available average plant values ($p = 0.013$), but, given the geological variability of the Vale, this may just be a matter of its inadequate characterisation (Figure 7). While dividing the results by individual site leads to sample sizes too small to test statistically, it can be noted that the sheep values from the two Ridgeway sites of Segsbury and Alfred's Castle are very similar, averaging 0.7084 ± 0.0005 and 0.7083 ± 0.0004, respectively. Since the sites date primarily to the EIA and MIA, respectively, this also suggests that the observed pattern persists over some centuries.

An outlying value of 0.7089 on a sheep from Alfred's Castle suggests that this animal, unlike the others, did spend time grazing in the Vale when this tooth was forming. An even more extreme outlier was found at Marcham, with a value of 0.7122, higher than any of the modern plant values in this study. Thus, this animal must have spent time in a more radiogenic location, the closest of which, using the available broad-scale Sr isoscape map for Britain, would be either to the north or to the west (Evans et al. 2010). However, isotope maps at this scale can mask considerable local variation (cf. Chenery et al. 2010), and it is possible that there is a closer source of enriched ^{87}Sr, hinted at by the three highest plants values (one of which was analysed twice, with close agreement – see above) from the Vale in the present study, averaging 0.7106 ± 0.0005. Nevertheless, there is certainly no reason to discount such long-distance movement/exchange of animals in the Iron Age (or in preceding periods for that matter: cf. Viner et al. 2010; Towers et al. 2010).

To explore variability within a single individual, vertical samples of the first, second and third permanent molars were taken from the same sheep mandible from Segsbury Camp (SC97-17). The results for the M1 and M3 are both considerably higher (ca. 0.7092) than is possible for the Chalk, and so this animal must have spent the time during which those teeth were forming on pasture in the Vale (or another area with similar Sr isotope ratios). None of the other sheep teeth from the Ridgeway sites gave values this enriched in ^{87}Sr, with the next highest being 0.7089. The M2 from the same individual, by contrast, yielded a lower value of 0.7082 that is consistent with plants on the Chalk. Therefore, this animal at least fits the model of movements between the Ridgeway and Vale, though it appears that it may be unusual in so doing.

Cattle

Cattle present a very different pattern. The ^{87}Sr/^{86}Sr measurements from the Ridgeway and Vale sites do not differ, and indeed largely overlap, except for a single Vale outlier with a higher value

(Figure 7). Moreover, the Ridgeway cattle differ markedly from values of the Chalk plants (Mann-Whitney U, $p = 0.003$), instead clearly grouping with those of the Vale ($p = 0.929$). It can also be noted that cattle from the two Ridgeway sites provide very similar values, so that this pattern is not being driven by the much larger Segsbury hillfort, which might be expected to be a more prominent hub in the local network of animal exchange and consumption, and so to have functioned differently than Alfred's Castle. Nor can any change over time be observed, i.e., the pattern persists from the EIA through the MIA.

To explore intra-tooth variation, four horizontal samples were taken on a *Bos* first molar from Alfred's Castle (AC-8), at approximately 1 cm intervals. The results show significant variation, with the second sample being more enriched in ^{87}Sr relative to the other three (Figure 8), indicating movement to different pastures during the months represented. The average of the four values is 0.70991 ± 0.00015, which, as would be expected, closely matches that of 0.70981 obtained on a vertically oriented sample from the same tooth.

Figure 8. $^{87}Sr/^{86}Sr$ results on four sequential samples from a first molar from Alfred's Castle, taken at ca. 10mm spacing starting near the occlusal surface (AC8-1); AC08 represents a separate measurement of a vertical sample from the same tooth (i.e., an averaged signal over the entire crown formation time).

Discussion

Contrary to the expectations set out in the beginning of this paper, both the bone collagen $\delta^{15}N$ and the $^{87}Sr/^{86}Sr$ results indicate the existence of distinct sheep flocks on the Ridgeway and Vale, with relatively little evidence for overlap, and hence movement, between these locations. The analysis of three molars in one animal, however, does suggest mobility for some individuals. It may be that additional sequential strontium and stable isotope measurements will provide further evidence for mobility. But if this were common, we would expect a more variable and intermediate Sr isotope signal, rather than the observed clear separation in their average values. While not differing in $\delta^{15}N$, the $^{87}Sr/^{86}Sr$ results for pigs also demonstrate the presence of distinct groups of animals on the Ridgeway and Vale. By and large, it seems that both sheep and pigs were raised and slaughtered locally.

The situation with cattle is considerably more complex. As with the sheep, the cattle bone collagen $\delta^{15}N$ results show a clear separation between the Ridgeway and the Vale, suggesting surprising little movement between the two areas. In contrast to those for the sheep and pigs, however, the strontium isotope results for the Ridgeway cattle group with the Vale plants. This indicates that most cattle spent the time during which their teeth were forming in the Vale (or in another region with similar $^{87}Sr/^{86}Sr$ values, but parsimony favours the Vale as their most probable origin). The apparent discrepancy in the scenarios presented by the two isotopes may relate to the different formation times represented by measurements on tooth carbonate and bone collagen. The former represents the restricted period during which the tooth formed, while the latter reflects a longer period, the duration of which depends on the animal's age at death. The teeth represented in the study, from deciduous premolars to permanent second molars, span *in utero* crown development to approximately the end of the first year of life in the case of M2s. The ages-at-death of the nine Ridgeway cattle analysed for strontium are more or less equally divided between juvenile (ranging 1–8 months to ca. 2 years) and fully adult (4+ years) animals (Table S2). Early skeletal growth is very rapid, so that new bone formation will quickly swamp earlier isotopic signals (Hedges et al. 2007).

The interpretation suggested above receives tentative support from two sources. First, there is a hint of a positive correlation between $^{87}Sr/^{86}Sr$ and $\delta^{15}N$ values on the Ridgeway cattle ($r^2 = 0.373$, $p = 0.143$, n = 8), though this only becomes statistically significant with the removal of one outlier (the lowest $\delta^{15}N$ value in the dataset, of 1.7‰; $r^2 = 0.787$, $p = 0.009$, n = 7). This is the trend that would be expected if animals were moved from the Vale to the Ridgeway at various times in their early lives, such that those moved while their tooth crowns were still forming would present lower $^{87}Sr/^{86}Sr$ values than those moved after their crowns were fully mineralised. The two cattle with the lowest $^{87}Sr/^{86}Sr$ values of ca. 0.7080 are consistent with the Chalk, and they also provide two of the lowest $\delta^{15}N$ values. It is possible that a small number of cattle were bred on the Ridgeway, as suggested by the presence of newborn calves in the faunal assemblages at both Segsbury and Alfred's Castle. While neonatal lambs were not found at Segsbury, they were recovered from Alfred's Castle (Lange 2013; Mulville and Powell 2005), which is consistent with the $^{87}Sr/^{86}Sr$ and $\delta^{15}N$ results for the existence of distinct flocks on the Downs.

Second, and following on from the above, there are the differences between the sequential dentine and bone collagen $\delta^{15}N$ results for the same individuals. While only based on two individuals from Alfred's Castle and one from Marcham, the dentine average is in all cases higher (by 0.4 to 1.1‰) than the bone collagen values of the same individuals, suggesting that during the period the second molar roots were forming, from approximately age 6 to 24 months, these animals were all kept predominantly on pastures in the Vale, relatively enriched in ^{15}N compared to those of the Ridgeway.

Cattle dominate the Iron Age faunal assemblages of the Vale (Birbeck 2001; Hey 1995), suggesting that they were of the greatest economic importance among the domestic stock. This is part of a pattern long recognised for the Iron Age of south-central England, in which cattle tend to dominate faunal assemblages in the lower-lying Upper Thames Valley, while sheep dominate the Downs (Grant 1984; Hambleton 1999); indeed, this division persists today. This difference in landscape use can be related both to the paucity of reliable sources of drinking water on the Downs, and to the preference of sheep for the better-drained Chalk grasslands, as they are more susceptible to liver fluke and foot-rot than cattle (Grant 1984). Sheep are able to obtain sufficient water from the grass they consume, but cattle are obligate drinkers, requiring daily watering. While the water table was higher in the Iron Age (Dark 2006; Robinson and Lambrick 1984), it is unlikely that there would be sufficient flowing water to supply the needs of substantial numbers of cattle (though see Levick 2015, 51-53). Bringing the cattle to the springs emerging from the lower slopes of the Downs would mitigate the scarcity of water on the Chalk to some extent, and might account for the dampened $\delta^{18}O$ signal seen in one of the cattle from Alfred's Castle (though not in the other animal analysed from the site). The floodplains of the river valleys, on the other hand, were very well suited to the pasturage of cattle (Grant 1984; Hesse 2011; Lambrick and Robinson 2005).

Furthermore, lactating cows require additional water (Dado and Allen 1994; Woodford et al. 1984), and so it would make sense to keep them in the Vale at least until their calves were fully weaned. Thus, cows at least may have been preferentially kept on the richer and better-watered pastures of the Vale during the calving and nursing season, before some were moved to the Ridgeway, so that their bone collagen values reflect the signature of the Chalk grasslands. Favourable pastures used repeatedly for cows in calf, for example, could lead to ^{15}N-enrichment of the soil through self-manuring, particularly as there are clear legacy effects (Commisso and Nelsen 2008; Bogaard et al. 2007). As mentioned above, the enclosure at Watchfield seems designed to manage large numbers of animals, and the site's faunal assemblage is dominated to an unusual extent by cattle (Lambrick and Robinson 2005, 265). The advantages of raising cattle in the Vale appears to have been recognised in the Romano-British period; Gill Mill, only 12km northwest of Marcham, has been suggested to have functioned as a specialised cattle-rearing site to supply markets at regional centres such as Cirencester (Booth 2016).

An obvious point of comparison for the results presented here is provided by the broadly contemporary sites of the Danebury Environs, located ca. 50km south of the Oxfordshire Ridgeway. The Danebury project set out to address some of the same questions posed here regarding animal management between an Iron Age hillfort and its surrounding farmsteads. Initially, the variability in $\delta^{13}C$ and $\delta^{15}N$ results on faunal remains from the Danebury hillfort suggested a scenario in which animals were brought to the site from a series of isotopically distinct parts of the surrounding landscape (Stevens et al. 2010), much as was originally proposed for the Ridgeway hillforts (cf. Madgwick and Mulville (2015) for a comparable example relating to an EIA feasting site in South Wales). However, a subsequent isotopic study of faunal remains from a number of contemporaneous unenclosed settlements found that, rather than the expected inter-site variability, they exhibited a high degree of intra-site variability (Stevens et al. 2013). Interpretation thus shifted to propose that each community had access to a range of different pastures, though whether these were to be found nearby or more distantly could not be determined with $\delta^{13}C$ and $\delta^{15}N$ data alone. The results of the present project suggest a third scenario, one in which animals were largely kept 'locally' (recognising that movement within either the Chalk or the Vale will not be discernable isotopically), regardless of whether the site was a 'hillfort' or unenclosed settlement. At the same time, there are some indications that young cattle born and raised in the Vale were moved to the Ridgeway and kept on pastures there for a year or more before slaughter. While this could imply a subordinate role for the unenclosed Vale settlements (paying tribute?), it could also be that these communities were compensated in some manner that it is not apparent archaeologically. It must also be reiterated that Marcham does not appear to have been a 'normal' domestic settlement, with possible evidence for a range of ritual activities. As such, it might have been expected to perform a similar integrative role to that proposed for the hillforts. In neither case, however, is there evidence for the significant presence of animals from the adjacent landform. There remain, then, many questions regarding the nature of the relationship between the Ridgeway and Vale in the Iron Age.

Conclusions

This study has provided new insights into animal management practices and mobility in the Early/Middle Iron Age of the Oxfordshire Ridgeway. A baseline of 29 modern plant $^{87}Sr/^{86}Sr$ measurements confirm and provide more detail on the expected difference between plants growing on the Cretaceous Chalk soils of the Ridgeway and the more varied geology of the Vale. As expected, pig enamel $^{87}Sr/^{86}Sr$ values closely followed the local plant values, consistent with these animals being raised locally. Unexpected was that sheep generally followed this same pattern, and clearly spent most of their time grazing either on the Ridgeway or in the Vale. Cattle showed a very different pattern to that seen in the other two species, with $^{87}Sr/^{86}Sr$ values consistent with grazing in the Vale, regardless of whether the animal was from a site in the Vale, or from a Ridgeway hillfort. In addition to these general patterns, more detailed analysis of a subset of samples highlights the mobility of individual animals.

Stable carbon and nitrogen isotope measurements on the bone collage of the same animals analysed for $^{87}Sr/^{86}Sr$ provide additional information. While not differing in $\delta^{13}C$, both sheep and cattle from the Ridgeway are on average lower in $\delta^{15}N$ than those from the Vale. This is somewhat surprising in the case of the cattle, since their enamel $^{87}Sr/^{86}Sr$ values strongly suggest origins in the Vale. A possible explanation for this is that calving and nursing took place in the Vale, after which some animals were moved to the Ridgeway, allowing the bone collagen to turn over to reflect Chalk pastures. The sequential dentine results, albeit on a very limited number of individuals, offers some tentative support for this scenario. While many isotopic studies of animals in prehistoric Britain are emphasising larger-scale mobility, the present study suggests instead persistence patterns in the use of the landscape at a very local level.

As well as Iron Age sites, the Ridgeway and Vale contain a number of Romano-British sites, often at the same locations. A strontium isotope study of Iron Age and Romano-British cattle teeth at the rural settlement of Owslebury, Hampshire, found a change in the scale of procurement, with greater evidence for the movement of cattle beginning the Late Iron Age and continuing into the Roman period (Minniti et al. 2013). Neither of these periods is well represented (if at all) in the present study, and it would be interesting to see whether a similar pattern holds for the Oxfordshire Ridgeway. The initial results presented here are certainly promising, and have already provided new insights – and raised new questions – regarding animal management in the Early/Middle Iron Age of south-central England. More broadly, they have highlighted the considerable potential in a targeted study of animal management practices using a multi-isotope approach within a small, well-defined region, where suitable variation in natural isotope systems exists.

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Table and Figure captions

Table 1. Summary faunal bone collagen $\delta^{13}C$ and $\delta^{15}N$ values from the Ridgeway and Vale. Alfred's Castle includes data previously published by Hamilton (2013). Individual measurements are provided in Table S2.

Table 2. Summary of sequential dentine $\delta^{13}C$ and $\delta^{15}N$ results from Alfred's Castle and Marcham. Individual measurements are provided in Table S3.

Table 3. Summary of sequential enamel $\delta^{18}O$ and $\delta^{13}C$ results from Alfred's Castle and Marcham. Individual measurements are provided in Table S4.

Table 4. Average $^{87}Sr/^{86}Sr$ values for tooth enamel and plants from Ridgeway and Vale sites.

Figure 1. Map of the study area showing study sites and plant sample locations.

Figure 2. Bar chart of the three main domestic species at the Ridgeway (Segsbury and Alfred's Castle) and the Vale (Marcham and Watchfield) sites (sources: Birbeck 2001; Lange 2013; Mulville and Powell 2005; P. Levick pers. comm.).

Figure 3a. $\delta^{13}C$ and $\delta^{15}N$ isotope results on faunal bone collagen from the Ridgeway and the Vale.

Figure 3b. Summary plot (mean ± 1 SD) of $\delta^{13}C$ and $\delta^{15}N$ isotope results on faunal bone collagen from the Ridgeway and the Vale.

Figure 4. Sequential dentine collagen $\delta^{13}C$ and $\delta^{15}N$ isotope results from Alfred's Castle and Marcham.

Figure 5. Sequential enamel carbonate $\delta^{18}O_c$ and $\delta^{13}C_c$ isotope results from Alfred's Castle and Marcham.

Figure 6. Plant $^{87}Sr/^{86}Sr$ isoscape for the study area (a) with associated prediction error map (b).

Figure 7. Boxplots of $^{87}Sr/^{86}Sr$ results for Ridgeway and Vales plants and fauna.

Figure 8. $^{87}Sr/^{86}Sr$ results on four sequential samples from a first molar from Alfred's Castle, taken at ca. 10mm spacing starting near the occlusal surface (AC8-1); AC08 represents a separate measurement of a vertical sample from the same tooth (i.e., an averaged signal over the entire crown formation time).

Supplementary Information

Appendix 1. Plant sample preparation for replicate $^{87}Sr/^{86}Sr$ analysis.

Table S1. Summary of main mammalian fauna from Early and Middle Iron Age contexts.

Table S2. Faunal bone collagen $\delta^{13}C$ and $\delta^{15}N$ values from the Ridgeway and Vale.

Table S3. Sequential dentine $\delta^{13}C$ and $\delta^{15}N$ results.

Table S4. Sequential enamel $\delta^{18}O_{cVPDB}$ and $\delta^{13}C_{cVPDB}$ results, with conversions to $\delta^{18}O_{cVSMOW}$ and $\delta^{18}O_{pVSMOW}$.

Table S5. Plant sample locations and $^{87}Sr/^{86}Sr$ results.

Table S6. $^{87}Sr/^{86}Sr$ results on sediment samples.

Table S7. $^{87}Sr/^{86}Sr$ results for tooth enamel from Ridgeway and Vale fauna.

Figure S1. Bedrock geology of the study area (DiGMapGB-625) showing study sites and plant sample locations.