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'Why so high?' Examining discrepancies between the Sr biosphere map and archaeological tooth data from the Peak District, England

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ABSTRACT

The analysis of $^{87}Sr/^{86}Sr$ isotope ratios in human and nonhuman tooth enamel is used worldwide for archaeological and forensic purposes to establish if an individual is likely to have grown up in the area from which their remains were excavated. The English Peak District has produced an unusually high proportion of archaeological humans who, based on Sr isotope ratios, appear to have come from elsewhere. We have used modern plant samples from the Peak to show that the current understanding of Sr isotope ratios for this area is incomplete – we found many plant samples growing on gritstone sediments had higher Sr values than would be expected based on the current literature. In addition we demonstrated that the taxonomy of the plant does not appear to affect the Sr isotope values (we also found that mycorrhizal type did not determine Sr isotope values in these plants), rather it is the substrate on which it is growing that is important. In terms of human movement, our work suggests it is likely that many archaeological individuals found in the Peak District are indeed local, rather than migrants. It is also possible that the expansion of blanket peat in the Peak has over time reduced the amount of Sr entering the food chain from mineral soils, reducing the radiogenic Sr isotope values in more recent teeth. While our case study is the Peak District, our findings have implications for anomalously high archaeological $^{87}Sr/^{86}Sr$ isotope values in other upland regions with similar geologies and blanket peats.

1. Introduction

Mobility is a key theme in archaeology, with multiple recent works examining movements from prehistory to the present day (e.g.; Montgomery et al., 2019; King et al., 2021; Snoeck et al., 2020). These studies use a variety of techniques, which can examine movement over very different timescales – from ancestral using ancient DNA (e.g. Gretzinger et al., 2022; Patterson et al., 2022) to the individual using strontium (Sr) and oxygen (O) isotope analyses (e.g. Shaw et al., 2016; O'Regan et al., 2020; Neil et al., 2020). Working on the principle that Sr is taken up from local soils or geology, via plants and into the food chain (Bentley, 2006), analysis of $^{87}Sr/^{86}Sr$ isotope values in human and nonhuman tooth enamel is now being used worldwide for archaeological, forensic and food provenance purposes (Aguzzoni et al., 2019; Frei and Frei, 2011; Knudson et al., 2005; Juarez, 2008). However, the robustness of the results is dependent on the comprehensiveness of the underlying geological mapping, and our theoretical understanding of likely complications and anomalies. Developed at the British Geological Survey National Environment Isotope Facility (BGS/NEIF) by Evans and colleagues, the UK biosphere map is now the foundation for much British research in this area (Evans et al., 2018).

Recently high radiogenic Sr isotope values have been described from environmental samples from some localized parts of South West England, raising questions about interpretations of high values from human remains in southern England (Müldner et al., 2022). However, the Peak District in England has also consistently produced higher radiogenic Sr isotope values in humans than predicted by the current Sr isotope biosphere model (including some of the most radiogenic tooth enamel values from humans in Britain), leading to the suggestion that many of these individuals have migrated from elsewhere (Parker Pearson et al., 2016; Montgomery et al., 2019; Neil et al., 2020). This makes the Peak District a key test of our understanding of environmental Sr isotope ratios and their application to archaeology. The problem can been seen in Fig. 1, where data from seven studies on human remains

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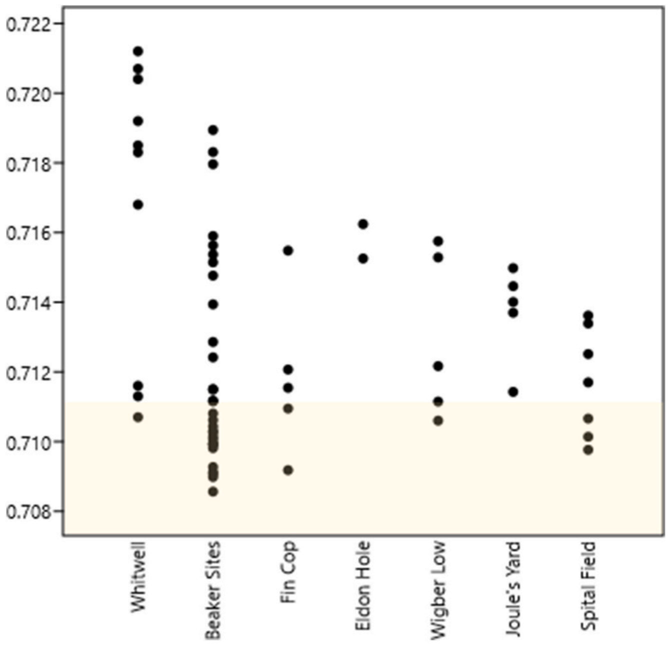

Fig. 1. All Derbyshire archaeological sites analysed for ^{86}Sr/^{87}Sr through time, from Whitwell (earliest) to Spital Field (latest). The yellow box indicates the Peak biosphere ^{86}Sr/^{87}Sr range from Neil et al. (2020), demonstrating the high numbers of individuals who lie outside it. For details on each site, see Table S1. Note that Whitwell lies 18 miles to the ESE of Hathersage (Fig. 2), so not in the Peak District proper, but also on limestone geology and well within Neolithic walking distance of the Dark Peak. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

from the Peak District and Derbyshire dating from the Neolithic (4000–2400 BC) to the medieval period (AD 1066–1485) are shown (see Table S1 for site details). Our current understanding of likely ^{87}Sr/^{86}Sr isotope values in the Peak Biosphere is indicated by the yellow box (min 0.7087, max. 0.7115 (Neil et al., 2020)), and it can be seen that a considerable number of sites and individuals exceed this, particularly for the prehistoric periods. Overall, only 48% of these human tooth enamel samples have produced a 'local' Sr isotope signature. To put these numbers in context, a study of Sr isotope values in Roman London, a location and period known to have experienced high levels of immigration yielded 70% ($n = 14/20$) of individuals consistent with being from the London area (Shaw et al., 2016).

Reference maps of Sr isotope values are created using a number of different methods but the aim is to create a spatial distribution of ^{87}Sr/^{86}Sr biosphere values against which human data can be compared. Material used for this mapping can include archaeological rodent teeth (Kootker et al., 2016), water (Frei and Frei, 2011), and soil leaches (Warham, 2012; Maurer et al., 2012) all of which have advantages and disadvantages (Evans and Tatham 2004). However, the majority of studies use plants because they form a prominent part of the food chain, occur everywhere and therefore provide good spatial cover. The overriding assumption is that the Sr isotope uptake by plants has not changed through time, and as long as modern pollution is monitored and assessed, plants provide data for the base of the food chain (Bentley, 2006). However, most studies have used a very limited range of plants that have only occasionally been identified to species level (e.g. Johnson et al., 2022; Müldner et al., 2022). The Sr isotope values from the plants are transferred, unfractionated, into animals that eat them, and in the case of mammals, are stored in teeth and bone. While archaeological bone and tooth dentine are subject to diagenesis during burial, tooth enamel is resistant to diagenesis, and the ^{87}Sr/^{86}Sr isotope values contained within it provide a snapshot of the individuals Sr intake during childhood. The second molar is usually preferred for archaeological studies, and this captures intake between the ages of approximately 2–8 years (Hillson 1996). Comparison of the tooth enamel isotope values with the values of the biosphere where the individual has been found buried provide the basis of studies of archaeological movement. If there is a difference, then it is usual to conclude that the individuals have moved during their lifetime. If there is no difference, then it cannot be proven that the individuals are local, but that is the most parsimonious solution (therefore Sr isotope analysis cannot determine with certainty where individuals are from, but it can exclude areas that they cannot have come from). While it is the high-profile sites where the majority of individuals appear to have moved that get the most publicity (e.g. Amesbury Archer, Boscombe Bowmen (Fitzpatrick 2013), Weymouth Vikings (Loe et al., 2014)) in most cases there is a good match between the biosphere and people who would be consistent with a local origin (Evans et al., 2012). Therefore, having one site with elevated numbers of movement would not be unexpected but it is the sustained levels of apparent movement at all sites over such a long time that makes the Peak District record so unusual.

To address this, here we aim to determine whether the Peak District has genuinely seen higher levels of immigration than any other UK region over a period of 5000+ years as implied by the Sr isotope results, or if our current biosphere mapping is flawed when applied to this upland area. While our focus here is on the Peak District as a case study, our analyses have implications for regions worldwide with similar geologies and/or peat covered landscapes.

1.1. What could be special about the vegetation of the Peak District - plant mycorrhizae and/or acid conditions?

If the explanation for the apparently large number of archaeological humans coming from outside the Peak is that current biosphere mapping is flawed, then an obvious possibility is that there is something about the nature of Peak District vegetation that has been overlooked. The Peak District has two contrasting geologies – gritstone (the Dark Peak) and limestone (the White Peak). Gritstone is an informal name for various formations of sandstones cemented by quartz (Fortey, 2010). Heather moorland, growing mainly on peat, features prominently in the parts of the area with a gritstone geology (Moss, 1913; Anderson, 2021; Willmot and Moyes, 2015), which suggests the possibility of a role for acid conditions and/or ericoid mycorrhizae associated with plants in the Ericaceae (heather family).

Mycorrhizae are a usually mutually beneficial interaction between plant roots and fungi living within them that can be important in facilitating plants' access to nutrients, including accessing some that may not otherwise be bioavailable (Allen, 2022). For example, Koele et al. (2014), in an experimental study on mycorrhizae in woodlands, confirmed previous work that mycorrhizae can aid the dissolution of minerals to access nutrients, through the mechanism of acidifying the soils. As a result, there is the potential for the isotopic composition of some plants to differ from the underlying geology as represented by the soils. Mycorrhizae come in a range of different types, and the upland vegetation of the Dark Peak is often dominated by heathers (ericoid mycorrhizae) and graminoids (often weakly arbuscular mycorrhizal) (Aerts, 2002). We therefore aimed to see if heathers (mainly *Calluna vulgaris*) and other upland plants with ericoid mycorrhizae have higher ^{87}Sr/^{86}Sr isotope values, which might imply that they are able to access otherwise bio-unavailable Sr (e.g. the more Rb rich micaceous components in the rock). If so, then animals that feed upon them, such as sheep, cattle or even bees, may also take up these more radiogenic values. These could then be passed into the human food chain through meat, cheeses, honey, or from manuring. In some cases there is also a direct link to human food, for example in the early 19th century in the Peak bilberry (see table 1 for scientific names of plants) was described as being 'gathered by the poor; and used for puddings and pies' while also being served 'at the tables of the more wealthy' (cited in Willmot and

Moyes, 2015).

To test for a possible role for mycorrhizae we targeted different species of mycorrhizal and non-mycorrhizal plants across the Dark Peak (i.e. the gritstone dominated area), focussing on the mineral soils formed on the gritstone. Here the plants are in direct contact with the substrate that could possibly yield high $^{87}\text{Sr}/^{86}\text{Sr}$ values - as opposed to those growing on the blanket bog, which can have 6+m of peat between the surface and the underlying sediments (e.g. Conway, 1947). These mineral soils would also have been more available in the past, before and during bog formation, which could help explain the drop off in high Sr isotope values between the early Bronze Age and Late Iron Age human samples shown in Fig. 1, and discussed further below. We therefore predicted that ericoid mycorrhizal plants growing on mineral soils would have the highest $^{87}\text{Sr}/^{86}\text{Sr}$ isotope values, while those without ericoid mycorrhizae would have the lowest..

An additional possibility is that acid conditions may be playing a role in making high $^{87}\text{Sr}/^{86}\text{Sr}$ isotope values available to the plants. Blanket peats, and associated runoff, create acid conditions (Rydin and Jeglum, 2013), and there are already suggestions in the literature that acid soils may be associated with raised $^{87}\text{Sr}/^{86}\text{Sr}$ isotope values. Recently Johnson et al. (2022) found unexpectedly high $^{87}\text{Sr}/^{86}\text{Sr}$ isotope values in soils from Sherwood Forest, Nottinghamshire, central England. They attributed this to acid conditions associated with the long-term presence of leaf litter. Certainly forest soils can be acidic for this reason – however there is a complication at Sherwood. Although Johnson et al. (2022) assumed long-term woodland ('since the early Holocene') the history of Sherwood is likely more complex and less forested. The limited environmental archaeological evidence, along with historical records, suggests that over the last 2000 years much of the area was open forest and wood pasture, often with a heathland vegetation (Hopkinson, 1927; Rackham, 2003; Chatters, 2021), and likely with more extensive agriculture in Roman times (Buckland et al., 2018). As with the Peak District heathland is associated with ericoid plant species, and acidic soils (Webb, 1986), making a well-controlled study of these factors a priority. An additional complication for the Peak District is its proximity to major coal burning industrial cities in the 19th and first half of the 20th century. Charles Moss (1913) described the 'permanently dirty appearance' of Peak District vegetation at the start of the 20th century due to smoke from coal burning, and Skeffington et al. (1998) calculated that since 1880 the Peak District uplands had experienced the equivalent of 1 L of concentrated sulphuric acid on every square metre, which highlights the intensive acid conditions that have been present in our study region.

2. Methods

To test our hypothesis that plants with ericoid mycorrhizae on mineral soils were the most radiogenic, we selected four sites for sampling plants growing on gritstone mineral soil in the Dark Peak (BV1-3, KM; Fig. 2, Table 1), and also sampled two localities that were expected to yield lower $^{87}\text{Sr}/^{86}\text{Sr}$ isotope values – one from plants growing on top of blanket peat (KP) isolated from the underlying gritstone sediments, and one from the limestone White Peak region (ID). The northernmost site was on Kinder Plateau (SK081922) and the most southerly at Ilam Rock, Dovedale (SK142532), both in Derbyshire. Some studies (e.g. Aguzzoni et al., 2019; Dambrine et al., 1997) have shown different isotope ratios at different depths in deep soils. Note that in our current study soil depth on the gritstone can be very shallow. On the Kinder Plateau mineral soil depth was only 1–2 cm. At the Burbage sites soil

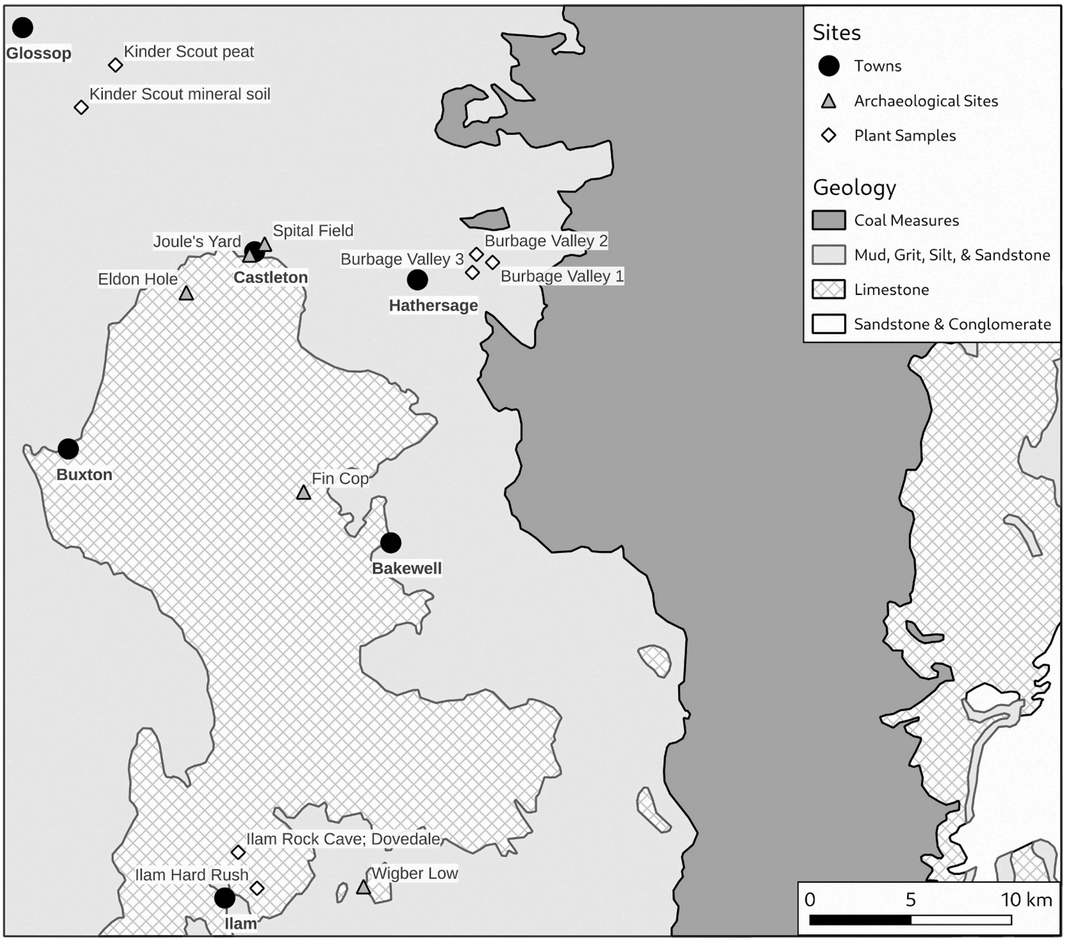

Fig. 2. Map of the Peak District showing the geology along with the location of the plant sampling locations and archaeological sites mentioned in the text.

Table 1
Species sampled at each site, and whether or not they have ericoid mycorrhizae. Location codes: ID = Ilam, Dovedale; BV = Burbage Valley; KM = Kinder Mineral soil; KP = Kinder Peat.

Taxon	Sites sampled	Ericoid mycorrhizae?
Alder (*Alnus glutinosa*)	ID	No
Hazel (*Corylus avellana*)	ID	No
Sessile oak (*Quercus petraea*)	BV	No
Bramble (*Rubus fruticosus* agg.)	ID	No
Nettle (*Urtica dioica*)	ID	No
Bracken (*Pteridium aquilinum*)	BV	No
Soft rush (*Juncus effusus*)	BV, KM	No
Hard rush (*Juncus inflexus*)	ID	No
Mixed grass/sedge (Poaceae and Cyperaceae)	ID, BV, KM, KP	No
Sedge (*Carex* sp.)	BV	No
Buckler Fern (*Dryopteris* sp.)	DI	No
Bilberry (*Vaccinium myrtillus*)	BV, KM, KP	Yes
Crowberry (*Empetrum nigrum*)	BV, KM, KP	Yes
Heather (*Calluna vulgaris*)	BV, KM, KP	Yes

depth was similarly shallow in most places with larger plants at 'Burbage 1' (see Fig. 2 and Table 1) rooted in cracks in the rock or soil filled spaces between fallen blocks. At each site we sampled a taxonomically diverse range of species including ericoid and non-ericoid plants, as well as targeting those that are known mammalian food sources such as crowberry, bilberry and graminoids. Where possible, we sampled similar species at each site (although few species are found in both the gritstone and limestone parts of the Peak District). For most plants, stems and leaves (i.e. the above ground parts) were sampled; in the case of trees leaves were sampled from several different branches and then pooled for analysis. Full details of the taxa sampled at each locality are given in Table 1. Plant nomenclature follows Stace (2019).

2.1. *Preparation and analysis of plant samples for Sr isotope analysis*

The samples were collected in paper bags and dried in the bags at 50 °C. They were reduced to "tea-leaf" consistency using an adapted DeLonghi™ Coffee grinder. About 200 mg of dried and crushed material was placed in microwave containers, and left on a hot plate at 60 °C overnight, with 8MHNO$_3$ and a small amount of spec pure H_2O_2 to accommodate the main gas release. The tubes were then sealed tightly, and the samples dissolved using a MARS™ microwave set to run for 20 min at 170 °C. The samples were transferred to Savillex beakers and 8M HNO$_3$ and spec pure H_20_2 was added until the solution turned very pale-yellow in colour. It was then evaporated down to dryness and converted to chloride form using 6MHCl produced by double distillation in sub-boiling point Teflon©C stills. The samples were then taken up in 2.5MHCl. Sr was separated from the samples using an Eichrom© AG50-X8 cation resin. The strontium isotope composition was determined by Thermal Ionisation Mass Spectrometry (TIMS) using a Thermo Triton© multi-collector mass spectrometer (TIMS). Samples were loaded on to single rhenium filaments using TaF activator following the method of Birck (1986). Samples were run in peak jumping mode for 100 scans and to an internal precision of ≤0.00001 (2SE). Strontium procedural blanks were~150 pg from microwave dissolution of plant samples. The reproducibility of the international standard NBS987 was ±0.000014 (2SD, n = 56) over the period of analysis. All data were corrected to an NBS-987 standard $^{87}Sr/^{86}Sr$ value of 0.710250. ^{87}Rb isobaric interference on ^{87}Sr can be discounted as a source of elevated $^{87}Sr/^{86}Sr$ values for the following reasons: 1) The ion exchange columns provide good separation of Rb from Sr 2) Rb burns off before Sr data are collected, during Thermal Ionisation Mass Spectrometry (TIMS) analysis and 3) any residual Rb is corrected out through monitoring of the $^{85}Rb/^{86}Sr$ ratio during analysis (Dickin 1995).

3. Results

The results of our analysis demonstrated that there were no clear differences between plant taxa with ericoid mycorrhizae and those without (Fig. 3, Ericoid mycorrhizae mean 0.7121 ± 0.0042 (2SD, n = 32); non-ericoid mycorrhizae mean 0.712 ± 0.0046 (2SD, n = 31)). However, we were able to demonstrate that there are very clear differences in $^{87}Sr/^{86}Sr$ values between the localities we sampled (Fig. S1, Table S2). Fig. 4 shows the samples divided between those plants growing on minerogenic gritstone soils and those that are on limestone or peat (Minerogenic soils mean 0.7133 ± 0.0029 (2SD, n = 41); non-minerogenic soils mean 0.7097 ± 0.0023 (2SD, n = 22)). This clearly shows that plants growing directly on gritstone mineral soils have much higher $^{87}Sr/^{86}Sr$ isotope values than those that do not, irrespective of the taxa involved. Therefore our hypothesis that ericoid mycorrhizae drive these differences was falsified. Instead we have demonstrated a clear relationship between plant Sr isotope values and their underlying substrate. This was seen across a wide range of plant taxa – including graminoids, herbs, trees and pteridophytes (ferns). It is also interesting to note that the highest $^{87}Sr/^{86}Sr$ isotope value (0.7138) from our Limestone control sample 'Dovedale' was from an alder tree with its roots trailing in the River Dove – which has its headwaters on the gritstone and is therefore likely to be carrying elevated Sr values within its waters.

Using the expected maximum $^{87}Sr/^{86}Sr$ isotope value for the Peak District biosphere (0.7115) as published by Neil et al. (2020), we can observe that 60% (n = 38) of our total sample is over this threshold, and 90% (n = 31) of the plants found growing on the gritstone soils (Fig. 4).

4. Discussion

Our results demonstrate that vegetation on the gritstones has much higher $^{87}Sr/^{86}Sr$ isotope values than are currently mapped for the Peak District. These results are seen across a wide range of distantly related plant taxa, and we have also formally falsified our hypothesis that ericoid mycorrhizae are involved in these unusual Sr isotope values. Indeed our plant samples include – as well as those with ericoid mycorrhizae – ones known to be associated with ectomycorrhizae, and arbuscular mycorrhizae, along with weakly mycorrhizal plants (Grime et al., 2007). The lack of association with any particular plant taxa, or mycorrhizal type, suggests the explanation for the high Sr isotope ratios lies in the sediment chemistry rather than in plant and/or fungal physiological ecology.

An important question is what statistic should be used to describe the

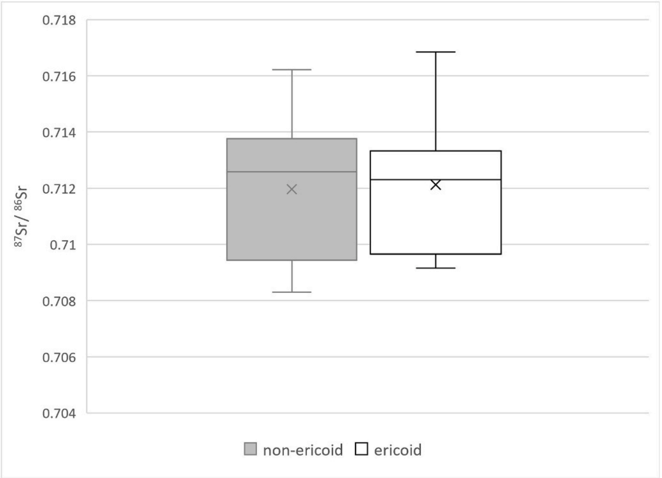

Fig. 3. Plants with ericoid mycorrhizae vs those without ericoid mycorrhizae showing there is very little difference in $^{86}Sr/^{87}Sr$ isotope values between the two, indicating that the presence of mycorrhizae does not affect Sr isotope values in the plants we have analysed.

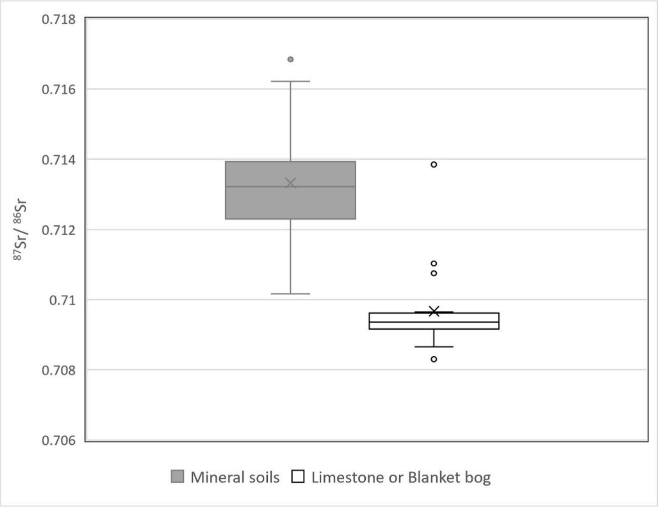

Fig. 4. Plant ^{86}Sr/^{87}Sr isotope values by substrate, showing a clear difference between those plants sampled growing on mineral soils immediately above the gritstone (sites BV and KM), and those plants growing on blanket peat or limestone (sites KP and ID).

modern plant Sr isotope ratios to be used in an archaeological context. An average plant value (mean or median with associated SD or interquartile ranges) is often calculated for a location and that value used to guide expected past ratios (e.g. Johnson et al., 2022; Müldner et al., 2022). However these have been studies where plant samples have not usually been identified to species. Typically a plant community will have a small number of dominant species, and a much longer list of rarer species (Grime, 2001). In such a case averaging will reduce the Sr isotope ratio consumed by herbivores if the dominant plants have high values and the rarer plants lower values. As the question above considers at what values is it safe to assume an individual human (or other animal) came from outside the local area, then the highest values found in (edible) dominant plant species set the upper boundary. A cautious approach is needed while the mechanisms that allow these high values are not fully understood. In an archaeological context it is important to guard against a false positive, inferring movement for someone who has grown up locally, as this will greatly affect subsequent interpretations. Several of the highest values in our study are dominant, or potentially dominant, species which could feed into the food chain (e.g., heather and bilberry).

If the plants on the gritstone mineral soils are able to access minerals with higher ^{87}Sr/^{86}Sr isotope ratios then the encroachment of peat over the Peak during the mid-late Holocene may have changed the biosphere by covering these soils, thus reducing the influence of a geogenic component through time. Broadly the blanket peat starts to expand in the later Mesolithic and Neolithic (Barnatt and Smith, 2004). The data on peat initiation in the area is not extensive ($n = 18$), with most of the associated radiocarbon dates being decades old from the work of John Tallis and others (e.g. Tallis and Switsur, 1973). Each of these dates represents a single point in the landscape, and it is possible for sites quite close together to have differing initiation dates. In addition dating basal peat is a complex process – with the potential for errors of up to two thousand years (Quik et al., 2022), and many of these complexities were not fully understood when most of the peat dates were obtained. However, the limited radiocarbon data available show an increasing amount of peat initiation occurring from 6000 BC (Fig. 5), and although the exact dates may be suspect by modern standards the broad pattern over time should be robust. Climate modelling by Gallego-Sala et al. (2016) suggests that in the Peak District climatic conditions for blanket peat formation became commoner after 6000 years ago. This means that there will have been a slow decline in the amount of mineral gritstone-derived soil available over the last 8000 years. As our data shows plants growing on deep peat – and so acquiring most nutrients from rainwater (Rydin and Jeglum, 2013) – have low Sr isotope ratios, potentially biasing our interpretations if only modern soils and vegetation are considered.

Therefore, we suggest the role of minerogenic soils needs to be considered when examining anomalously high ^{87}Sr/^{86}Sr isotope values in archaeological human and non-human samples from upland areas. This has particular relevance for prehistory when we consider that many of these minerogenic soils now lie under metres of blanket peat. Recent work on ancient woodland has also highlighted the potential for vegetation to change Sr isotope values within soil and indeed that study found ^{87}Sr/^{86}Sr isotope values of 0.7179 and 0.7176 in two oak trees (Johnson et al., 2022). Given that there is a progressive loss of forest, with tree remains underlying some of the peat deposits (Tallis, 1975), it is possible that two potential sources of high human Sr values have been lost between prehistory and the present. For upland areas in particular foodstuffs farmed or gathered or animals grazed on these now buried minerogenic soils may have had higher ^{87}Sr/^{86}Sr isotope values and thus

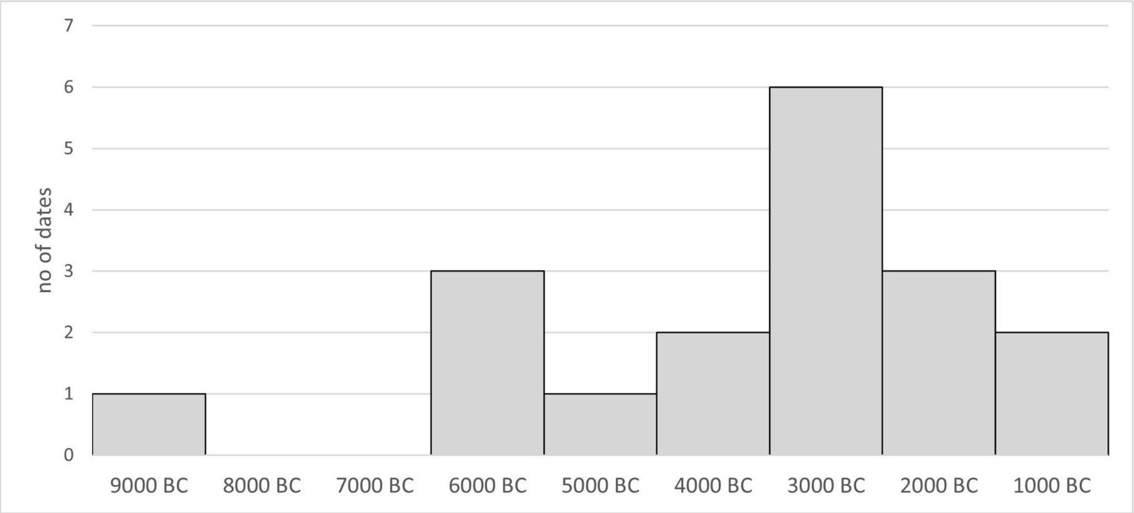

Fig. 5. Radiocarbon dates for peat inception in the Peak District. Data plotted using the mid point of calibrated ranges for peat dates using Oxcal v.4.4. Scale: 2000 = dates between 2000 and 2999 BC, 3000 = dates between 3000–3999BC, etc. Calibrated dates are given in BC for ease of comparison with archaeological sites. Sources of data: Garton (2017), Hicks (1971), Johnson et al. (1990), Tallis and Switsur (1973; 1983), Wilkinson (2021)).

been a source for higher dietary values in humans. We can therefore infer that high Sr isotope values in prehistory, particularly in upland areas, may not be immediately indicative of movement and should be further investigated by a multi-isotope approach.

Note however that the extremely high Sr isotope values seen at Whitwell (Fig. 2; Neil et al., 2020), and in some of the Beaker People from the White Peak (Parker Pearson et al., 2016) have not yet been identified in later populations or in our plant analyses or those of Johnson et al. (2022). Thus, Sr Isotope values over 0.7179 are still unknown locally, suggesting that these individuals do indeed represent long-distance movements. However, an alternative hypothesis is that there have been changes in the availability of Sr isotopes over time, potentially through leaching. For example, the high levels of acid rain in the area over the last couple of centuries may have led to very different conditions to those in prehistory. A second possibility is that soils containing these high values are now buried under extensive peat cover. Until we have a better understanding of the mechanisms underlying the observed high Sr isotope ratios it is difficult to evaluate such ideas.

5. Conclusion

We have demonstrated unexpectedly high Sr isotope ratios in the Peak District, and that plant-mycorrhizal fungi mutualism does not determine Sr isotope values in the plants from the Peak. We have also demonstrated that the taxonomy of the plant does not appear to affect the Sr isotope values, rather it is the substrate on which it is growing. In terms of human movement, it is likely that more archaeological individuals found in the Peak District are indeed local, rather than migrants. Based on our findings we suggest that only those individuals with values above the highest found in the local biosphere can confidently be said to be from elsewhere, while many others fall within a zone that could indicate indigeneity or movement. For example, there are still some individuals from the Beaker project (Montgomery et al., 2019) and from Whitwell bone cairn (Neil et al., 2020) that far exceed our highest value of 0.716 and Johnson et al. (2022) highest value of 0.7179, and may represent genuine migrants. A potential modifier to this conclusion is the possibility that high Sr isotope bearing soils have increasingly been covered by blanket peats in this region (and others of high anomalous Sr isotope values such as Dartmoor) during the Holocene. Relatively little recent research is available for dating this peat inception and spread, but we have shown on the data available that much of the peat begins to form in the Late Neolithic and continues to spread well into the Bronze Age. We postulate that some of these very high values *could* have been found on soils that are now either buried or leached, and that this deserves further study. While our study has focussed on the Peak District in England, our results have implications for any region of the world with minerogenic soils, blanket peat and/or that may have experienced high levels of acid leaching. We strongly suggest the sampling of plants, particularly those that are edible, which have grown directly on the soils that underlie peats to identify the highest likely Sr isotope values within each local biosphere.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2023.105826.

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