

## **Common Ground: Investigating land use and community through strontium isotope analysis of Bronze Age cremations from Dunragit, southwest Scotland**

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### **Abstract**

*While commonly used in the identification of 'non-locals', strontium isotopes ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) can also inform on landscape use by the local community. Here, we report strontium isotope and concentration values for 24 Bronze Age cremations from Dunragit, southwest Scotland, together with measurements on 23 modern plants to refine the available regional isoscape. Aside from one or two marginal outliers that might indicate the presence of non-locals, the results are largely consistent with the regional catchment. Dividing the  $^{87}\text{Sr}/^{86}\text{Sr}$  results by period, however, shows a clear difference between the Early (2200–1700/1600 cal BC) and Middle (1700/1600–1200 cal BC) Bronze Ages, with the latter being slightly but significantly higher on average. There is also a marked shift in the relationship between  $^{87}\text{Sr}/^{86}\text{Sr}$  and elemental Sr concentration values. This suggests a change over time in which parts of the surrounding landscape were emphasised for subsistence, primarily as relates to arable farming given that plants are the main source of strontium. We employ a novel method of spatial assignments at the community level to visualise the shift in landscape use between the two periods.*

## 1. Introduction

Since first introduced in archaeology by Ericson (1985), by far the main use of strontium isotope analysis ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) has been in the study of mobility, often focusing on the identification of a small number of 'outsiders' (e.g., Bentley et al. 2002; 2003; Buzon et al. 2007; Eckardt et al. 2009; Frei et al. 2015; Knudson and Buikstra 2007; Montgomery 2010; Montgomery et al. 2003; Price et al. 1994; 2001; 2004; 2008; 2015; 2019; Slovak et al. 2009; Snoeck et al. 2018; Whelton et al. 2018; Wright 2005). Differences are sought between an individual's childhood  $^{87}\text{Sr}/^{86}\text{Sr}$  value and that expected for their burial location later in life as determined by local baseline environmental samples, or by comparison to a regional strontium 'isoscape'. When they do not match, the individual is seen as being of non-local origin. While this approach has yielded many valuable insights, the focus on mobility and the identification of outsiders has the corollary that the majority of isotopic results in most studies are not discussed any further. At most, they corroborate the expected range for 'locals'. Persistent connections between neighbouring communities are eschewed in favour of the handful of exotic individuals from distant places (cf. Pouncett 2019; 2020).

'Mobility' has also been conceived of more broadly at the community or population level, such that greater variability in  $^{87}\text{Sr}/^{86}\text{Sr}$  results within one group compared to another, or against the expectations of the 'local' baseline, is inferred to reflect higher mobility and use of resources across the wider landscape. This approach is usually applied to either hunter-gatherers or to pastoralists, both of which are anticipated to show higher mobility than farmers (e.g., Barberena et al. 2017; Frei et al. 2019; Giblin et al. 2013; Standen et al. 2018; Tafuri et al. 2006). Even though we are dealing with a well-established mixed farming and herding economy, in this paper we are more closely allied with the second approach, employing strontium isotopes to inform more broadly on human landscape use (cf. Sabaux et al. 2021; Snoeck et al. 2015; Veselka et al. 2021a). Our study differs, however, in that we explore diachronic changes in landscape use, but not necessarily involving greater mobility. Our case study presents strontium isotope results for 24 directly  $^{14}\text{C}$ -dated Early and Middle Bronze Age cremations from two localities near Dunragit, Dumfries and Galloway, southwest Scotland. We also analyse 23 modern plant samples to provide a regional baseline, complementing the currently available strontium isoscape for Britain.

While not downplaying its usefulness, we highlight and accept the contingent nature of spatial modelling.

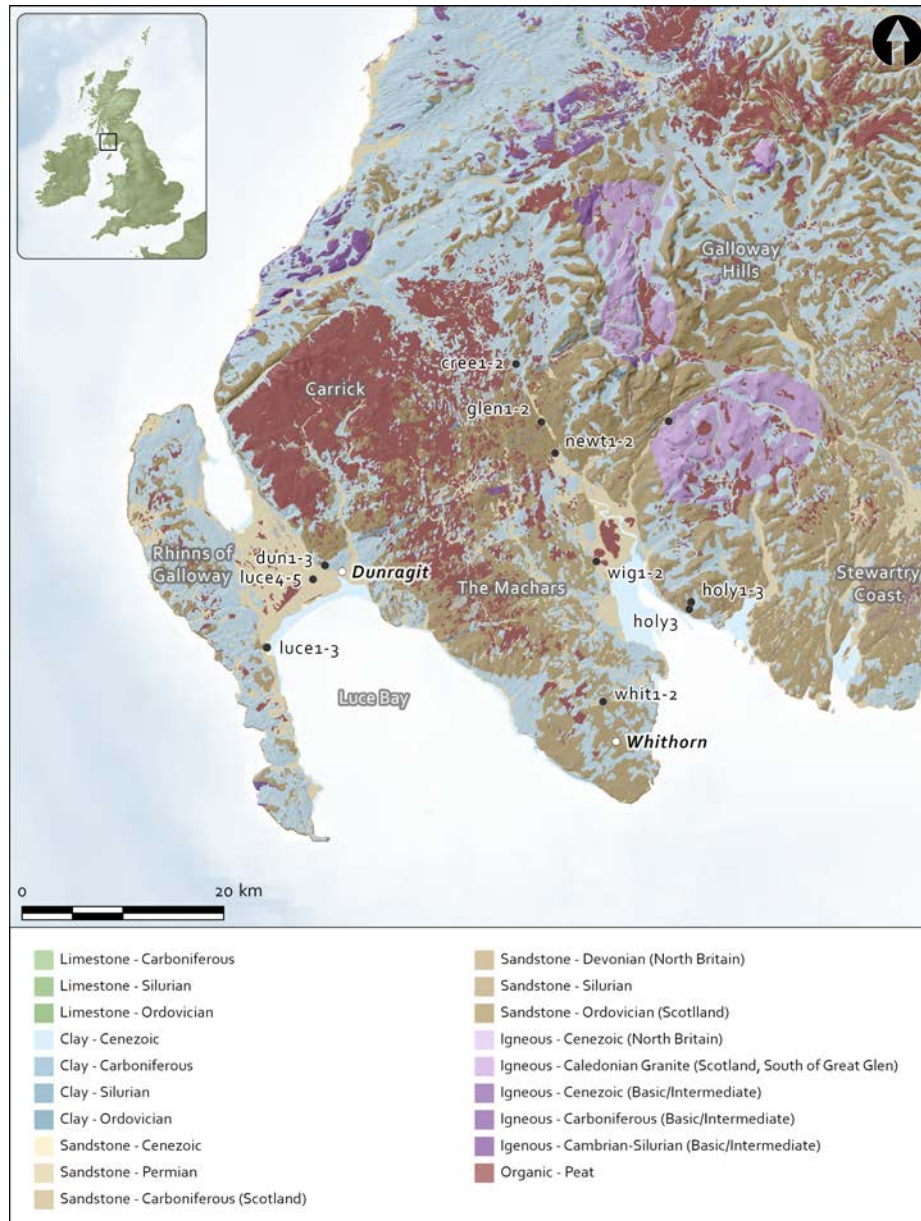
## **2. Excavations at Dunragit Bypass**

Dunragit is located on the Stranraer Isthmus in Dumfries and Galloway, southwest Scotland, in a relatively flat area comprised of well-drained sands and gravels deposited at the end of the last glaciation (Figure 1). The low-lying (ca. 20m OD) isthmus connects the Rhinns of Galloway to the mainland. Its soils provide some of the best arable farmland in western Scotland, being more free-draining than those of the Rhinns to the west and The Machars to the southeast (Cowley 2002, fig. 2). The Machars also have good arable land in pockets with good drainage. The Carrick uplands to the northeast present much poorer agricultural soils and are unlikely to have been utilised other than for rough grazing and hunting and gathering activities. Extensive hillside blanket peat accumulations begin only ca. 5 km north of Dunragit and were likely present well before the Bronze Age (Tipping 2021, illus 1.2).

Dunragit is situated near the boundaries of three major geological formations. It is on the western edge of the Portpatrick and Glenwhargen Formations of wacke sandstone dating to the Ordovician (British Geological Survey 1977; 2001; Greig and Pringle 2014). Less than 1 km to the east is the Stewartry Group, a mix of sandstone, breccia and conglomerate dating to the Early Permian. Within less than 5 km to both the southeast and southwest is the Gala Group Queensberry Grits/Strangford Group comprised of wacke sandstone, siltstone and mudstone dating to the Silurian. Overlying the bedrock are surficial deposits that constitute the parent material of the region's soils, often primarily through bedrock weathering, but also with additional inputs (e.g., glacial deposition, aeolian sediments, alluvium and colluvium) (Figure 1).

Excavations at Dunragit were undertaken in 2012/13 prior to the construction of a bypass (Bailie 2021). Two concentrations of pits containing cremated remains were recorded: a smaller group at Drumflower, and a larger group of 20 cremation deposits at Boreland Cottage Upper some 3km to the east. Of these, 12 were located southwest of a small ring-ditch, with another eight scattered across the site (Figure 2). Two cremation deposits were found in the centres of two of three ring-ditches, representing either levelled barrows or

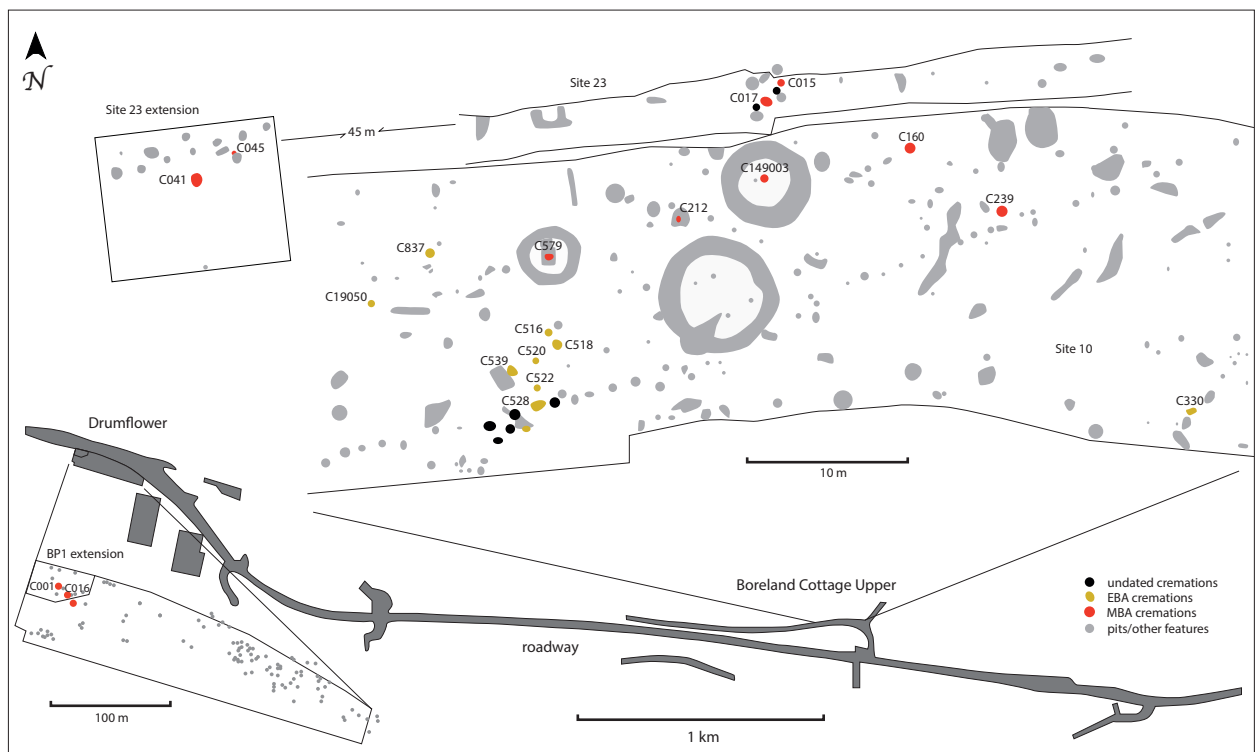
fenced enclosures (Arabaolaza 2021, 334) (Figure 3). This concentration of cremations has no parallels locally, though the archaeological visibility of such sites is low. Further details concerning the excavation and the archaeological context of the cremations and other finds can be found in the site monograph (Baillie 2021).



**Fig. 1.** Western Dumfries & Galloway, southwest Scotland, showing locations of Dunragit and plant samples on soil parent material. Contains British Geological Survey materials © UKRI 2011.

Radiocarbon dates were previously obtained directly on calcined bone for 24 cremation deposits (Hamilton 2021; a small number of additional cremation deposits dated by

associated charcoal do not feature here). The results are evenly divided into the Early Bronze Age (2200–1700/1600 cal BC) and the Middle Bronze Age (1700/1600–1200 cal BC). The EBA features were generally small, unurned ‘token’ deposits made in pits and possibly re-used postholes. As far as could be determined, each represented only a single adult individual, though one pit (528) held two distinct cremation deposits (Kilpatrick 2021). The MBA cremation deposits were both urned and unurned (Figure 4), with a number of examples of multiple individuals (two adults and a subadult, an adult and two subadults, and an adult and subadult).



**Fig. 2.** Plan of Dunragit showing locations of cremations analysed in this study (numbered) (after Bailie 2021, Illus 2.19a, 2.107, 2.127).



**Fig. 3.** Ring ditch containing central cremation deposit, with other pits containing cremated remains visible in the background (after Bailie 2021, Illus. 2.119)



**Fig. 4.** Urn (C041) containing cremated remains dated to the Middle Bronze Age (after Bailie 2021, Illus. 2.131)

### **3. Strontium isotopes in the biosphere**

#### *3.1 Background*

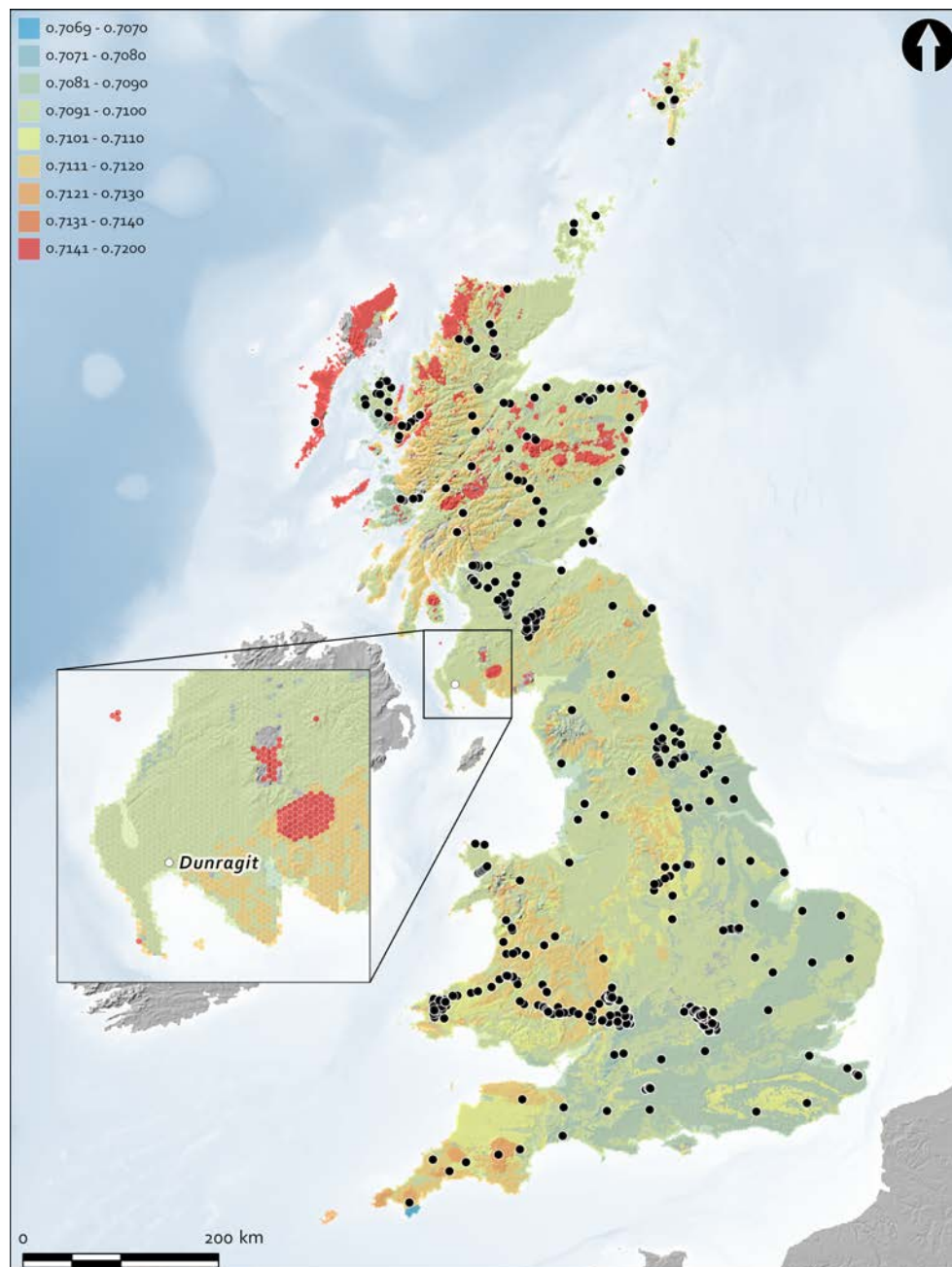
The ratio of two isotopes of strontium,  $^{87}\text{Sr}$  and  $^{86}\text{Sr}$ , vary across geological formations, resulting from the initial amount of the precursor of radiogenic  $^{87}\text{Sr}$  (rubidium,  $^{87}\text{Rb}$ ) in bedrock and the passage of geological time, such that older formations become progressively enriched in  $^{87}\text{Sr}$  (Faure 1986). Strontium is incidentally taken up in lieu of calcium and becomes incorporated into human tissues, mainly bones and teeth as these are the body's repositories for calcium. Their measurement provides information regarding an individual's origins and mobility (Bentley 2006; Montgomery 2010). Plants are the main

source of strontium, since meat and milk contain far lower elemental concentrations as a result of biopurification (Sillen and Kavanagh 1982). The usefulness of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios depends on the presence of sufficient geological (and hence isotopic) variability at a scale relevant to the population under consideration. There are also issues of equifinality, often requiring the use of additional sources of information or arguments (e.g., spatial proximity may be argued to rule out more distant locations with similar  $^{87}\text{Sr}/^{86}\text{Sr}$  values) to suggest particular directions of movement (cf. Pouncett 2020; Snoeck et al. 2018). Thus, it is often easier to determine that an individual was not local (i.e., if their  $^{87}\text{Sr}/^{86}\text{Sr}$  value does not match that of their find location) rather than to specify where they were from.

The preferred tissue for  $^{87}\text{Sr}/^{86}\text{Sr}$  analysis in archaeological contexts is tooth enamel, since it is much more resistant to diagenesis than bone (Hoppe et al. 2003). Conversely, strontium from the burial environment can either partially or completely override the endogenous signal in bone, tending to make individuals look 'local' regardless of whether or not this was actually the case (Budd et al. 2000; Hoppe et al. 2003). Thus, measurements on unburnt bone or tooth dentine are sometimes used to characterise the local  $^{87}\text{Sr}/^{86}\text{Sr}$  value (Montgomery 2010). This situation changes with cremated remains, which typically lack enamel as it spalls off during burning. Experiments have shown that the process of cremation preserves the *in vivo*  $^{87}\text{Sr}/^{86}\text{Sr}$  signal, as bone and structurally similar tooth dentine once fully calcined become highly crystalline and therefore equally or more resistant to diagenesis than enamel (Snoeck et al. 2015; cf. Harvig et al. 2014). Following the demonstration of the method's reliability, a number of Neolithic and Bronze Age cremated remains have been analysed in Britain and Ireland (Snoeck et al. 2016; 2018; 2020). A major difference in analysing cremated bone compared to tooth enamel is that the latter reflects the time of crown formation, while measurements made on adult bone reflect the average intake of strontium over the decade or so prior to death. While this makes the analysis of cremated bone less useful for investigating childhood origins (though this is still possible where tooth roots and/or the petrous bone are available, e.g., Veselka et al. 2021b), it does offer the potential to investigate medium-term (decadal) landscape use during the later life of the individual.

### 3.2 British strontium isoscapes

Evans et al. (2010, Fig. 1b) provided the first comprehensive strontium isoscape for Britain with predicted  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges for bedrock using a combination of different samples types (plants, shell, soil, water, dentine). This has recently been updated with additional samples and a shift to preferentially using plant values where available given problems in the interpretation of other materials (cf. Holt et al. 2021), though retaining the use of bedrock geology for spatial mapping (Snoeck et al. 2018, Fig. 2). An alternative approach recently adopted by the British Geological Survey is to use soil parent material instead of bedrock (Evans et al. 2018). This is because, while there is a strong relationship between the two, they may diverge, and parent material is more relevant to biologically available strontium. Bedrock is often used simply because bedrock geology maps are usually more accessible. Whichever isoscape is used, as no baseline environmental samples were previously available from southwest Scotland (Figure 5), these ranges are extrapolated from samples obtained elsewhere on comparable geological formations. Also relevant for the present study is Dunragit's proximity to the coast, only about 2 km from Luce Bay. Modern ocean water has a very consistent  $^{87}\text{Sr}/^{86}\text{Sr}$  value of 0.7092 (Hoddell et al. 1990), that can be imparted to humans either through the direct consumption of marine foods or, more likely in the Bronze Age, through the transference of oceanic strontium to the land via the sea-spray effect (Alonzi et al. 2020; Evans et al. 2012; Snoeck 2014; Snoeck et al. 2016; Whipkey et al. 2000), and hence to coastal pastures and/or arable fields, the latter being a more important source of strontium given the aforementioned process of biopurification.



**Fig. 5.** Strontium isoscape for Britain extrapolated from parent material (Evans et al. 2018), with inset showing location of Dunragit. Black symbols show locations of samples on which the isoscape is based, filtered to show only modern plants used preferentially to construct our baseline for southwest Scotland and highlight the absence of previous samples from the region addressed in our study. Contains British Geological Survey materials © UKRI 2018.

## 4. Materials and Methods

### 4.1 Materials

Twenty-four cremated bone fragments were analysed for  $^{87}\text{Sr}/^{86}\text{Sr}$  from the Dunragit excavations. All but one of these made use of the same bone fragment used for radiocarbon dating, providing robust chronological control. In the case of the single exception (C240), different bone samples from the same cremation of a single adult individual were subjected to dating and to isotopic analyses. Based on osteological analysis, most of the contexts represent single cremations, though at least two individuals – adult and non-adult – were identified in four cases (Kilpatrick 2021). Only adult remains were sampled, and the bone was fully calcined in all cases.

The current strontium isoscape for Britain lacks any datapoints from southwest Scotland (Evans et al. 2010, Fig. 1a; Snoeck et al. 2018). To address this, 23 modern plant samples were collected in 2019 following the sampling procedure described in Snoeck et al. (2020), comprising 13 grass specimens, nine trees and one gorse bush. Sampling locations were recorded using a hand-held Garmin GPSMAP 62. Plants were targeted as by definition they provide data informing directly on bioavailable strontium, avoiding problems inherent in measuring soil leachates and water, the latter having additional issues in terms of characterising points on the landscape (Ryan et al. 2018).

## 4.2 Methods

### 4.2.1 Strontium isotope analysis

Cremated bone samples were pretreated with 1M acetic acid for 10 min in an ultrasonic bath, followed by three rinses with milliQ water and 10 min ultrasonication. After pre-treatments, the samples were dried overnight at 50°C before being crushed using a mortar and pestle. Approximately 15mg of bone was then taken for acid digestion. For the cremated bone samples, the entire acid digestion process and subsequent Sr purification were undertaken under a class 100 laminar flow hood in a class 1000 clean room (Université Libre de Bruxelles, Belgium, ULB). Samples were then digested in sub-boiled concentrated  $\text{HNO}_3$  at 120°C for 24 h, before purification of the Sr analyte through a chromatographic technique using ion-exchange resins (see Snoeck et al. 2015). The isotope ratios of the purified cremated bone strontium samples were then measured on a Nu Plasma MC-ICP mass spectrometer at ULB (Nu015 from Nu instruments, Wrexham, UK).

For plant samples, 0.25g of material was first microwave-digested in 4mL 14M HNO<sub>3</sub> and 0.5mL HF in a Milestone UltraWAVE, 0.5mL of H<sub>2</sub>O<sub>2</sub> were added, and evaporated to dryness. Strontium was extracted through column chemistry using ion exchange resin (Sr-Spec, Triskem). In short, the columns and resin were rinsed 2 x 2M HNO<sub>3</sub> then 2 x 7M HNO<sub>3</sub>, samples loaded in 7M HNO<sub>3</sub>, charged 4 x 1mL 7MHNO<sub>3</sub>, rinsed using 5 x 1mL 7MHNO<sub>3</sub> and Sr was collected with 6 x 1mL 0.05M HNO<sub>3</sub> and evaporated again to dryness. Measurement of plant <sup>87</sup>Sr/<sup>86</sup>Sr was carried out on a Nu Plasma 3 MC-ICP-MS (PD017 from Nu Instruments, Wrexham, UK) at VUB.

Repeated measurements of the NBS987 standard solution yielded a mean <sup>87</sup>Sr/<sup>86</sup>Sr value of 0.710214 ± 40 (±2SD for 15 analyses at ULB) and 0.710244 ± 18 (±2SD for five analyses at VUB) which is comparable with the mean of 0.710252 ± 13 (n = 88) obtained using TIMS (Thermal Ionization Mass Spectrometry) (Weis et al. 2006). All the data were corrected for mass fractionation by internal normalization to <sup>86</sup>Sr/<sup>88</sup>Sr = 0.1194. The raw data were normalized using a standard-sample bracketing method with the recommended value of <sup>87</sup>Sr/<sup>86</sup>Sr = 0.710248 (Weis et al. 2006). For each sample the <sup>87</sup>Sr/<sup>86</sup>Sr value is reported with a ±2SE error (absolute error value of the individual sample analysis – internal error). When comparing individual measurements, meaningful differences are seen at the fourth decimal.

#### *4.2.2 Strontium concentration analysis*

For the measurement of strontium concentrations ([Sr]) the sample digests (see above) were diluted with 3% HNO<sub>3</sub>, before being analysed by a Thermo Scientific Element 2 sector field ICP mass spectrometer in low (<sup>88</sup>Sr) and medium (<sup>44</sup>Ca) resolution mode using indium as an internal standard and external calibration vs. various reference materials (SRM1400, CCB01) at the Vrije Universiteit Brussel (VUB), Belgium. The actual [Sr] values were then calculated by normalizing the calcium data ([Ca]) to 40wt%. Accuracy was determined by the analysis of two internal bioapatite standards (ENF and CBA). Based on repeated digestion and measurements of these reference materials, the analytical precision of the applied procedure is estimated to be better than 5% RSD (1SD, n = 33 for CBA and n = 5 for ENF).

#### *4.2.3 Spatial analysis*

An isoscape characterising spatial variation in  $^{87}\text{Sr}/^{86}\text{Sr}$  values was generated for southwest Scotland using multi-level spatial aggregation, following Pouncett (2020).  $^{87}\text{Sr}/^{86}\text{Sr}$  plant values from the current study were combined with previously published (Evans et al, 2018; Snoeck et al. 2018; Schulting et al. 2019) and unpublished plant values (Schulting et al. n.d.). Values were aggregated by polygons from the British Geological Survey 1:50,000 Soil Parent Material Model, grouped by surface geology and domains based on minimum era and dominant mineralogy and geographic region (after Evans et al. 2018). Descriptive statistics were calculated for each polygon, with statistics for polygons that have not been directly sampled estimated from values for plants from comparable soil parent material. The median and median absolute deviation (MAD) provide estimates of the expected values and variability of bioavailable strontium within the study area.

Geographic assignments for the two groups of cremations were subsequently calculated using Bayes' theorem (cf. Bowen et al. 2014; Pouncett 2020; Wunder et al. 2005). The isoscape for southwest Scotland was converted to a raster dataset with a cell size of 100m and a focal function was used to calculate the median of the expected  $^{87}\text{Sr}/^{86}\text{Sr}$  values for all of the soils within 5km of each cell, assuming that this distance is most likely to capture the most intensively used arable fields by Bronze Age communities (cf. Chisholm 1968). Probability densities reflecting the likelihood that each group of cremations came from a given location were calculated from the resultant raster dataset using a uniform distribution as the prior probability distribution and a normal distribution as the sampling probability distribution. The scale and location of the normal distribution used as the sampling probability distribution for each group of cremations were estimated using the median of the  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the group and the sum of the MAD of the  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the group and the MAD for the isoscape. The posterior probability distributions were rescaled by the largest observed density, with the resultant probability densities ranging between 0 and 1. Thus, rather than assign potential areas of landscape meeting the  $^{87}\text{Sr}/^{86}\text{Sr}$  requirements to each individual (cf. Snoeck et al. 2018), we use the median ( $\pm$  MAD) values for the combined EBA and MBA individuals to investigate any changing patterns in landscape use at the population or community level.

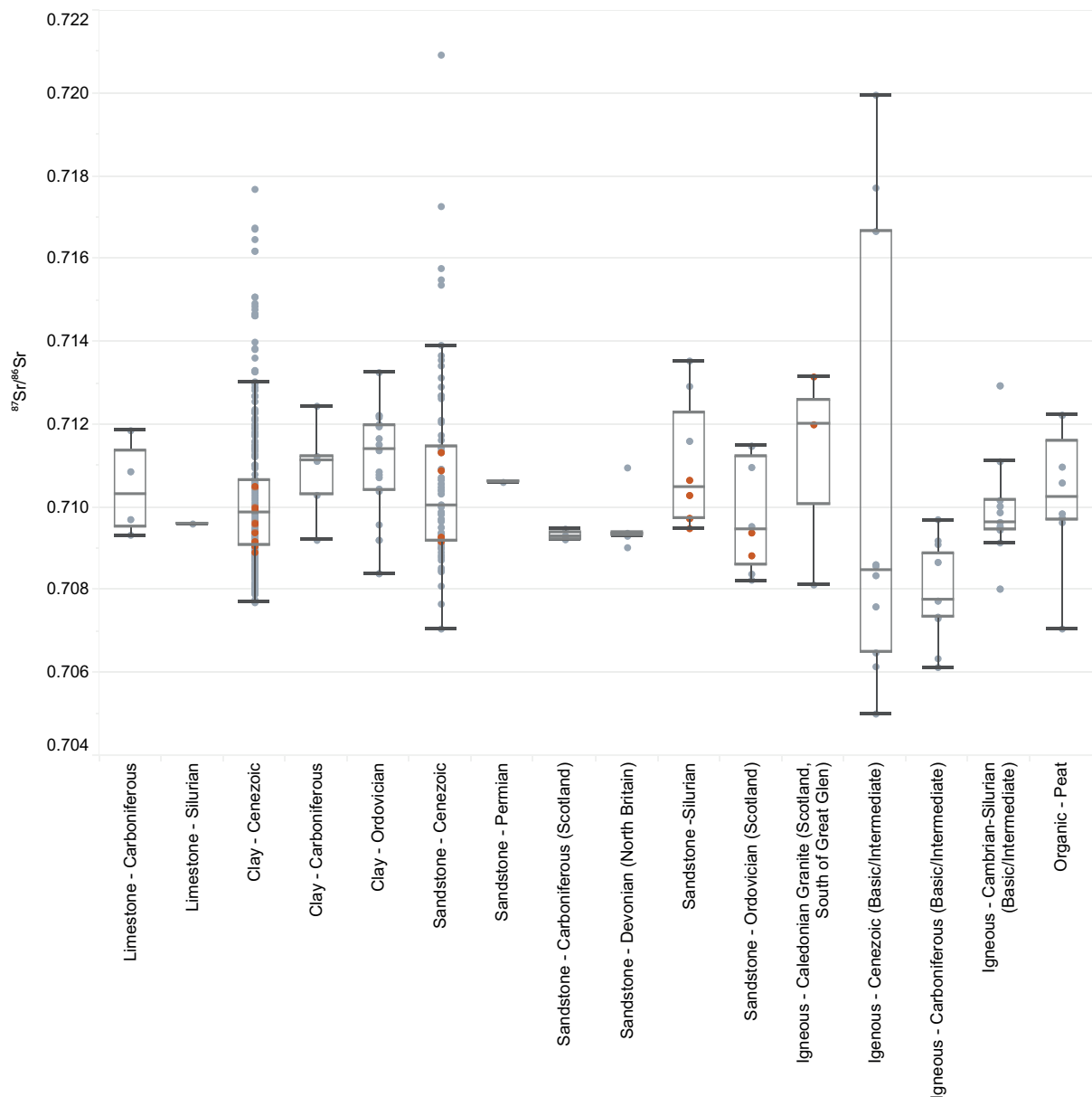
## 5. Results

### 5.1 Plant strontium results

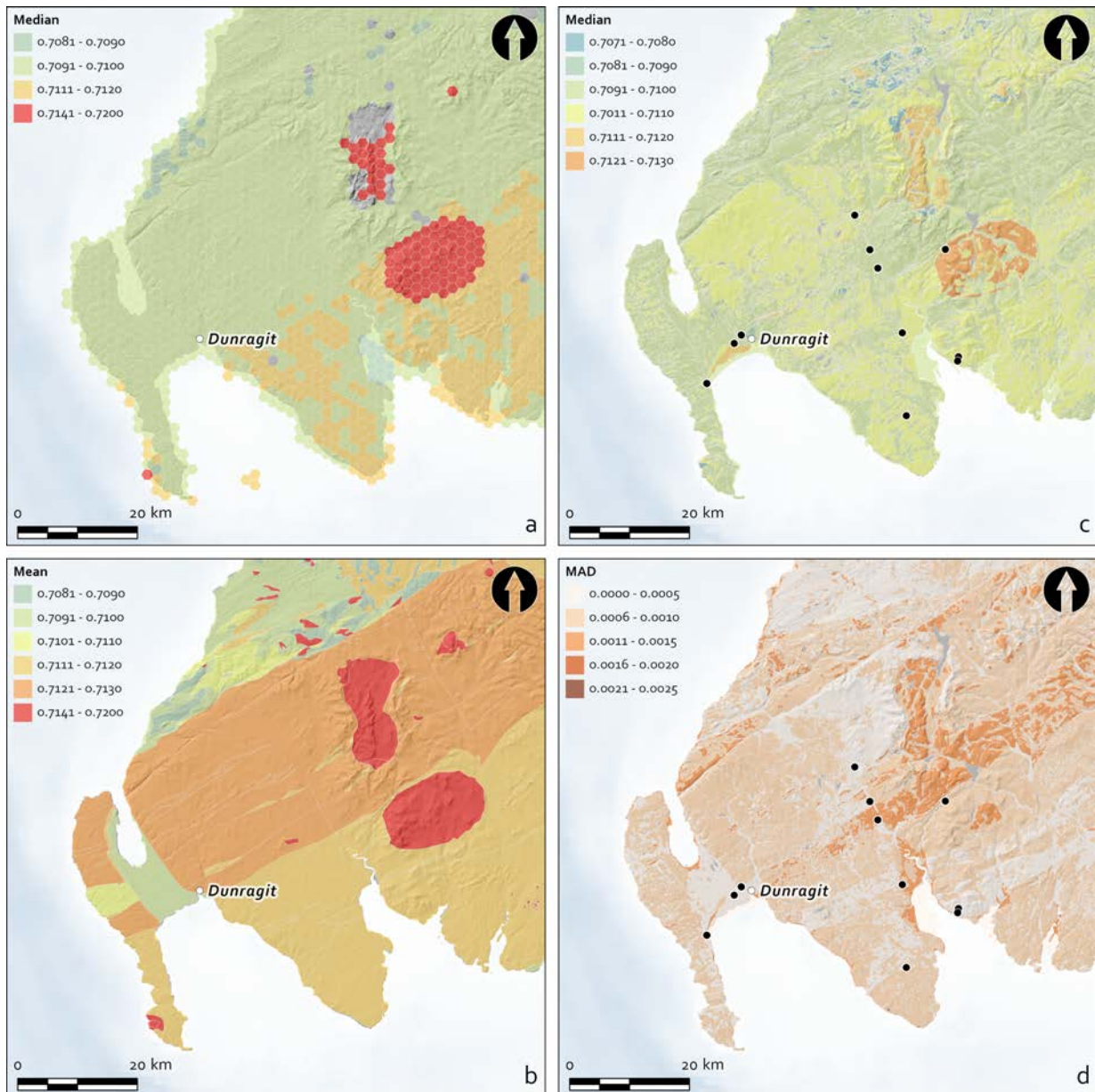
The 23 plant samples provide a mean  $^{87}\text{Sr}/^{86}\text{Sr}$  of  $0.70991 \pm 0.00109$  (Table 1). The data are not normally distributed (Shapiro-Wilk test,  $p = 0.001$ ), being skewed towards a small number of more radiogenic values. Due to the degree of disturbance related to the road construction that led to the excavations, it was not possible to sample plants directly from the sites. The 'local' signal is therefore represented by three samples (dun1-3) on the same bedrock geology (Ordovician wacke sandstone) from ca. 1.5km to the northwest yielding a mean of  $0.70902 \pm 0.00011$  ( $n = 3$ ). The three samples closest to the coast at Luce Bay (luce1-3) show values nearer that of ca. 0.7092 expected for the modern ocean, averaging  $0.70913 \pm 0.00006$  ( $n = 3$ ), suggesting some influence from sea-spray. That this effect is restricted to a narrow coastal strip is suggested by two samples from Torrs Warren (luce4, 5), just over 2km inland from the coast (at high tide) in a forest backing the Luce Sands, showing higher values of  $0.71110 \pm 0.00030$  ( $n = 2$ ); these, incidentally, are among the four most radiogenic samples in the study, contributing to the right skew noted above. Another plant sample (holy3) taken only 0.5km from the Wigtown Bay to the east has a value of 0.71050, higher than that of two other samples (holy1, 2) taken further inland on the same transect, averaging  $0.70955 \pm 0.00047$  ( $n = 2$ ); as these are on the same geology, any impact from marine-derived strontium should result in the sample nearest the coast having the lowest value rather than the highest. From this we infer that, despite the position of the Scottish west coast facing the prevailing winds, the sea-spray effect is very limited here, as was also found on the west coast of Ireland (Snoeck 2014; Snoeck et al. 2020; though see Alonzi et al. 2020).

The choice of isoscape greatly influences the goodness of fit of the new data. Both the absolute values of our plant samples and their distribution on the landscape differs substantially from the bedrock isoscape (Evans et al. 2010; Snoeck et al. 2018), in which isotope 'packages' of 0.711–0.712 and 0.712–0.713 dominate southwest Scotland. There is, however, a closer fit with the more recent isoscape based on soil parent material (Evans et al. 2018), in which the predominant packages are shifted down to 0.7091–0.7100 and 0.7110–0.7120, with a notable absence of any modelled values in the intervening range 0.7011–0.7110. The addition of our new plant values shifts constrains the upper range of The Machars and Carrick to 0.7091–0.7100 and 0.7011–0.7110, respectively. Furthermore, rather than confirming the north-south separation seen in both the bedrock and soil parent material isoscapes, these two isotope packages are much more dispersed across the

landscape (Figure 7). While more radiogenic than the other packages, the modelled values for a Devonian granite upland to the east are also reduced substantially in the new isoscape, from 0.7141–0.7200 to 0.7121–0.7130. This demonstrates, as many studies have, the central importance of revisiting baselines in the construction of spatial models (cf. Schulting et al. 2018).



**Fig. 6.**  $^{87}\text{Sr}/^{86}\text{Sr}$  values for modern plant samples from this study (red) and available values for relevant domains (parent material) elsewhere in Britain (data from Evans et al. 2018; Schulting et al. n.d.)



**Fig. 7.** Isoscapes for southwest Scotland, based on: a) currently available plant  $^{87}\text{Sr}/^{86}\text{Sr}$  median values on parent material (Evans et al. 2018); b) previously available plant  $^{87}\text{Sr}/^{86}\text{Sr}$  mean values on bedrock (after Evans et al. 2010; Snoeck et al. 2018); c) revised plant  $^{87}\text{Sr}/^{86}\text{Sr}$  median values on parent material; d) the error ranges (mean absolute deviation) for the isotope packages in (c). Contains British Geological Survey materials © UKRI 2011 and 2018.

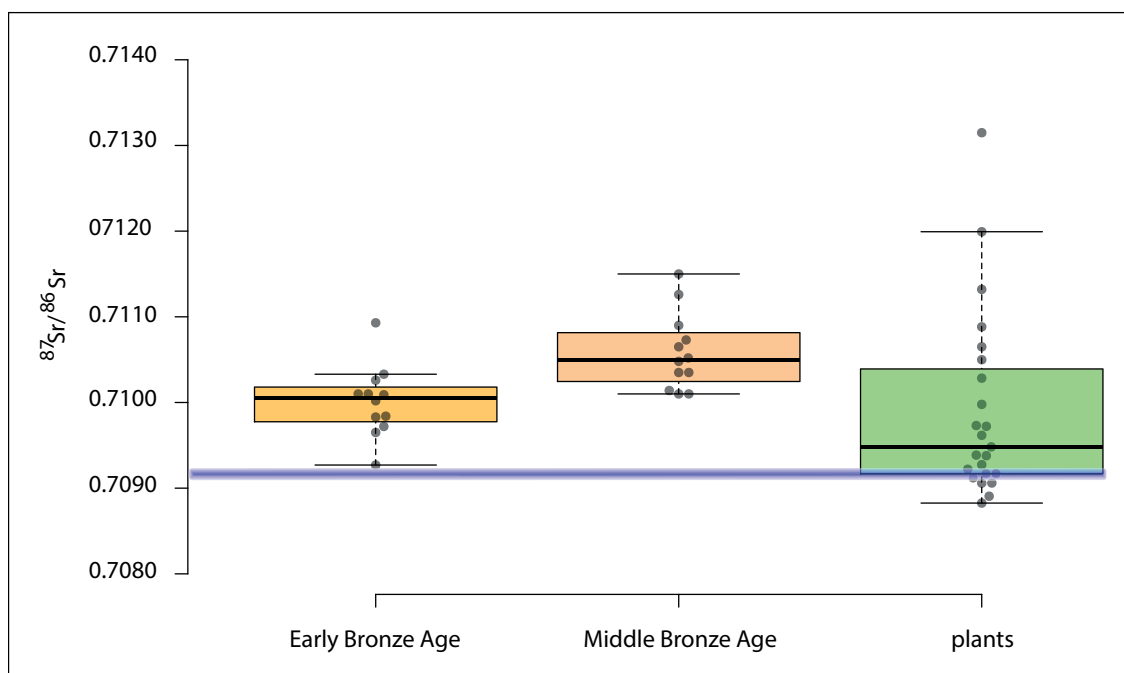
## 5.2 Human strontium results

The human  $^{87}\text{Sr}/^{86}\text{Sr}$  results have a mean of  $0.7103 \pm 0.0005$ , ranging from 0.7093 to 0.7115 (Tables 2 and 3). One sample (C527) was analysed in duplicate with good agreement (0.70964, 0.70965). The data are normally distributed (Shapiro-Wilk test,  $p =$

0.709), though with one mild outlier (0.71150 from C041) lying just over 1.5 times the interquartile range (IQR).

Group	N	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 1\text{ SD}$	median	MAD	Min	Max	[Sr]	$\pm 1\text{ SD}$
plants	23	0.70991	0.00109	0.70948	0.00042	0.70883	0.71315		
humans	24	0.71029	0.00051	0.71020	0.00030	0.70927	0.71150	97	24
EBA	12	0.71001	0.00041	0.71006	0.00022	0.70927	0.71093	100	27
MBA	12	0.71060	0.00045	0.71050	0.00030	0.71010	0.71150	93	22

**Table 3.** Summary  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr concentration [Sr] statistics for Dunragit.



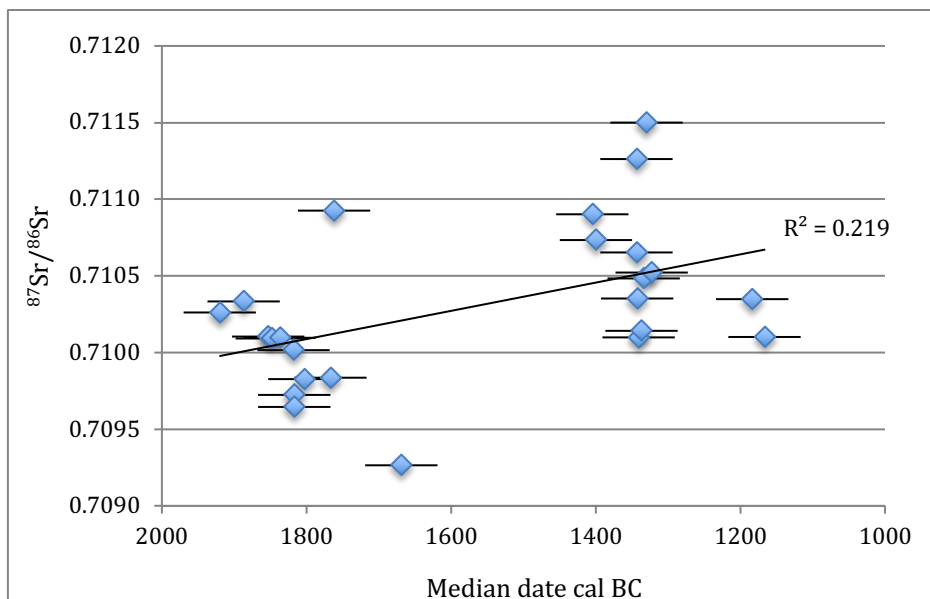
**Fig. 8.** Boxplots showing  $^{87}\text{Sr}/^{86}\text{Sr}$  results from Dunragit by period. The horizontal line marks the modern ocean value of ca. 0.7092.

As noted above, the radiocarbon dates indicate the presence of two distinct phases, one in the Early Bronze Age (ca. 1900–1700 BC) and another in the Middle Bronze Age (ca. 1400–1200 BC) based on unmodelled median calibrated dates (Table 2). Separating the  $^{87}\text{Sr}/^{86}\text{Sr}$  results into these two periods shows lower mean values in the Early Bronze Age ( $0.7100 \pm 0.0004$ ) than in the Middle Bronze Age ( $0.7106 \pm 0.0005$ ) (Table 3; Figure 8). Neither subset departs significantly from a normal distribution. A single mild outlier is identified in the EBA group (0.71093 from C837), though the outlier highlighted above for the overall dataset is no longer considered as such within its MBA group. While there is some overlap

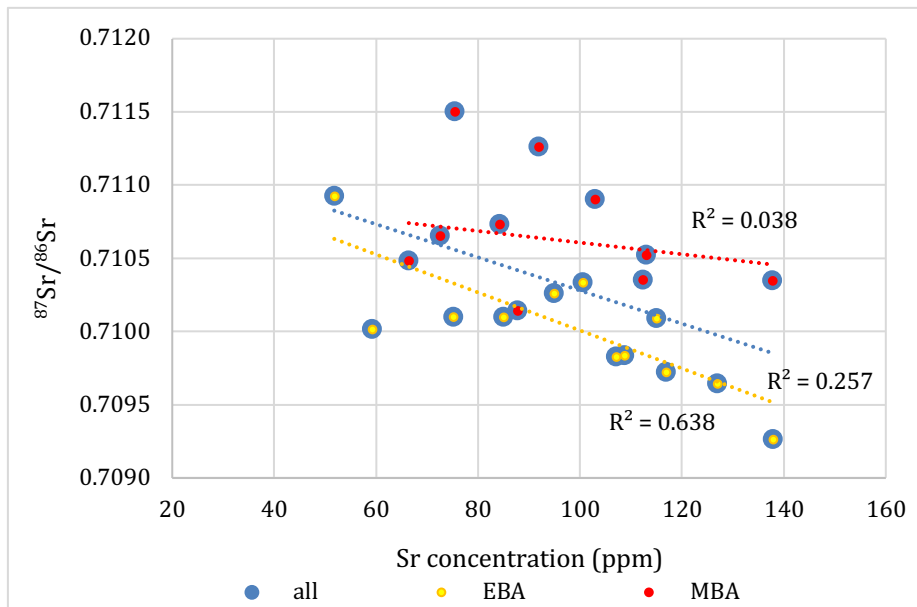
in the results, the difference between  $^{87}\text{Sr}/^{86}\text{Sr}$  means for the EBA and MBA is statistically significant (Student's  $t$ -test,  $t = 3.207$ ,  $p = 0.003$ , d.f. = 22), supported by a large effect size (Cohen's  $d = 1.35$ ). Despite this, there is no evidence for a bimodal distribution in the data, and the difference between the periods would have gone completely unnoticed had the cremations used in the analysis not all been directly radiocarbon dated. There is no indication of any trend within each period (Figure 9).

Another difference between the EBA and the MBA involves the relationship between  $^{87}\text{Sr}/^{86}\text{Sr}$  values and elemental strontium concentrations (Figure 10). For the EBA, there is a clear negative correlation between the two ( $r^2 = 0.638$ ,  $p = 0.003$ , d.f. = 10) that is not seen in the MBA ( $r^2 = 0.038$ ,  $p = 0.564$ , d.f. = 10). In the absence of strontium concentration data for the plants (assumed to make by far the largest contribution to strontium intake) in the study area, interpretation of this trend is difficult. We revisit this below.

Finally, while the EBA values do not differ significantly from the plants as a whole (Mann-Whitney U-test,  $Z = 1.477$ ,  $p = 0.140$ ), the MBA values are on average slightly but significantly more radiogenic by ca. 0.0010 ( $Z = 2.625$ ,  $p = 0.008$ ).



**Fig. 9.** Bivariate plot showing unmodelled median date cal BC with approximate  $\pm 1$  sigma error bars and  $^{87}\text{Sr}/^{86}\text{Sr}$  values for 24 cremations at Dunragit.



**Fig. 10.** Bivariate plot of human <sup>87</sup>Sr/<sup>86</sup>Sr and Sr concentration values for Dunragit.

## 6. Discussion

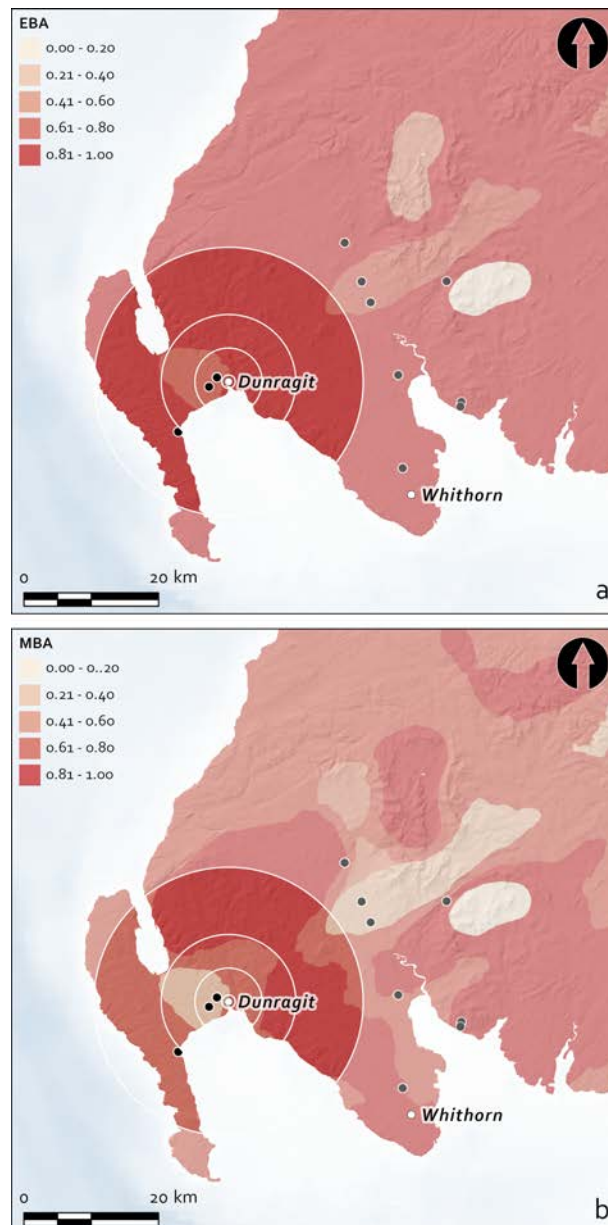
The first point to note is that the new plant <sup>87</sup>Sr/<sup>86</sup>Sr values obtained as part of this study have modified the modelled isotope packages for southwest Scotland, with implications for adjacent regions with comparable geologies to the north and the east (see Figure 5). This is emphatically not a criticism of the existing isoscapes for Britain, which are among the most comprehensive in the world and were groundbreaking when first created (Evans et al. 2010). Moreover, the need to fill gaps in the available data was explicitly acknowledged by these authors (Evans et al. 2010, 3). Spatial modelling of isotopic data, especially at a large scale, needs to be continually revised and updated (e.g., compare the isoscapes for Northern Ireland produced in Snoeck et al. 2016, Fig. 4 and Snoeck et al. 2020, Fig. 5). This also makes most discussions (i.e., apart from those focusing on very homogeneous and isotopically distinct geologies) contingent and subject to future revision as more data become available. While this may seem an obvious point, it is worth repeating.

With the updated baseline data, then, many of the human <sup>87</sup>Sr/<sup>86</sup>Sr values obtained for Dunragit (ranging 0.7093 to 0.7115) are now more in keeping with the immediate vicinity of the site than previously assumed (Schulting and Snoeck 2021). The most important result is the unexpected clear shift in average <sup>87</sup>Sr/<sup>86</sup>Sr results between the Early and Middle Bronze Age cremations. There is no indication of any gradual trend within each period (Figure 9); rather, the difference is seen between the two periods as a whole,

although the intervening gap of one to two centuries in the directly dated cremations leaves open the question of how this transitional period should be characterised. Any sudden migration of individuals in the MBA can be immediately discounted, as the results on calcined bone represent an average of a decade or more of an individual's life, so that anyone moving into the region would, through the consumption of local foods, come to reflect the local  $^{87}\text{Sr}/^{86}\text{Sr}$  range before their death. Moreover, the dates span some two centuries, and are consistent throughout this period. While the correlation between  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr concentration values could be interpreted as offering tentative support for consumption of marine foods, this is seen as unlikely given the paucity of evidence – archaeological (material culture), zooarchaeological and stable isotopic (carbon and nitrogen) – across Britain as a whole for the use of this resource during the Neolithic and Bronze Age (Parker Pearson et al. 2019; Schulting 2013; Schulting and Borić 2007; Schulting and Richards 2002). It also seems highly improbable that substantial quantities of staple crops would be imported from outside the region during the Bronze Age. This leaves two possible explanations, one involving a change in the landscape itself, and the other a change in how the surrounding landscape was used.

The first of these alternatives is that the bioavailable  $^{87}\text{Sr}/^{86}\text{Sr}$  signal of the landscape itself changed between the two periods. The west coast of Scotland is geologically stable, so that any major tectonic activity (e.g., volcanism) can be ruled out, nor is there any evidence for such activity in the geomorphological record. This leaves the potential impact of a decrease in the impact of marine-derived  $^{87}\text{Sr}/^{86}\text{Sr}$  between the EBA and MBA (as the EBA mean is closer to the ocean value of 0.7092). While sea-level change should not be a significant factor in the third millennium BC, given the site's proximity to the coast, and the fact that the Isthmus presents the best arable land locally, any heightened storminess during the Early Bronze Age could have resulted in a stronger impact of sea-spray, as suggested by Tipping et al. (2021, 304-5). The available data on dune formation (as a proxy for storminess) are far too patchy to permit an assessment of this possibility. However, given the prevailing strong western winds on the west coast of Britain and the proximity of much of the region's best arable land to the sea, it seems unlikely that a moderate increase in storminess (assuming that that a strong increase would be more visible in the geomorphological record) would have a marked effect on bioavailable strontium. This is supported by our results on modern plants, which do not show a clear sea-spray effect

extending inland for any great distance. Given the adverse effects on crop yields of high salinity, it is also perhaps less likely that crops would be planted very near the coast under conditions of increased storminess.



**Fig. 11.** Geographic assignments calculated using Bayes' theorem, using a non-informative prior and a normal distribution as the sampling probability distribution. The parameters of the normal distribution are estimated using the median and MAD of the  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the EBA (a) and MBA (b) cremations and the MAD for the isoscape of southwest Scotland. The circles show BASr catchments with 5, 10, and 20 km radii from the site.

The second possible explanation – the one we favour here – would see a changing pattern in how the surrounding landscape was used for subsistence between the two periods, with the Middle Bronze Age communities represented by the cremations making greater use of the more radiogenic formations east of the site on the western part of The Machars, the peninsula to the south on which the medieval monastery of Whithorn Priory is situated<sup>1</sup>. This is illustrated in Figure 11, which assigns probability bands to the surrounding landscape in relation to the median ( $\pm$  MAD)  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the EBA and MBA. There is a subtle but visible shift between the two periods, with the EBA looking more ‘local’ while for the MBA there is a strong probability that the focus of arable farming shifted to the east of Dunragit. While The Machars and the Carricks currently cannot be distinguished isotopically, the early onset of peat formation (Tipping 2021) makes utilisation of the Carricks for arable cultivation unlikely. This has the corollary that the MBA cemetery is situated on the western edge of a territory that is primarily focused to the southeast, perhaps to demarcate the boundary of that territory, though this is admittedly speculative. Nevertheless, following the idea through, this shift could perhaps be related to increased local population density in the Middle Bronze Age curtailing access to the landscape to the west, where less radiogenic values are found.

The Middle Bronze Age in Britain is seen as a period with much greater evidence for field systems and permanent settlements compared to the EBA (Bradley 2007; Fleming 1988; Yates 2007). While this impression derives largely from southern England, there is a case to be made for similar transformations of the landscape in northern Britain, though the forms it took may have differed (Halliday 2021). While our isotopic results appear to be consistent with this characterisation, the comparison is a difficult one, as landscape use in the EBA may have been equally constrained; here we run into the well-known problem of equifinality in isotopic studies. Nevertheless, at least in a broad sense, we can identify a change in landscape use between the two periods that meets with archaeological expectations of a significant restructuring of the subsistence/settlement system at this juncture.

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<sup>1</sup> The mean of  $0.71012 \pm 0.00065$  ( $n = 12$ ) for human dental enamel from medieval Whithorn (Müldner et al. 2009) is similar to that of the EBA cremations at Dunragit, and consistent with the Priory’s location near the southern end of The Machars.

How the strong negative correlation between strontium isotope values and elemental concentrations during the EBA, but not the MBA, fits into the story is at present unclear, beyond noting that for the EBA the correlation suggests variable consumption between two endmembers, one with more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  but lower Sr concentration, and another with the opposite. We have already argued above that marine resources *per se* are unlikely to constitute one of these endmembers, though near-coastal fields might be considered pending information on strontium concentrations on crops in such a setting. Another related possibility would involve manuring with seaweed, recently demonstrated experimentally to raise strontium concentrations in crops (Blanz et al. 2019; see also Dockrill and Bond 2009 for manuring practices in North Atlantic European prehistory). Alternatively, we may be seeing varying contributions of strontium from animals (from upland areas with higher  $^{87}\text{Sr}/^{86}\text{Sr}$  values but lower elemental concentrations due to biopurification) and plants from different parts of the landscape. But even without specifying its mechanism, that this difference persists in calcined bone – representing consumption over the last decade or more of life – is itself interesting, and could imply either that the cremated remains of individuals from different communities in the surrounding area were being brought to the site, or that diets differed markedly within the same community, perhaps related to socioeconomic status.

Methodologically, Dunragit demonstrates how human (and faunal) strontium isotope results can be used to investigate questions concerning landscape use at the ‘population’ or community level, rather than a focus on individual mobility. This is a novel approach in the spatial analysis of strontium isotope data, taking into account both the central tendency and the variability in a dataset, and contrasts to other recent studies that use a similar approach but for the assignment of individuals (Bataille et al. 2021; Ma et al. 2020). Instead of running one assignment per individual (with the parameters of the normal distribution used for the sampling probability function estimated using the value of the Sr ratio for the individual and the sum of the analytical error for the individual and the sampling error for the baseline), we ran separate assignments for the two populations (with the parameters of the normal distribution used for the sampling probability function estimated using the median of the Sr ratios for the respective populations and the sum of the MADs for the respective populations and the sampling error for the baseline).

The approach is particularly appropriate in the analysis of cremated human bone, which lack the comparatively high temporal resolution of enamel, and instead provide an averaged signal from the foods consumed over a decade or more prior to the death of the individual. We have also emphasised how spatial modelling of isotopic data is always a work in progress, and we fully expect that future refinements of the strontium isoscape for Britain will modify the results presented here. Nevertheless, the difference between the Early and Middle Bronze Age cremations remains robust, even if our understandings of how that maps out onto the landscape may change (cf. Burton and Hahn 2015). Dunragit also emphasises the importance of a robust chronology in the interpretation of isotopic results: the pattern identified here would never have been found were it not for the systematic dating programme undertaken as part of the original excavations.

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<i>Code</i>	<i>Material</i>	<i>ID</i>	<i>Bedrock</i>	<i>Lat</i>	<i>Long</i>	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2SE$
luce1	grass		Strangford Group	54.805098	-4.961057	0.709166	0.000007
luce2	tree	large sycamore	Strangford Group	54.804990	-4.962342	0.709167	0.000008
luce3	tree	medium sycamore	Strangford Group	54.804682	-4.961258	0.709059	0.000008
luce4	grass		Stewartry Group	54.866803	-4.894590	0.711320	0.000009
luce5	tree	small tree, beech?	Stewartry Group	54.866802	-4.894588	0.710883	0.000009
dun1	grass		Shinell Formation	54.879938	-4.877655	0.709121	0.000007
dun2	tree	medium sycamore	Shinell Formation	54.879945	-4.877653	0.709060	0.000007
dun3	grass		Shinell Formation	54.879327	-4.876868	0.708906	0.000008
whit1	grass		Hawick Group	54.768027	-4.440285	0.710650	0.000009
whit2	gorse	gorse	Hawick Group	54.767900	-4.440573	0.709482	0.000008
wig1	grass		Strangford Group	54.892227	-4.458527	0.709731	0.000008
wig2	tree	large hawthorn	Strangford Group	54.892233	-4.458525	0.709722	0.000008
holy1	grass		Hawick Group	54.857717	-4.310550	0.709617	0.000008
holy2	grass		Hawick Group	54.858948	-4.309965	0.710284	0.000010
holy3	tree	large sycamore	Hawick Group	54.852425	-4.312295	0.710499	0.000007
newt1	grass		Shinell Formation	54.987753	-4.528358	0.709221	0.000008
newt2	tree	ash	Shinell Formation	54.987758	-4.528380	0.709274	0.000009
glen1	grass		Portpatrick Frmn	55.014903	-4.551107	0.708826	0.000008
glen2	tree	small oak	Portpatrick Frmn	55.014943	-4.551073	0.709379	0.000006
cree1	grass		Kirkcolm Formation	55.065980	-4.593930	0.709978	0.000007
cree2	tree	medium hawthorn	Kirkcolm Formation	55.065978	-4.593923	0.709386	0.000008
goat1	grass		igneous intrusion	55.019410	-4.353713	0.711993	0.000007
goat2	grass		igneous intrusion	55.019672	-4.353957	0.713149	0.000009

**Table 1.** Plant  $^{87}\text{Sr}/^{86}\text{Sr}$  results for southwest Scotland

Site		Cremation	Context	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2 SE$	[Sr]	$\pm$	SUERC-	$^{14}\text{C yr}$	$\pm$	cal BC (95%)	median	Period	
<i>Boreland Cottage Upper</i>														
	10	522	521	0.710262	0.000014	95	11	87526	3569	25	2017	1782	1920	EBA
	10		19050	0.710334	0.000014	101	10	87516	3547	47	1954	1774	1887	EBA
	10	516	515	0.710105	0.000011			87523	3532	24	1938	1771	1853	EBA
	10	520	519	0.710092	0.000010	115	9	87525	3531	25	1937	1771	1848	EBA
	10		330	0.710097	0.000011	85	12	87522	3524	25	1929	1766	1837	EBA
	10	539	538	0.710016	0.000008	59	17	87531	3493	23	1887	1748	1818	EBA
	10	adj to 528	629	0.709724	0.000017	117	9	87532	3492	23	1886	1747	1817	EBA
	10		527	0.709649 0.709644	0.000018 0.000015	127	8	87530	3491	24	1187	1746	1817	EBA
	10	518	517	0.709828	0.000014	107	9	87524	3471	24	1881	1698	1803	EBA
	10		808	0.709837	0.000010	109	9	87534	3455	24	1879	1692	1767	EBA
	10	837	670	0.710926	0.000015	52	19	87533	3452	23	1877	1691	1762	EBA
	10	528	SF95	0.709266	0.000014	138	7	87536	3376	24	1741	1619	1669	EBA
	10	149003		0.710902	0.000017	103	10	87520	3126	23	1449	1303	1405	MBA
	10	160	93	0.710734	0.000018	84	12	87521	3122	24	1446	1302	1400	MBA
	10	579	SF92	0.710653	0.000011	72	14	87535	3086	24	1416	1281	1344	MBA
	10	212	urn	0.711263	0.000013	92	11	87540	3085	23	1415	1282	1344	MBA
	10	239	240	0.710522	0.000014	113	9	88508	3057	30	1408	1231	1323	MBA
	23	017	18	0.710100	0.000014	75	13	87545	3073	24	1411	1268	1341	MBA
	23	015	16	0.710484	0.000014	66	15	87544	3061	24	1407	1260	1334	MBA
	23 ext	045	47	0.710142	0.000011	88	11	87546	3064	24	1408	1262	1337	MBA
	23 ext	041	19	0.711500	0.000015	75	13	87550	3058	23	1404	1236	1330	MBA
<i>Drumflower</i>														
	BP 1 ext	001	9	0.710353	0.000013	112	9	87542	3083	23	1415	1281	1343	MBA
	BP 1 ext	001	2	0.710349	0.000015	138	7	87541	2969	24	1266	1112	1184	MBA
	BP 1 ext	016	16	0.710100	0.000014			87543	2955	24	1259	1057	1167	MBA

**Table 2.**  $^{14}\text{C}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$  and Sr concentration [Sr] results from Dunragit Bypass; \*[Sr] are normalized to 40% (wt.) Ca