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Strontium isoscapes in The Netherlands. Spatial variations in $^{87}Sr/^{86}Sr$ as a proxy for palaeomobility

Lisette M. Kootker [a,b,*], Rowin J. van Lanen [c,d], Henk Kars [b], Gareth R. Davies [a]

[a] Geology & Geochemistry Cluster, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
[b] CLUE +, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
[c] Cultural Heritage Agency, Smallepad 5, 3811 MG, Amersfoort, The Netherlands
[d] Faculty of Geosciences, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

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ABSTRACT

Strontium isotope analysis has been successfully applied to archaeological questions of residential mobility and animal husbandry for over three decades. To obtain a full understanding of variations in archaeological samples, spatial variations in bioavailable strontium should be accurately mapped or inferred. This paper presents the first archaeological bioavailable strontium map of The Netherlands. The map is compiled solely from archaeological enamel samples of rodents and selected mammals as they are considered to provide the best proxy of bioavailable Sr. The diversity of the Dutch geological subsurface is directly reflected in the spatial distribution of $^{87}Sr/^{86}Sr$ ratios. Six isoscapes are defined: A) Lower terrace of the river Meuse (0.7074–0.7091, $n = 2$); B) Marine and river Rhine sediments (0.7088–0.7092; $n = 85$); C) Holland peat area, Kempen and northern sand areas (0.7091–0.7095, $n = 14$); D) Rur Graben (0.7095–0.7105, $n = 11$); E) Push moraines (0.7095–0.7110, $n = 7$) and F) Northern and southern loess areas (0.7104–0.7113, $n = 15$). Although individual isoscapes may show some overlap, the mean of each isoscape is statistically significant different, except for zones D and E. Five other geological environments yielded no archaeological data, mainly due to poor preservation in acidic soils. To fill this data gap, additional biosphere samples will be collected and analysed. This approach, however, will require validation of the extent to which specific floral are offset compared to the average archaeological bioavailable strontium. The base map presented here now allows such a detailed assessment of potential offsets in the $^{87}Sr/^{86}Sr$ recorded by different proxies at the regional scale.

1. Introduction

Archaeological migration models used to be based on the spatial dispersal of cultural artefacts. This approach, however, has led to a lively debate about whether the archaeological cultural record represents the actual movement of people or the broader diffusion of cultural heritage in the form of ideas, materials and objects (Childe, 1925; Burmeister, 2000; Hakenbeck, 2008). Over the last three decades, advances in several bioarchaeological disciplines, such as DNA and isotope research, have offered new perspectives on this debate. Stable isotopes, such as carbon (C) and nitrogen (N), are used to address very diverse archaeological questions. Originally introduced by Van der Merwe and Vogel (1977), both isotopes are now established as invaluable tools for the reconstruction of palaeodiet, the determination of patterns of breastfeeding and weaning age, and the investigation of animal husbandry (e.g. Richards et al., 2002; Mays and Beavan, 2012; Hammond and O'Connor, 2013). Moreover, the use of the radiogenic strontium isotope system ($^{87}Sr/^{86}Sr$) in bioarchaeological research has matured into an established tool for providing information about human and animal residential mobility and husbandry practices in prehistory (see Bentley, 2006; Schwarcz et al., 2010; Slovak and Paytan, 2011 for review).

Strontium isotope ratios serve as a proxy of palaeomobility due to the geographical variation in ^{87}Sr produced by the β-decay of ^{87}Rb as a result of the spatial variations in the initial amount of ^{87}Rb in the geological bedrock and the age of the lithology. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) are released to the environment through the weathering of rocks (Capo et al., 1998). Strontium isotope ratios in soil substrates, however, can deviate significantly from the biologically-available Sr that is taken up by vegetation and introduced into our food chain due to inputs from the atmosphere, such as precipitation and sea-spray, and outputs through stream- and groundwater (Fig. 1; Price et al., 2002; Hedman et al., 2009). Ultimately, the bioavailable strontium is conveyed into the skeletal tissues of human and animals through their diet where it substitutes for calcium in the structure of hydroxyapatite in bone, dentine, enamel, keratin, ivory and shell. Tooth enamel is formed during childhood and barely undergoes any change after mineralisation and during burial (Nelson et al., 1986; Budd et al.,

* Corresponding author at: Geology & Geochemistry Cluster, Vrije Universiteit Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands.
E-mail address: lisette.kootker@vu.nl (L.M. Kootker).

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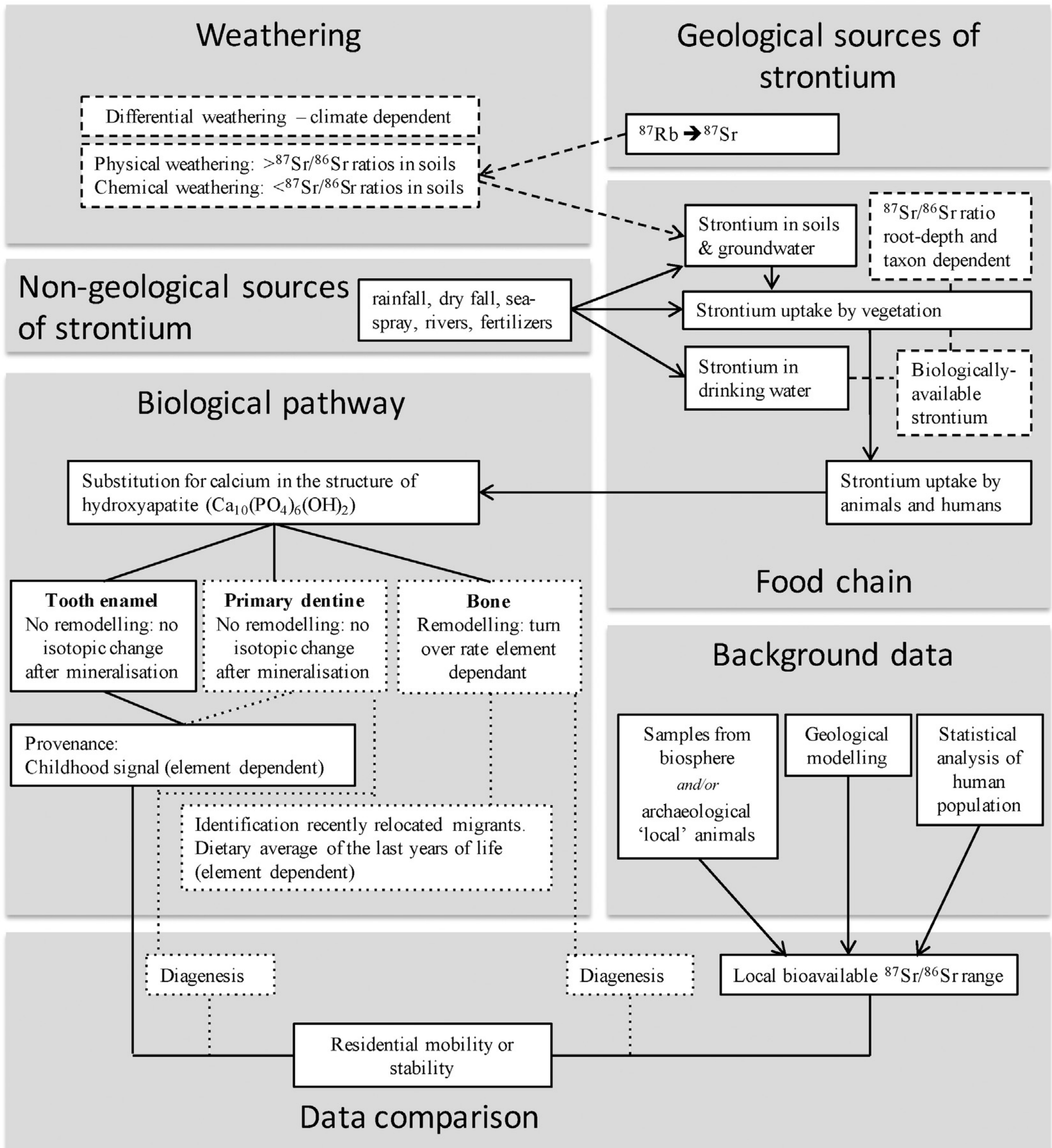

Fig. 1. Schematic diagram showing the basic principle of strontium isotope analysis of archaeological skeletal material. Key: - - - - $^{87}Sr/^{86}Sr$ dependent on differential weathering or differential uptake; ····· biomaterials susceptible to diagenetic alterations.
Modified from Tütken et al. (2008).

2000; Hoppe et al., 2003). Hence, the $^{87}Sr/^{86}Sr$ ratio in tooth enamel reflects the strontium intake during childhood, and thus can serve as a tracer of the geological area where the individual grew up, assuming that his or her diet was dominated by locally grown foods (Hillson, 1986; Price et al., 2002; Pye, 2004).

The main principle of this provenance technique is to compare the isotopic signatures from an individual to the local bioavailable strontium. Differences between the $^{87}Sr/^{86}Sr$ of an individual's dental enamel and the local bioavailable strontium range indicate the individual did not live in the region during their youth and has migrated from an isotopically different geographical location (Fig. 1). In contrast, similarities between the local biosphere strontium signal and the individual's biogenic signal indicate residential stability or residential mobility between two geographic locations with similar isotopic signatures.

A prerequisite for the interpretation of strontium isotope signatures in archaeological organic materials is the accurate mapping of the spatial variations in bioavailable $^{87}Sr/^{86}Sr$ ratios within the study area, or the development of accurate so-called isoscapes (Bowen, 2010). In Europe, $^{87}Sr/^{86}Sr$ reference maps have been published for the United Kingdom (Evans et al., 2009, 2010), Denmark (Frei and Frei, 2011; Frei and Price, 2012), Sweden (Sjögren et al., 2009), France (Willmes et al., 2014), Greece (Nafplioti, 2011) and southwest Germany (Bentley et al., 2004; Bentley and Knipper, 2005). To date, however, there is no baseline information for bioavailable $^{87}Sr/^{86}Sr$ in The Netherlands. The aim of this paper is to present a first archaeological $^{87}Sr/^{86}Sr$ spatial distribution map. This study approach allows us to evaluate the spatial variation in bioavailable $^{87}Sr/^{86}Sr$ in The Netherlands and to assess migration in an archaeological context. Moreover, the data presented here contributes significantly to our understanding of the European strontium isoscapes, and ultimately allows a more accurate investigation of ancient intra-European mobility.

2. Building Sr isotope reference datasets

A large variety of methods are used to investigate regional variability in $^{87}Sr/^{86}Sr$ ratios (Hodell et al., 2004; Evans et al., 2010; Viner et al., 2010; Maurer et al., 2012). Since the $^{87}Sr/^{86}Sr$ ratio is directly related to the initial amount of ^{87}Rb in rocks and the age of the lithology, direct strontium isotope measurements of regional biosphere material, such as soil leachates, water and vegetation, may appear to be a fast and simple way to create reference databases (Capo et al., 1998; Beard and Johnson, 2000; Faure and Mensing, 2005; Evans et al., 2010; Voerkelius et al., 2010). However, the release of $^{87}Sr/^{86}Sr$ from geological bedrock into soils through weathering is climate controlled. Chemical weathering (>precipitation), for instance, acts as a catalyst in the removal of the radiogenic strontium fraction from the environment due to the preferential breakdown of rubidium-rich minerals, resulting in relatively low radiogenic soils compared to the source rock (see Jung et al., 2004 for references). A similar, but opposing, process occurs in a controlled laboratory environment, where soil leachates are extracted; these leachates will be biased towards higher radiogenic strontium values, as this fraction is preferentially released compared to the non-radiogenic fraction (e.g. Bagard et al., 2013). Moreover, variations in soil mineral contents due to pedological processes may result in large variability in $^{87}Sr/^{86}Sr$ ratios between subsamples (Borg and Banner, 1996; Price et al., 2002; Jung et al., 2004; Bentley, 2006; Evans et al., 2009). These factors, together with the input of strontium from non-geological sources, the use of modern fertilizers, negate the assumption that bedrock $^{87}Sr/^{86}Sr$ values are directly related to the $^{87}Sr/^{86}Sr$ values that enter the environmental cycle (Capo et al., 1998; Price et al., 2002).

A second, perhaps more reliable approach is to use vegetation samples to map the spatial variations in strontium isotope compositions. Strontium passes from the geological bedrock to soil in solution and can be readily absorbed into vegetation and thus enter the food chain (Miller et al., 1993; Capo et al., 1998; Price et al., 2002; Bentley, 2006). The uptake of strontium by vegetation is, however, dependent among other factors on climate, fungi, root-depth and taxon (Isermann, 1981; Dijkstra et al., 2003). Vegetation samples therefore may provide a biased signal, unless a vast quantity of different species of vegetation is collected. Moreover, the $^{87}Sr/^{86}Sr$ ratio of plants may reflect modern soil conditions that are likely to be altered by various soil modification methods, such as use of (synthesized) fertilizer and ploughing, rather than being typical of archaeological soil conditions (Evans et al., 2009; Viner et al., 2010; Maurer et al., 2012).

A third approach to defining regional isotopic isoscapes is to collect teeth of archaeological animal remains, preferably small rodents and/or mammals that forage in a restricted area and consumed a similar diet to humans. Similar to vegetation, animal skeletal tissue displays homogeneity in $^{87}Sr/^{86}Sr$ ratios, averaging local variations (Price et al., 2002). Although the selection of species to for use as an isotopic proxy depends on local conditions, it is vital to avoid larger animals. Recent stable isotope and DNA studies have shown that long-distance acquisition and exchange of medium and large domestic mammals has taken place from early prehistory onwards (Schweissing and Grupe, 2003; Bentley and Knipper, 2005; Viner et al., 2010; Maurer et al., 2012; Oelze et al., 2012; Van der Jagt et al., 2012; Price, 2013; Colominas et al., 2015). The use of exclusively low-mobility rodents as a proxy for bioavailable strontium values, may, however, provide $^{87}Sr/^{86}Sr$ ratios restricted to a too local geological area such that they do not represent a 'local' human dietary average. Further potential restrictions for the interpretation of human and animal provenance based on mapping local bioavailable strontium ratios come from the food they consumed. The increasing share of imported arable crops in human diet, for instance, from prehistory onwards will have an influence on the dietary intake of strontium (Bakels and Jacomet, 2003; Livarda, 2011). Plants have relatively high strontium concentrations compared to meat, which has undergone greater biopurification and hence contains less strontium (Burton, 2008). At least in Medieval Europe, grains such as wheat and barley dominated the daily diet (Singman, 1999); the possible modification of the local $^{87}Sr/^{86}Sr$ ratio because of the ingestion of high amounts of non-local strontium through imported vegetation therefore needs to be taken into account.

A fourth approach uses a GIS-based model to that estimates the $^{87}Sr/^{86}Sr$ of bioavailable strontium as a function of strontium inputs from a variety of sources (Bataille and Bowen, 2012; Bataille et al., 2012). Although this method requires no samples, and therefore may appear to be a cost-effective technique, their multi-source mapping approach preferable requires validation through the 'conventional' analysis of biosphere or archaeological samples.

A fifth and final method to determine the local strontium range was initially proposed by Wright (2005). She used a statistical approach to identify local individuals and to determine the local strontium range, based on the assumption that $^{87}Sr/^{86}Sr$ ratios of a local population record a normal (Gaussian) distribution. By excluding statistical outliers, the local strontium range can be established.

In summary, the effect of sample selection on the definition of the local bioavailable strontium signatures should not be underestimated. In particular the paper by Maurer et al. (2012) stresses that the determination of the bioavailable strontium values that entered the local archaeological food chain is challenging, as it remains unclear which environmental resources are most appropriate. Their study emphasizes that careful selection of the bioavailable samples is of key importance to enable a reliable and accurate determination of local $^{87}Sr/^{86}Sr$ ratios. Socio-economic differences within ancient (Medieval) populations, for instance, might have led to a diverse origin of the food resources between the wealthy and the poor; the former might have had access to more exotic food resources, resulting in the consumption food with different isotopic ratios (Grumbkow et al., 2013. See also Price et al. (2006) for an example of a different archaeological time period). As a result, assumed 'non-local $^{87}Sr/^{86}Sr$ ratios' do not necessarily point towards non-local origins, but to differences in origin of diet. Therefore, the most conservative approach to determine the $^{87}Sr/^{86}Sr$ ratios that entered the local food chain is to combine the statistical assessment of the investigated population with archaeological and (modern) biosphere samples, although in the latter case an assessment is needed of potential anthropogenic influences from the use of fertilizers and regional pollution. In The Netherlands, however, an in-depth study to investigate the possible offset between the various proxies used in strontium isotope studies has not yet been undertaken.

3. Regional setting

Located in northwest Europe, The Netherlands is bordered by the North Sea to the north and west, Belgium to the south and Germany to the east. The majority of the landscape was formed by the estuary of three major river systems: Rhine, Meuse and Scheldt. The country consists of lower flat-lying areas with Holocene deposits (Stouthamer and Berendsen, 2000, 2007; Vos, 2015) and relatively higher, stable Pleistocene areas (Koomen and Excaltus, 2003; Vos et al., 2011; Vos and De Vries, 2013; Vos, 2015). Most of the sediments covering The Netherlands have been deposited during the Quaternary period (2.6 MA–present) and consist of fluviatile, marine and glacigenic sediments, and local terrestrial deposits such as loess (aeolian) and peat (De Mulder et al., 2003; Weerts et al., 2003; Van der Veer, 2006). The generally low-lying character of the country has led to the development of large-scale mires and bogs throughout the Holocene, especially after ca. 7000–6000 BC (Petzelberger et al., 1999). From the Iron Age (800–12 BC) onwards, humans had a significant effect on the landscape (Lascaris and De Kraker, 2013). Rapid deforestation, agricultural activities and later large-scale dike building extensively changed the landscape. During the Roman and Medieval periods, large parts of The Netherlands were still covered by peat; this situation remained unchanged until the start of the large-scale reclamation activities in the 10th–12th century in the west (De Bont, 2008) and 16th century in the eastern of the country (Borger, 1992; Gerding, 1995). Today, over 70% of the total land surface in The Netherlands has been cultivated (Zwart et al., 2008; CBS, 2009). Less than 15% of the Dutch surface is designated as nature reserve, production woods or recreation park (CBS, 2009).

4. Material

4.1. Sample selection

Over a period of three years, 187 teeth of archaeological small ($n = 20$), medium ($n = 39$) and large ($n = 5$) domestic mammals, medium wild mammals ($n = 2$) and rodents ($n = 121$) were collected and analysed. Based on the published and unpublished results, and recent research on the long-distance acquisition and exchange livestock (Bentley and Knipper, 2005; Van der Jagt et al., 2012), it was decided to exclude the strontium isotope data of *Sus domesticus*, *Ovis aries*/*Capra hircus* and *Bos taurus* from this study. As a result, a total of 143

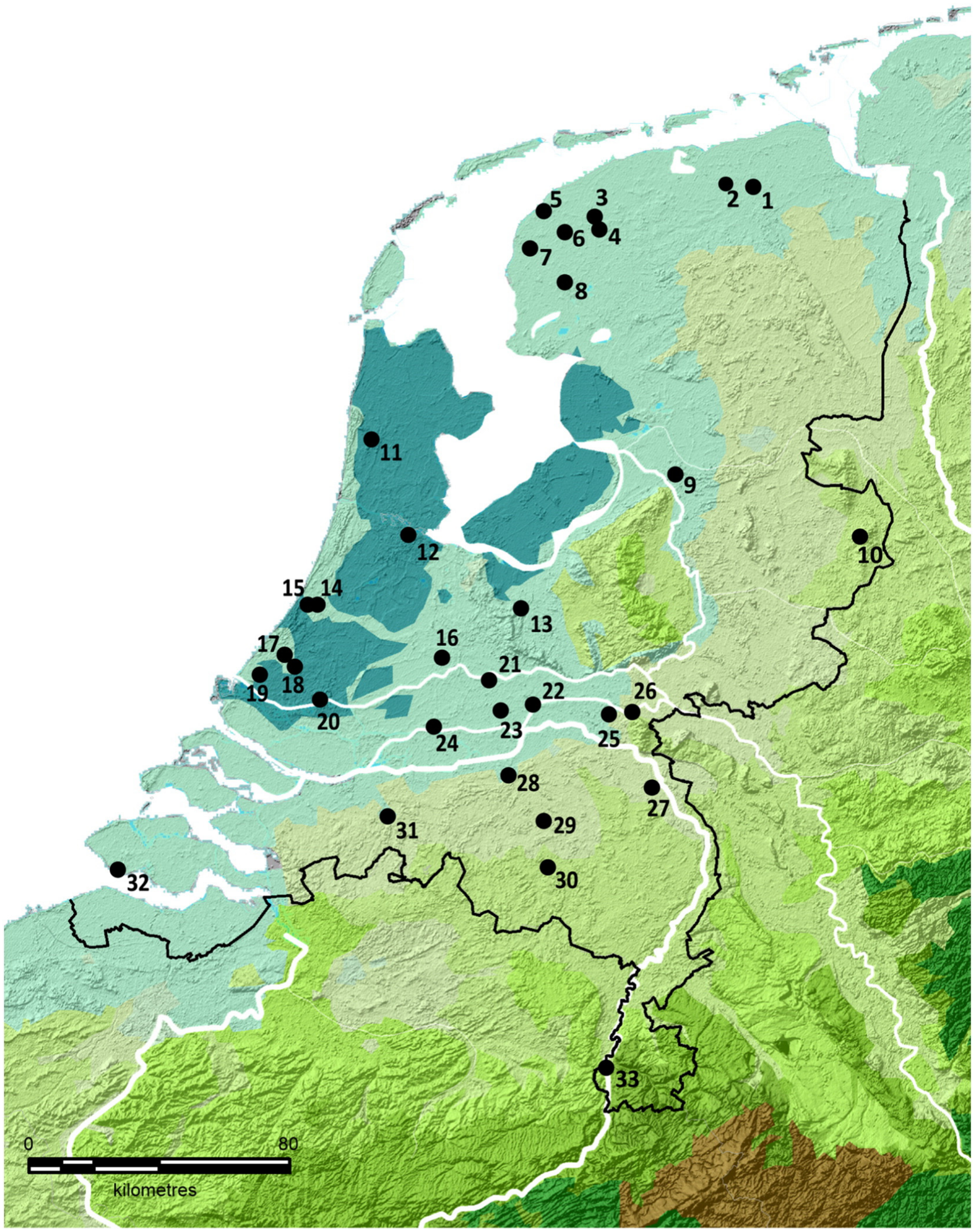

Fig. 2. Map of The Netherlands showing the spatial distribution of the sampled archaeological sites.

incisors and molars of archaeological rodents, small domestic mammals and medium sized wild mammals from 38 sites throughout The Netherlands are presented (Fig. 2). The vast majority of the rodent samples are assigned to true mice and rats (*Muroidea*) and voles (*Microtus* sp.): species with restricted extents of movement of on average less than 1.5 km^2. If possible, the rodent and domestic mammal remains were collected from well-dated Medieval and post-Medieval cesspits. The urban context of the cesspits limits the possibility that intrusive (modern) rodents were sampled. Cats (*Felis catus*) and foxes (*Vulpes vulpes*) are the main contributors of the small and medium mammal samples. In particular fox territories vary in size: the poorer the habitat, the larger the territory. Recent research, however, established that the territory of modern foxes in Southern Limburg usually do not exceed 0.65 km^2 (Mulder, 2007). Given the stability of their habitat, it is assumed that their territories were similar in size in medieval times.

Teeth were sampled from locations that cover nearly all main archaeological landscape types of The Netherlands (see Section 4.3), but the coverage is not equally distributed due to for example varying preservation conditions (e.g., soil pH), restricted sample availability, differences in economic pressure across the country that lead to differences in construction related excavations, and varying excavation policies between provinces/archaeological regions (see Kootker and Davies (2016). To enable a meaningful comparison between the $^{87}Sr/^{86}Sr$ ratios of the main archaeological landscape types, it was decided to base the dataset presented in this study on one type of proxy. Additional isotopic data are available on parts of the Dutch biosphere (e.g., McManus et al., 2013) but it is beyond the scope of this article to conduct detailed comparisons between different local data sets in order to increase the spatial coverage of the Sr isotope ratios in The Netherlands.

4.2. Sampling protocol

The outer surface of the incisors of large rodents (all *Rattus* sp., *Oryctolagus cuniculus* and *Lepus europaeus*) and molars (other mammals) was mechanically cleaned using a diamond-topped dental drill. Approximately 1–3 mg of enamel power was sampled and sealed in pre-cleaned 2 ml polyethylene Eppendorf® centrifuge tubes. The size of the incisors of the small rodent species, such as *Muroidea* and *Microtus* sp., was often too small to collect pure enamel. The entire dental elements were therefore cleaned and bulk sampled (enamel and dentine). The presence of the dentine could possibly influence the $^{87}Sr/^{86}Sr$ ratio of the enamel, altering the signal more towards diagenetic ("local" and/or modern) values. To limit effects of diagenetic alteration, dentine was physically removed from the incisors as much as possible and samples were leached with 0.1 N acidic acid to remove any labile Sr on/in the dentine and enamel (see Grumbkow et al., 2013). All samples were transferred to the US Federal standard Class 100 clean laboratory facility at the Vrije Universiteit Amsterdam for Sr purification.

4.3. Archaeological landscape map of The Netherlands

A geomorphological-dependent approach was used to produce $^{87}Sr/^{86}Sr$ isoscapes. The main geomorphological landscape units were derived from the Archaeological Landscape Map of The Netherlands, which represents the most detailed geomorphological map of The Netherlands to date (RCE, 2015). This dataset separates the overarching main landscape types from more detailed local landscape zones on a 1:50,000 scale. The dataset is primarily based on the Geomorphological map of The Netherlands (Koomen and Excaltus, 2003; Koomen and Maas, 2004), but each individual landscape unit is defined through a combination of geomorphological, archaeological, historical, geological and soil data. The map contains references to external datasets, such as geomorphological and soil maps, the European Landscape Map classifications (LANMAP2), and defines the natural boundary conditions for (current) anthropogenic use.

5. Analytical methods

5.1. Strontium isotope analysis

A detailed description of the column extraction and the sample loading procedures is given in (Grumbkow et al., 2013). The strontium isotope compositions were measured on a MAT-Finnigan 262 multicollector mass spectrometer and on a ThermoFinnigan Triton at the Vrije Universiteit Amsterdam. The ratios were determined using a static routine and were corrected for mass-fractionation correction. Over the course of the research, measurements of NBS987 gave mean $^{87}Sr/^{86}Sr$ values for the MAT262 and Triton of 0.710240 ± 0.000009 (2SE, $n = 41$) and 0.710249 ± 0.000009 (2SE, $n = 4$) respectively. The individual measurements were normalized to 0.710240 using the value of NBS987 measured in the same sample turret. The procedural blanks contained an average of <0.06 ng strontium ($n = 27$), a negligible amount compared to the average amount of strontium present in enamel samples (50–500 ng/mg;Kohn et al., 1999).

5.2. Spatial analysis

Geographical Information System (GIS) was used to create spatial overviews of sample locations and isoscapes in The Netherlands. For each sample location coordinates were extracted and converted to the Amersfoort/RD new — EPSG:28992 coordinate system and overlaid on a current relief map of The Netherlands. The main landscape type was determined for each sample location using the Archaeological Landscape Map of The Netherlands. Main landscape types that share a similar origin and parent material type were grouped into one isoscape. Sites located near the boundary of two main landscape types were individually analysed to determine the most dominant landscape type.

5.3. Statistical analysis

The distribution of $^{87}Sr/^{86}Sr$ datasets were analysed using SPSS 22.0 (IBM SPSS Statistics for Macintosh, Armonk, IBM Corp.). Statistical outliers were removed from the dataset using Extreme Value Analysis (EVA). Firstly, the distribution of the variables per isoscape was checked to identify values that deviate from a normal distribution. In addition, values were classified as (extreme outliers) if $X < Q1 - 3 * $ interquartile range (IQR) or $X > Q3 + 3 * IQR$. Using both methods, identified statistical outliers were removed, resulting in trimmed $^{87}Sr/^{86}Sr$ datasets. Following (Price et al., 2002), the local $^{87}Sr/^{86}Sr$ range per main landscape type was obtained by calculating the mean $^{87}Sr/^{86}Sr$ ratios of the (trimmed) dataset $\pm$ two standard deviations (2σ).

6. Results

All strontium isotope results are shown in a relative probability diagram (Fig. 3). The figure shows a positive skewed distribution of the data, with a median of approximately 0.7091. Following the methodology described in Section 5.2, each sample was assigned to a main landscape type. Landscape types where no samples have been collected were assigned to lithological and geogenetic similar landscape types (conform Evans et al., 2010, see Appendix A). This approach resulted in six different landscape groups (or isoscapes), identified by the letters A to F, representing 22 main landscape types (Appendix A). The unique origin and/or parent materials source of five landscape types precluded the possibility to infer the Sr isotope composition from other landscape types and therefore these areas remain with no data coverage (isoscape X). The $^{87}Sr/^{86}Sr$ data per landscape group is listed in Appendix B.

The $^{87}Sr/^{86}Sr$ ratios of each isoscape are assessed by the Shapiro–Wilk's normality test. The data of isoscapes B and C are not normally

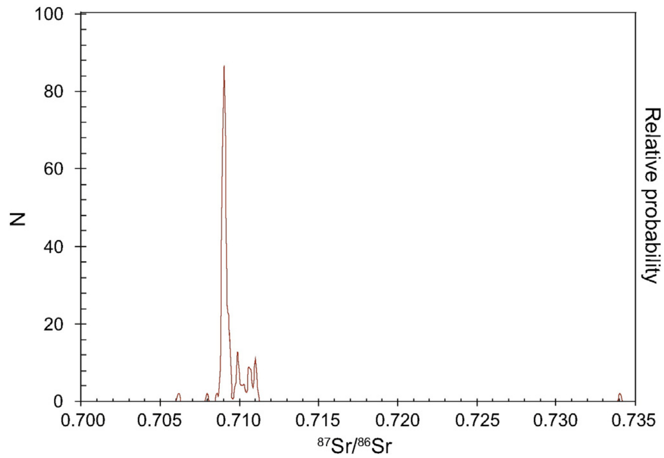

Fig. 3. A relative probability diagram of the obtained $^{87}Sr/^{86}Sr$ values ($n = 143$). The curve and histogram are constructed allocating an arbitrary error to each data point set at 0.0001 to account for intra-sample variation.

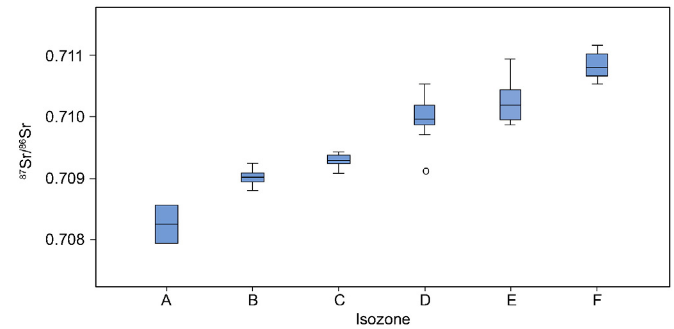

Fig. 4. Tukey's schematic boxplot showing $^{87}Sr/^{86}Sr$ variation per isoscape in The Netherlands. Key: the boxes represent the interquartile range (IQR: Q3–Q1), the central line indicates the median. The whiskers represent Q1 − 1.5 IQR and Q3 + 1.5 IQR. The circle represents an extreme outlier (>3 IQR). A) Lower terrace of the river Meuse; B) Marine and river Rhine sediments; C) Holland peat area, Kempen and northern sand area; D) Rur Graben; E) Push moraines and F) Northern and southern loess areas.

distributed ($p < .01$), but become so after removal of the most extreme values ($p > .01$, Table 1. $N = 6$ in isoscape B, $n = 2$ in isoscape C). The sample size of isoscape A ($n = 2$) is too small to allow statistical assessment. Tukey's schematic boxplot in Fig. 4 displays the intra- and inter-isoscape variations in $^{87}Sr/^{86}Sr$. Despite the apparent normal distribution of $^{87}Sr/^{86}Sr$ data of isoscape D, one datum is flagged as an extreme outlier as the value deviates more than three times the interquartile range (IQR) from the median, and was therefore removed from dataset D.

An independent-sample t-test was run to determine if there were significant differences in mean $^{87}Sr/^{86}Sr$ ratios between the different isoscapes. Levene's test for equality of variances showed no homogeneity of variance in the data, except for isoscapes B–C, D–E, D–F and E–F (Table 2). Despite most isoscapes show an overlap in the range of $^{87}Sr/^{86}Sr$, the mean value of each isoscape is statistically different ($p = <.05$), except for isoscapes D (Rur Graben) and E (Push moraines, $p = .214$), indicating substantial differences in the spatial variation of $^{87}Sr/^{86}Sr$ ratios in The Netherlands.

Based on the Archaeological Landscape Map of The Netherlands, the selected sampling strategy, and the statistical considerations, the first spatial distribution of bioavailable $^{87}Sr/^{86}Sr$ within The Netherlands is presented in Fig. 5.

7. Discussion

Although The Netherlands is geologically homogeneous relative to the entire variations of continental Europe, being predominantly made up from Holocene (45%) and Pleistocene (50%) deposits, there is a significant spatial patterning in $^{87}Sr/^{86}Sr$ ratios that records the inter- and intra-lithological variations. Based on the data presented above, six isoscapes have been defined, each characterized by a distinct range in $^{87}Sr/^{86}Sr$ ratios.

7.1. Isoscape A: Lower terrace of the river Meuse (0.7074–0.7091, n = 2)

Isoscape A is based on two measurements and is therefore only considered as indicative of river Meuse sediments and the data cannot be used to infer minimum and maximum values. The sediments deposited by the river Meuse system belong to the Beegden Formation, which generally consists of course sands to heavy clays that locally can be calcareous (De Mulder et al., 2003; Van der Veer, 2006). Although the topsoil near the sampling location appears to be predominantly non-calcareous (www.bodemdata.nl), the $^{87}Sr/^{86}Sr$ ratios indicate that one rodent's diet included unradiogenic Sr, possibly derived from a calcareous-rich region. The $^{87}Sr/^{86}Sr$ signature of Meuse water averages around 0.7094 (Petelet-Giraud et al., 2009). Obviously, more data are needed to delineate this isoscape more accurately.

7.2. Isoscape B: Marine and river Rhine sediments (0.7088–0.7092; n = 85)

The range in $^{87}Sr/^{86}Sr$ ratios of the Holocene soil parent regions in isoscape B is consistent with the expected range of modern seawater (0.70917) and river Rhine water (0.7084–0.7091: Burke et al., 1982; Palmer and Edmond, 1989; Veizer, 1989; Buhl et al., 1991). Hence, $^{87}Sr/^{86}Sr$ ratios between 0.7088 and 0.7092 are representative of over 45% of the surface of The Netherlands.

7.3. Isoscape C: Holland peat area, Kempen and northern sand areas (0.7091–0.7095, n = 14)

A mix of sediments characterizes isoscape C. The Pleistocene northern sand deposits belong to the Boxtel Formation and are of local aeolian

Table 1
Statistical assessment of $^{87}Sr/^{86}Sr$ data from archaeological animal remains, for the complete and trimmed datasets per isoscape.

Statistics	A	B	Trimmed B	C	Trimmed C	D	Trimmed D	E	F
N	2	91	85	16	14	12	11	7	15
Mean $^{87}Sr/^{86}Sr$	0.70826	0.70901	0.70903	0.71088	0.70930	0.70996	0.71004	0.71023	0.71084
Standard deviation (1σ)	0.00043	0.00032	0.00010	0.00618	0.00011	0.00035	0.00025	0.00039	0.00020
Variance	1.87E−07	1.05E−07	9.28E−09	3.80E−05	1.11E−08	1.27E−07	6.26E−08	1.51E−07	4.08E−08
Minimum	0.70795	0.70617	0.70882	0.70910	0.70910	0.70912	0.70970	0.70985	0.71054
Maximum	0.70857	0.70941	0.70926	0.73405	0.70945	0.71052	0.71052	0.71092	0.71117
Range	0.00062	0.00324	0.00044	0.02495	0.00035	0.00140	0.00082	0.00107	0.00063
Median	0.70826	0.70904	0.70903	0.70932	0.70931	0.70994	0.70998	0.71016	0.71081
Shapiro–Wilk p value	–	0.000	0.872	0.000	0.622	0.363	0.469	0.359	0.193

Key: A) Lower terrace of the river Meuse; B) Marine and river Rhine sediments; C) Holland peat area, Kempen and northern sand area; D) Rur Graben; E) Push moraines and F) Northern and southern loess areas.

Table 2
Results of the independent sample t-tests comparing mean $^{87}Sr/^{86}Sr$ ratios between the isoscapes. Isoscape A is excluded from statistical analyses, because of its small sample size.

Isoscape	A	B	C	D	E	F	
A	–	–	–	–	–	–	
			0.859	0.000	0.000	0.000	*p* value Levine's test
B		–	0.00028	0.00101	0.00121	0.00182	mean difference
			0.000	0.000[a]	0.000[a]	0.000[a]	t probability independent samples t-test
				0.011	0.002	0.001	
				0.00077	0.00093	0.00154	
C			–	0.000[a]	0.000[a]	0.000[a]	
					0.223	0.691	
					0.00020	0.00081	
D				–	0.214	0.000	
						0.059	
						0.00061	
E					–	0.000	
F						–	

Key: A) Lower terrace of the river Meuse; B) Marine and river Rhine sediments; C) Holland peat area, Kempen and northern sand area; D) Rur Graben; E) Push moraines and F) Northern and southern loess areas.

[a] Welch–Satterthwaite correction applied for nonhomogeneity of variance and/or unbalanced design of the datasets.

origin. In the Kempen region, located in southwest North-Brabant, soils are formed from local aeolian and fluviatile clay and loamy sandy deposits that belong to the Stamproy Formation. At the beginning of the Holocene, sea level rose, resulting in the formation of extensive intertidal areas. In the western and northern parts of The Netherlands, peat developed at the margins of these areas (Nieuwkoop Formation), which are often overlain by marine and fluviatile/estuarine clays of Holocene age (De Mulder et al., 2003; Van der Veer, 2006).

The $^{87}Sr/^{86}Sr$ ratios of the bioavailable Sr in these districts range from similar to the marine values up to 0.7095. The origin of the underlying lithology or the geographical setting of the sample locations may explain the relative low $^{87}Sr/^{86}Sr$ ratios, especially for the Pleistocene sand districts. The formation of the southern sand area (Stamproy Formation) is highly influenced by the fluviatile deposits of local rivers draining Pleistocene Meuse sediments from the Kempish Massif in Belgium. The sample locations representing the northern sand district were collected close to the former Zuider Sea coastline. It can therefore be assumed that the influence of marine derived strontium, such as sea-spray (Fig. 1), might have been substantial, lowering $^{87}Sr/^{86}Sr$ ratios towards marine values. More comprehensive data coverage is expected to expand the observed range in $^{87}Sr/^{86}Sr$ ratios towards higher values, or even to divide isoscape C into several separate zones.

7.4. Isoscape D: Rur Graben (0.7095–0.7105, n = 11)

The Rur Graben is located directly east of the Kempen sand district that defines isoscape C, but is characterized by more radiogenic $^{87}Sr/^{86}Sr$ signatures. The sedimentary sequence in the Rur Valley Graben differs significantly from its neighbour. The Liempde Member, part of the Boxtel Formation, is a lithostratographic unit exclusive to the Rur Valley Graben. This Member includes reworked aeolian loess and sandy loess deposits (De Mulder et al., 2003; Schokker et al., 2007). The topsoil of this isoscape consists predominantly of aeolian sedimentation, with loess deposits occurring in the upper part of the sedimentary sequence (Schokker et al., 2007). Strontium isotope ratios range from 0.7095 up to 0.7105.

7.5. Isoscape E: Push moraines (0.7095–0.7110, n = 7)

The relief formed by the push moraines stands out compared to the general flat topography of The Netherlands. Formed by the glaciers during the Weichselian, (the remains of) ice-pushed ridges are found in the middle and eastern parts of The Netherlands. $^{87}Sr/^{86}Sr$ ratios were determined on seven samples from Oldenzaal, situated in the eastern part of the country near the German border. In contrast to the push moraines in the centre of The Netherlands, the eastern push moraines consist of Tertiary marine clays and glacial deposits (boulder clay) derived from the Scandinavia (Berendsen, 1998; De Mulder et al., 2003; Jongmans et al., 2013). In particular boulder clay is expected to exhibit highly radiogenic $^{87}Sr/^{86}Sr$ ratios due to derivation from Proterozic and Archaean basement rocks. In the central parts of The Netherlands, pre-Saalian fluviatile deposits, derived from the pre-Rhine–Meuse system as well as the Eridanos river system, crop out in the ice-pushed ridges (Berendsen, 1998; Overeem and Kroonenberg, 2002; De Mulder et al., 2003; Van der Veer, 2006). Van der Veer (2006) showed that *reworked deposits from these* "*mixed*" [fluviatile and glacial] *sediments are characterized by elevated contributions of alkali-feldspars*. Alkali feldspars have high levels of rubidium and low levels of strontium, resulting in elevated $^{87}Sr/^{86}Sr$ ratios. The diversity of the sediments characterizing this isoscape resulted in a wide range of $^{87}Sr/^{86}Sr$ ratios, from 0.7095 to 0.7110.

7.6. Isoscape F: Northern and southern loess areas (0.7104–0.7113, n = 15)

The samples used to define the bioavailable strontium range in the southern part of the province of Limburg were collected in Borgharen, located within the valley of the river Meuse. Measured $^{87}Sr/^{86}Sr$ ratios were more radiogenic than might be expected from river Meuse sediments (Petelet-Giraud et al., 2009). Moreover, geological explorations showed that the soil is predominantly made up of gravel in a matric of alluvial loess, re-deposited by the river Meuse (Huisman et al., 2011). The samples from Borgharen were therefore assigned to the northern and southern loess areas, rather than to the river Meuse valley.

The coverage of these silty aeolian (re-deposited) sediments of Saalian and Weichselian age is restricted to the southern and southeastern parts of The Netherlands (De Mulder et al., 2003; Van der Veer, 2006). Bioavailable strontium in European loess soils range from 0.7086 and 0.7111 (Price et al., 2003; Nehlich et al., 2009 and references therein). The local bioavailable strontium in the Dutch loess region is characterized by more radiogenic Sr isotope ratios (0.7104 to 0.7113) due to the breakdown of alkali feldspar.

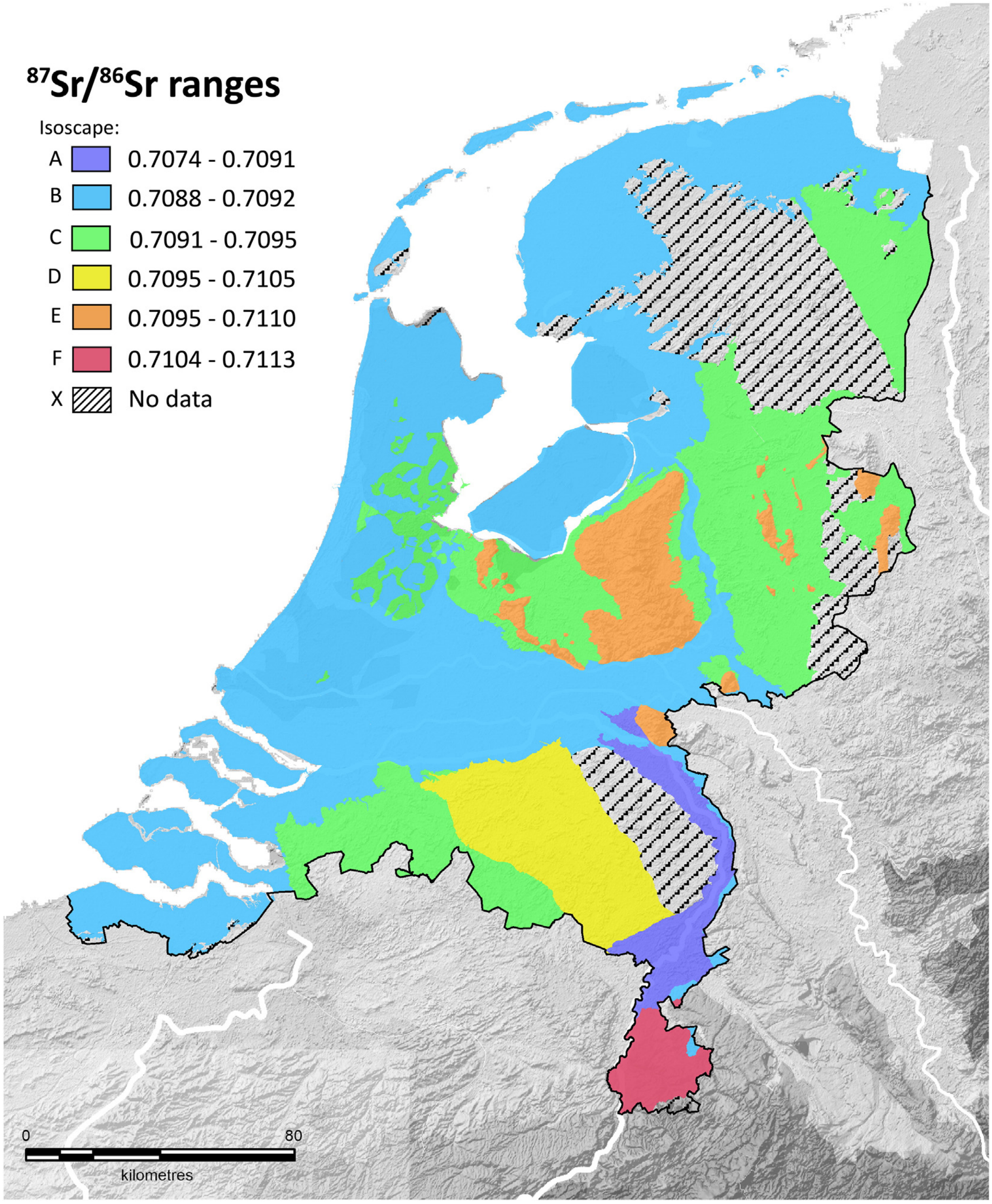

Fig. 5. Bioavailable strontium isoscape map of The Netherlands.

7.7. Isoscape X: no data coverage

The newly developed bioavailable strontium map of The Netherlands lacks data coverage for approximately 15%. This includes two major regions: the boulder clay areas in the northern parts of The Netherlands and the Peelhorst, a district located east of the Rur Graben (isoscape D). In particular the former region is expected to exhibit high $^{87}Sr/^{86}Sr$ values (>0.7113; see also McManus et al., 2013), increasing the range of isotopic variations within The Netherlands. The latter region is comprised of fluviatile and aeolian sands of the Beegden and Boxtel Formations; sediments from both formations will be characterized by unradiogenic $^{87}Sr/^{86}Sr$ values, averaging around 0.7092. Additional analysis will hopefully enable the designation of this area to an existing or new isoscape. Due to the restricted availability of archaeological fauna samples in these parts of The Netherlands, however, may require a different sampling strategy.

8. Conclusion

Correct interpretation of strontium isotope data in respect of potential past migration among archaeological human and animal populations requires the establishment of regional maps of local bioavailable strontium. The primary aim of this paper was to present a preliminary archaeological bioavailable $^{87}Sr/^{86}Sr$ ratio map of The Netherlands. This research has shown that the diversity in the Dutch geological subsurface is directly reflected in the spatial distribution of the strontium values: large isotopic differences are apparent between the measured bioavailable strontium in Holocene and Pleistocene formations. As a result, The Netherlands could be divided into six bioavailable strontium isoscapes on the basis of the isotopic analysis of 143 archaeological rodents, and small and medium mammals. Ultimately, this map can be used to help improve our understanding of the intensity and extent of mobility in Dutch and European archaeological context. It must be taken into account, however, that the isoscapes presented here only give guidance to the isotopic variations that can be expected in The Netherlands. Variations in $^{87}Sr/^{86}Sr$ ratios in human populations due to differences in diet or the origin of the food resources, may be larger than the intra-isoscape variation. The best approach to study palaeomobility in ancient populations is therefore to combine the isoscape map with appropriate (modern) biosphere samples and a statistical assessment of the investigated population.

An idealistic archaeological approach was taken to avoid potential problems of human influence by cultivation (ploughing, fertilizers, irrigation and drainage changes); however, this approach did not yield 100% coverage. Therefore, to improve its predictive power and to refine the presented bioavailable strontium map to provide a more comprehensive coverage, the analysis of archaeological samples will be continued for the foreseeable future. Due to the restricted availability of archaeological fauna samples in certain parts of The Netherlands, however, additional biosphere samples will need to be analysed. Validation of this approach will be needed, however, with studies to establish the extent to which specific floral are offset compared to the average archaeological bioavailable strontium. The base map presented here now allows a detailed assessment of potential offsets in the $^{87}Sr/^{86}Sr$ recorded by different proxies at the regional scale. Consequently, to enable a meaningful comparison, a separate biosphere strontium map will be constructed that covers all main landscape types in The Netherlands. Although such an approach will require calibration for use in an archaeological context, it may prove to be directly appropriate for (modern) forensic purposes.

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Appendix A. Dataset used for extrapolation

Main landscape type with data coverage	Isoscape
Lower Meuse terraces	A
Dunes, beaches and beach barriers	B
Wadden Sea clay area	B
Rhine–Meuse delta	B
Zeeland clay area	B
Young coastal accretion area	B
Holland peat area	C
Kempen aeolian sand deposits	C
Northern aeolian sand deposits	C
Rur Graben	D
Push moraines	E
Meuse valley	F
Northern loess area	F
Southern loess area	F
Main landscape type without data coverage	Isoscape used for extrapolation
Meuse valley	A
“Droogmakerijen” (Polders)	B
IJssel valley	B
Higher Rhine terraces	B
Lower Rhine terraces	B
Wadden Sea peat area	B
North Holland clay area	B
In historical times severely flooded areas	B
Aeolian sand deposits and boulder clay	–
Limestone hills of Münster	–
Peelhorst aeolian sand deposits	–
Flemisch aeolian sand deposits	–
Ardennes foothills	–

Appendix B. Archaeological bioavailable $^{87}Sr/^{86}Sr$ data from The Netherlands per isoscape (A–F). Asterisks indicate statistical outliers. Latitude and longitude information conform to WGS84 geodetic datum

Identifier	Main landscape type	Site	Taxon	$^{87}Sr/^{86}Sr$	±2SE	Latitude	Longitude
A	Lower Meuse terraces	Boxmeer	*Muroidea*	0.70795	0.00001	51.65	5.95
			Rattus sp.	0.70857	0.00001		
			Average	0.70826			
			1σ	0.00043			
			N	2			
B	Dunes, beaches and beach barriers	Alkmaar	*Lepus europaeus*	0.70896	0.00001	52.63	4.74
			Lepus europaeus	0.70898	0.00001		
			Lepus europaeus	0.70901	0.00001		
			Lepus europaeus	0.70905	0.00001		
			Rattus sp.	0.70915	0.00001		
			Lepus europaeus	0.70916	0.00001		
			Lepus europaeus	0.70920	0.00001		
			Muroidea	0.70934*	0.00001		
			Lepus europaeus	0.70936*	0.00001		
		Naaldwijk	*Microtus oeconomus*	0.70894	0.00001	51.99	4.21
			Microtus sp.	0.70897	0.00001		
			Microtus oeconomus	0.70898	0.00001		
	Wadden Sea clay area	Achlum	*Muroidea*	0.70904	0.00001	53.15	5.48
			Muroidea	0.70906	0.00001		
			Microtus sp.	0.70906	0.00001		
			Microtus sp.	0.70907	0.00001		
			Microtus sp.	0.70911	0.00001		
			Microtus sp.	0.70913	0.00001		
		Firdgum	*Microtus* sp.	0.70891	0.00001	53.25	5.56
		Hatsum	*Muroidea*	0.70910	0.00001	53.20	5.64
			Muroidea	0.70913	0.00001		
		Jelsum	*Muroidea*	0.70901	0.00001	53.23	5.78
			Muroidea	0.70902	0.00001		
			Microtus sp.	0.70906	0.00001		
			Muroidea	0.70907	0.00001		
			Muroidea	0.70908	0.00001		
			Muroidea	0.70915	0.00001		
		Leeuwarden	*Muroidea*	0.70926	0.00001	53.20	5.80
			Muroidea	0.70932*	0.00001		
			Muroidea	0.70941*	0.00001		
		Tirns	*Muroidea*	0.70904	0.00001	53.06	5.63
		Englum	*Muroidea*	0.70905	0.00001	53.31	6.40
			Muroidea	0.70905	0.00001		
			Muroidea	0.70907	0.00001		
	Young coastal area accretion	Wetsingermaar	*Muroidea*	0.70914	0.00001	53.30	6.52
			Muroidea	0.70916	0.00001		
	Rhine–Meuse delta	Beuningen	*Sorex coronatus*	0.70617*	0.00001	51.86	5.77
			Muroidea	0.70885	0.00001		
			Sorex coronatus	0.70887	0.00001		
		Culemborg	*Muroidea*	0.70902	0.00001	51.96	5.24
			Microtus sp.	0.70906	0.00001		
			Muroidea	0.70909	0.00001		
		Lent	*Muroidea*	0.70884	0.00001	51.86	5.86
		Meteren	*Muroidea*	0.70890	0.00001	51.88	5.29
		Nijmegen-Lent	*Apodemus sylvaticus*	0.70895	0.00001	51.86	5.86
		Tiel	*Muroidea*	0.70888	0.00001	51.89	5.43
		IJsselstein	*Muroidea*	0.70923	0.00001	52.02	0.50
		Gorinchem	*Muroidea*	0.70886	0.00001	51.84	4.98
			Muroidea	0.70891	0.00001		
			Muroidea	0.70894	0.00001		
		Oegstgeest	*Felis catus*	0.70889	0.00001	52.18	4.47
			Felis catus	0.70892	0.00001		
			Felis catus	0.70893	0.00001		
			Felis catus	0.70895	0.00001		
			Felis catus	0.70896	0.00001		
			Felis catus	0.70897	0.00001		
			Felis catus	0.70899	0.00001		
			Muroidea	0.70909	0.00001		
			Felis catus	0.70910	0.00001		
			Felis catus	0.70911	0.00001		
		Rotterdam	*Arvicola amphibius*	0.70882	0.00001	51.92	4.49
			Felis catus	0.70895	0.00001		
			Felis catus	0.70914	0.00001		
		Valkenburg	*Rattus* sp.	0.70873*	0.00001	52.18	4.43
			Muroidea	0.70891	0.00001		
			Rattus sp.	0.70898	0.00001		

(*continued*)

Identifier	Main landscape type	Site	Taxon	$^{87}Sr/^{86}Sr$	±2SE	Latitude	Longitude
			Muroidea	0.70907	0.00001		
			Muroidea	0.70908	0.00001		
	Zeeland clay area	Vlissingen	*Oryctolagus cuniculus*	0.70902	0.00001	51.45	3.57
			Rattus sp.	0.70903	0.00001		
			Muroidea	0.70910	0.00001		
			Felis catus	0.70915	0.00001		
		Delft	*Muroidea*	0.70889	0.00001	52.01	4.36
			Arvicolinae	0.70891	0.00001		
			Arvicolinae	0.70893	0.00001		
			Muroidea	0.70899	0.00001		
			Muroidea	0.70905	0.00001		
			Muroidea	0.70906	0.00001		
			Muroidea	0.70906	0.00001		
			Rattus sp.	0.70911	0.00001		
			Rattus sp.	0.70920	0.00001		
			Rattus sp.	0.70920	0.00001		
		Rijswijk	*Muroidea*	0.70897	0.00001	52.04	4.32
			Muroidea	0.70899	0.00001		
			Muroidea	0.70900	0.00001		
			Muroidea	0.70900	0.00001		
			Muroidea	0.70900	0.00001		
			Muroidea	0.70901	0.00001		
			Muroidea	0.70903	0.00001		
			Muroidea	0.70909	0.00001		
			Muroidea	0.70914	0.00001		
			Average	0.70903			
			1σ	0.00010			
			N	85			
C	Holland peat area	Amsterdam	*Rattus rattus*	0.70925	0.00001	52.37	4.90
			Rattus rattus	0.70926	0.00001		
			Microtus sp.	0.70932	0.00001		
			Rattus rattus	0.70975*	0.00001		
	Kempen aeolian sand deposits	Breda	*Muroidea*	0.70910	0.00001	51.59	4.78
			Muroidea	0.70917	0.00001		
			Muroidea	0.70919	0.00001		
			Muroidea	0.70932	0.00001		
			Muroidea	0.70935	0.00001		
			Muroidea	0.70944	0.00001		
			Muroidea	0.70945	0.00001		
			Muroidea	0.73405*	0.00001		
	Northern aeolian sand deposits	Zwolle	*Felis catus*	0.70929	0.00001	52.51	6.11
			Felis catus	0.70930	0.00001		
			Felis catus	0.70939	0.00001		
		Amersfoort	*Rattus* sp.	0.70944	0.00001	52.16	5.39
			Average	0.70930			
			1σ	0.00011			
			N	14			
D	Rur Graben	‘s-Hertogenbosch	*Soricida*	0.70912*	0.00001	51.70	5.32
			Muroidea	0.70989	0.00001		
			Microtus sp.	0.71024	0.00001		
			Microtus sp.	0.71039	0.00001		
			Microtus sp.	0.71052	0.00001		
		Eindhoven	*Muroidea*	0.70984	0.00001	51.44	5.47
			Muroidea	0.70986	0.00001		
			Muroidea	0.70991	0.00001		
			Muroidea	0.70998	0.00001		
			Muroidea	0.71003	0.00001		
		Sint-Oedenrode	*Microtus* sp.	0.70970	0.00001	51.57	5.46
			Lepus europaeus	0.71011	0.00001		
			Average	0.71004			
			1σ	0.00025			
			N	11			
E	Push moraines	Oldenzaal	*Felis catus*	0.70985	0.00001	52.31	6.93
			Felis catus	0.70991	0.00001		
			Felis catus	0.70995	0.00001		
			Felis catus	0.71016	0.00001		
			Oryctolagus cuniculus	0.71029	0.00001		
			Felis catus	0.71056	0.00001		
			Lepus europaeus	0.71092	0.00001		
			Average	0.71023			
			1σ	0.00039			

(continued on next page)

(*continued*)

Identifier	Main landscape type	Site	Taxon	$^{87}Sr/^{86}Sr$	±2SE	Latitude	Longitude
			N	7			
F	Northern and southern loess areas	Borgharen	*Muroidea*	0.71054	0.00001	50.88	5.69
			Muroidea	0.71059	0.00001		
			Muroidea	0.71062	0.00001		
			Muroidea	0.71067	0.00001		
			Muroidea	0.71068	0.00001		
			Muroidea	0.71074	0.00001		
			Muroidea	0.71074	0.00001		
			Muroidea	0.71081	0.00001		
			Muroidea	0.71093	0.00001		
			Muroidea	0.71101	0.00001		
			Muroidea	0.71102	0.00001		
			Vulpes vulpes	0.71102	0.00001		
			Muroidea	0.71102	0.00001		
			Vulpes vulpes	0.71107	0.00001		
			Muroidea	0.71117	0.00001		
			Average	0.71084			
			1σ	0.00020			
			N	15			

References

Bagard, M.-L., Schmitt, A.-D., Chabaux, F., Pokrovsky, O.S., Viers, J., Stille, P., Labolle, F., Prokushkin, A.S., 2013. Biogeochemistry of stable Ca and radiogenic Sr isotopes in a larch-covered permafrost-dominated watershed of Central Siberia. Geochim. Cosmochim. Acta 114, 169–187.

Bakels, C., Jacomet, S., 2003. Access to luxury foods in Central Europe during the Roman period: the archaeobotanical evidence. World Archaeol. 34, 542–557. http://dx.doi.org/10.1080/0043824021000026503.

Bataille, C.P., Bowen, G.J., 2012. Mapping $^{87}Sr/^{86}Sr$ variations in bedrock and water for large scale provenance studies. Chem. Geol. 304–305, 39–52. http://dx.doi.org/10.1016/j.chemgeo.2012.01.028.

Bataille, C.P., Laffoon, J., Bowen, G.J., 2012. Mapping multiple source effects on the strontium isotopic signatures of ecosystems from the circum-Caribbean region. Ecosphere 3. http://dx.doi.org/10.1890/es12-00155.1 (art118).

Beard, B.L., Johnson, C.M., 2000. Strontium isotope composition of skeletal material can determine the birth place and geographic mobility of humans and animals. J. Forensic Sci. 45, 1049–1061.

Bentley, R.A., 2006. Strontium isotopes from the earth to the archaeological skeleton: a review. J. Archaeol. Method Theory 13, 135–187.

Bentley, R.A., Knipper, C., 2005. Geographical patterns in biologically available strontium, carbon and oxygen isotope signatures in prehistoric SW Germany. Archaeometry 47, 629–644.

Bentley, R.A., Price, T.D., Stephan, E., 2004. Determining the 'local' $^{87}Sr/^{86}Sr$ range for archaeological skeletons: a case study from Neolithic Europe. J. Archaeol. Sci. 31, 365–375.

Berendsen, H.J.A., 1998. De vorming van het land. Inleiding in de geologie en de geomorfologie. 3rd ed. Van Gorkum & Comp. B.V., Assen.

Borg, L.E., Banner, J.L., 1996. Neodymium and strontium isotopic constraints on soil sources in Barbados, West Indies. Geochim. Cosmochim. Acta 60, 4193–4206.

Borger, G.J., 1992. Draining–digging–dredging; the creation of a new landscape in the peat areas of the low countries. Geobotany 18, 131–171.

Bowen, G.J., 2010. Isoscapes: spatial pattern in isotopic biogeochemistry. Annu. Rev. Earth Planet. Sci. 38, 161–187. http://dx.doi.org/10.1146/annurev-earth-040809-152429.

Budd, P., Montgomery, J., Barreiro, B., Thomas, R.G., 2000. Differential diagenesis of strontium in archaeological human dental tissues. Appl. Geochem. 15, 687–694.

Buhl, D., Neuser, R.D., Richter, D.K., Riedel, D., Roberts, B., Strauss, H., Veizer, J., 1991. Nature and nurture: environmental isotope story of the River Rhine. Naturwissenschaften 78, 337–346. http://dx.doi.org/10.1007/bf01131605.

Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F., Otto, J.B., 1982. Variation of seawater $^{87}Sr/^{86}Sr$ throughout Phanerozoic time. Geology 10, 516–519. http://dx.doi.org/10.1130/0091-7613(1982)10<516:vosstp>2.0.co;2.

Burmeister, S., 2000. Archaeology and migration: approaches to an archaeological proof of migration. Curr. Anthropol. 41, 539–567. http://dx.doi.org/10.1086/317383.

Burton, J., 2008. Bone chemistry and trace element analysis. In: Katzenberg, A., Saunders, S.R. (Eds.), Biological Anthropology of the Human Skeleton, second ed. John Wiley & Sons Inc., pp. 443–460.

Capo, R.C., Stewart, B.W., Chadwick, O.A., 1998. Strontium isotopes as tracers of ecosystem processes: theory and methods. Geoderma 82, 197–225.

CBS, 2009. http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=71284NED&D1=0,2&D2=0&D3=0-9&HD=091110-0913&HDR=G1,G2&STB=T.

Childe, V.G., 1925. The Dawn of European Civilization. Kegan Paul, Oxford.

Colominas, L., Edwards, C.J., Beja-Pereira, A., Vigne, J.-D., Silva, R.M., Castanyer, P., Tremoleda, J., Saña Seguí, M., Pérez-Ripoll, M., Goyache, F., Howe, C.J., Barker, G., Bower, M.A., 2015. Detecting the T1 cattle haplogroup in the Iberian Peninsula from Neolithic to Medieval times: new clues to continuous cattle migration through time. J. Archaeol. Sci. 59, 110–117. http://dx.doi.org/10.1016/j.jas.2015.04.014.

De Bont, C.H.M., 2008. Vergeten land; ontginning, bewoning en waterbeheer in de westnederlandse veengebieden (800–1350). Wageningen University, Wageningen (PhD thesis).

De Mulder, E.F.J., Geluk, M.C., Ritsema, I., Westerhoff, W.E., Wong, T.E., 2003. De ondergrond van Nederland. TNO, Utrecht.

Dijkstra, F.A., Van Breemen, N., Jongmans, A.G., Davies, G.R., Likens, G.E., 2003. Calcium weathering in forested soils and the effect of different tree species. Biogeochemistry 62, 253–275. http://dx.doi.org/10.1023/A:1021132132199.

Evans, J.A., Montgomery, J., Wildman, G., 2009. Isotope domain mapping of $^{87}Sr/^{86}Sr$ biosphere variation on the Isle of Skye, Scotland. J. Geol. Soc. 166, 617–631.

Evans, J.A., Montgomery, J., Wildman, G., Boulton, N., 2010. Spatial variations in biosphere $^{87}Sr/^{86}Sr$ in Britain. J. Geol. Soc. 167, 1–4.

Faure, G., Mensing, T., 2005. Isotopes: Principles and Applications. Wiley, Hoboken.

Frei, K.M., Frei, R., 2011. The geographic distribution of strontium isotopes in Danish surface waters: a base for provenance studies in archaeology, hydrology and agriculture. Appl. Geochem. 26, 326–340.

Frei, K.M., Price, T.D., 2012. Strontium isotopes and human mobility in prehistoric Denmark. Archaeol. Anthropol. Sci. 4, 103–114. http://dx.doi.org/10.1007/s12520-011-0087-7.

Gerding, M.A.W., 1995. Vier eeuwen turfwinning. De verveningen in Groningen, Friesland, Drenthe en Overijssel tussen 1550–1950A.A.G. Bijdragen 35. Landbouwuniversiteit Wageningen, Wageningen.

Grumbkow, P.v., Frommer, S., Kootker, L.M., Davies, G.R., Mazanec, J., Hummel, S., 2013. Kinship and mobility in 11th-century A.D. Gammertingen, Germany: an interdisciplinary approach. J. Archaeol. Sci. 40, 3768–3776. http://dx.doi.org/10.1016/j.jas.2013.05.001.

Hakenbeck, S., 2008. Migration in archaeology: are we nearly there yet? Archaeol. Rev. Cambridge 23 (2), 9–26.

Hammond, C., O'Connor, T., 2013. Pig diet in medieval York: carbon and nitrogen stable isotopes. Archaeol. Anthropol. Sci. 5, 123–127. http://dx.doi.org/10.1007/s12520-013-0123-x.

Hedman, K.M., Curry, B.B., Johnson, T.M., Fullagar, P.D., Emerson, T.E., 2009. Variation in strontium isotope ratios of archaeological fauna in the Midwestern United States: a preliminary study. J. Archaeol. Sci. 36, 64–73.

Hillson, S., 1986. Teeth. Cambridge University Press, Cambridge.

Hodell, D.A., Quinn, R.L., Brenner, M., Kamenoc, G., 2004. Spatial variation of strontium isotopes ($^{87}Sr/^{86}Sr$) in the Maya region: a tool for tracking ancient human migration. J. Archaeol. Sci. 31, 585–601.

Hoppe, K.A., Koch, P.L., Furutani, T.T., 2003. Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. Int. J. Osteoarchaeol. 13, 20–28.

Huisman, D.J., Van Os, B.J.H., Jans, M.M.E., 2011. 6. Resultaten degradatieonderzoek. In: Lauwerier, R.C.G.M., Müller, A., D.E. S (Eds.), Merovingers in een villa. Romeinse villa en Merovingisch grafveld Borgharen – Pasestraat. Onderzoek 2008–2009. Rijksdienst voor het Cultureel Erfgoed, Amersfoort, pp. 39–44.

Isermann, K., 1981. Uptake of stable strontium by plants and effects on plant growth. In: Skoryna, S.C. (Ed.), Handbook of Stable Strontium. Springer, US, pp. 65–86 http://dx.doi.org/10.1007/978–1-4684-3698-3_5.

Jongmans, A.G., Van den Berg, M.W., Sonneveld, M.P.W., Peek, G.J.W.C., Berg van Saparoea, R.M., 2013. Landschappen van Nederland: geologie, bodem en landgebruik. Wageningen Academic, Wageningen.

Jung, S.J.A., Davies, G.R., Ganssen, G.M., Kroon, D., 2004. Stepwise Holocene aridification in NE Africa deduced from dust-borne radiogenic isotope records. Earth Planet. Sci. Lett. 221, 27–37. http://dx.doi.org/10.1016/S0012-821X(04)00095-0.

Kohn, M.J., Schoninger, M.J., Barker, W.W., 1999. Altered states: effects of diagenesis on fossil tooth chemistry. Geochim. Cosmochim. Acta 63, 2737–2747.

Koomen, A.J.M., Excaltus, R.P., 2003. De vervlakking van Nederland; naar een gaafheidkaart voor reliëf en bodem. Alterra-rapport 740. Alterra Research Institute, Wageningen.

Koomen, A.J.M., Maas, G.J., 2004. Geomorfologische Kaart Nederland (GKN); Achtergronddocument bij het landsdekkende digitale bestand. Alterra-rapport 1039. Alterra Research Institute, Wageningen.

Kootker, L.M., Davies, R.D., 2016. Bones, teeth and invisible tracers: the current state of human bioarchaeological isotope geochemistry research in The Netherlands. In: Kluiving, S.J., Kootker, L.M., Hermans, R.A.E. (Eds.), Interdisciplinarity Between Humanities and Science, Festschrift Prof. Dr. H. Kars (submitted for publication).

Lascaris, M.A., De Kraker, A.M.J., 2013. Dikes and other hydraulic engineering works from the Late Iron Age and Roman period on the coastal area between Dunkirk and the Danish Bight. In: Thoen, E., Borger, G., De Kraker, A.A.M.J., Soens, T., Tys, D., Vervoet, L., Weerts, H.J.T. (Eds.), Landscapes or Seascapes? The History of the Coastal Environment in the North Sea Area Reconsidered. CORN Publication Series 13, pp. 177–198.

Livarda, A., 2011. Spicing up life in northwestern Europe: exotic food plant imports in the Roman and medieval world. Veg. Hist. Archaeobot. 20, 143–164. http://dx.doi.org/10.1007/s00334-010-0273-z.

Maurer, A.-F., Galer, S.J.G., Knipper, C., Beierlein, L., Nunn, E.V., Peters, D., Tütken, T., Alt, K.W., Schöne, B.R., 2012. Bioavailable $^{87}Sr/^{86}Sr$ in different environmental samples — effects of anthropogenic contamination and implications for isoscapes in past migration studies. Sci. Total Environ. 433, 216–229.

Mays, S., Beavan, N., 2012. An investigation of diet in early Anglo-Saxon England using carbon and nitrogen stable isotope analysis of human bone collagen. J. Archaeol. Sci. 39, 867–874.

McManus, E., Montgomery, J., Evans, J., Lamb, A., Brettell, R., Jelsma, J., 2013. "To the land or to the sea": diet and mobility in Early Medieval Frisia. J. Isl. Coast. Archaeol. 8, 255–277. http://dx.doi.org/10.1080/15564894.2013.787565.

Miller, E.K., Blum, J.D., Friedland, A.J., 1993. Determination of soil exchangeable-cation loss and weathering rates using Sr isotopes. Nature 362, 438–441.

Mulder, J.L., 2007. Vossenbeheer voor hamsters, (hoe) heeft het gewerkt? Rapport Bureau Mulder-natuurlijk 2007-02, pp. 1–40

Nafplioti, A., 2011. Tracing population mobility in the Aegean using isotope geochemistry: a first map of local biologically available $^{87}Sr/^{86}Sr$ signatures. J. Archaeol. Sci. 38, 1560–1570.

Nehlich, O., Montgomery, J., Evans, J., Schade-Lindig, S., Pichler, S.L., Richards, M.P., Alt, K.W., 2009. Mobility or migration: a case study from the Neolithic settlement of Nieder-Mörlen (Hessen, Germany). J. Archaeol. Sci. 36, 1791–1799.

Nelson, B.K., Deniro, M.J., Schoeninger, M.J., De Paolo, D.J., Hare, P.E., 1986. Effects of diagenesis on strontium, carbon, nitrogen and oxygen concentration and isotopic composition of bone. Geochim. Cosmochim. Acta 50, 1941–1949.

Oelze, V.M., Nehlich, O., Richards, M.P., 2012. 'There's no place like home'—no isotopic evidence for mobility at the early Bronze age cemetery of Singen, Germany. Archaeometry 54, 752–778. http://dx.doi.org/10.1111/j.1475-4754.2011.00644.x.

Overeem, I., Kroonenberg, S.B., 2002. De Amazone in de Noordzee. Nat. Tech. 70 (1), 66–71.

Palmer, M.R., Edmond, J.M., 1989. The strontium isotope budget of the modern ocean. Earth Planet. Sci. Lett. 92, 11–26.

Petelet-Giraud, E., Klaver, G., Negrel, P., 2009. Natural versus anthropogenic sources in the surface- and groundwater dissolved load of the Dommel river (Meuse basin): constraints by boron and strontium isotopes and gadolinium anomaly. J. Hydrol. 369, 336–349. http://dx.doi.org/10.1016/j.jhydrol.2009.02.029.

Petzelberger, B.E.M., Behre, K., Geyh, M.A., 1999. Beginn der Hochmoorentwicklung und Ausbreitung der Hochmoore inNordwestdeutschland–ersteErgebnisseeinesneuen Projektes. Telma 29, 21–38.

Price, T.D., 2013. Human mobility at Uppåkra. A preliminary report on isotopic proveniencing. In: Hårdh, B., Larsson, L. (Eds.), Studies at Uppåkra, an Iron Age city in Scania. Institute of Archaeology, Lund, Sweden, pp. 157–169.

Price, T.D., Burton, J.H., Bentley, R.A., 2002. The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. Archaeometry 44, 117–135.

Price, T.D., Wahl, J., Knipper, C., Burger-Heinrich, E., Kurtz, G., Bentley, R.A., 2003. Das bandkeramische Gräberfeld vom „Viesenhäuser Hof" bei Stuttgart-Mühlhausen: Neue Untersuchungsergebnisse zum Migrationsverhalten im frühen Neolithikum. In: Funda, D.T. (Ed.), Fundberichte aus Baden-Württemberg. Kommissionsverlag Konrad Theiss Verlag, Stuttgart, Germany, pp. 23–58.

Price, T.D., Wahl, J., Bentley, R.A., 2006. Isotopic evidence for mobility and group organization among Neolithic farmers at Talheim, Germany, 5000 BC. Eur. J. Archaeol. 9, 259–284.

Pye, K., 2004. Isotope and trace element analysis of human teeth and bones for forensic purposes. Geol. Soc. Lond., Spec. Publ. 232, 215–236.

RCE, 2015. Archeologische landschappenkaart (versie 1.0), Amersfoort.

Richards, M.P., Mays, S., Fuller, B.T., 2002. Stable carbon and nitrogen isotope values of bone and teeth reflect weaning age at the Medieval Wharram Percy site, Yorkshire, UK. Am. J. Phys. Anthropol. 119, 205–210. http://dx.doi.org/10.1002/ajpa.10124.

Schokker, J., Weerts, H.J.T., Westerhoff, W.E., Berendsen, H.J.A., Den Otter, C., 2007. Introduction of the Boxtel Formation and implications for the Quaternary lithostratigraphy of the Netherlands. Neth. J. Geosci. Geol. Mijnb. 86 (3), 197–210.

Schwarcz, H.P., White, C.D., Longstaffe, F.J., 2010. Stable and radiogenic isotopes in biological archaeology: some applications. In: West, J.B., G.J.B., Dawson, T.E., Tu, K.P. (Eds.), Understanding movement, pattern, and process on Earth through isotope mapping. Springer Science, Netherlands, pp. 335–356.

Schweissing, M.M., Grupe, G., 2003. Tracing migration events in man and cattle by stable strontium isotope analysis of appositionally grown mineralized tissue. Int. J. Osteoarchaeol. 13, 96–103. http://dx.doi.org/10.1002/oa.652.

Singman, J.L., 1999. Daily Life in Medieval Europe. Greenwood Press, Westport, Connecticut.

Sjögren, K.-G., Price, T.D., Ahlström, T., 2009. Megaliths and mobility in south-western Sweden. Investigating relationships between a local society and its neighbours using strontium isotopes. J. Anthropol. Archaeol. 28, 85–101.

Slovak, N.M., Paytan, A., 2011. Applications of Sr isotopes in archaeology. In: Baskaran, M. (Ed.), Handbook of Environmental Isotope Geochemistry. Spinger-Verlag, Heidelberg, pp. 743–768.

Stouthamer, E., Berendsen, H.J.A., 2000. Factors controlling the Holocene avulsion history of the Rhine–Meuse delta (The Netherlands). J. Sediment. Res. 70 (5), 1051–1064.

Stouthamer, E., Berendsen, H.J.A., 2007. Avulsion, an autogenic or allogenic controlled process? Sediment. Geol. 198, 309–325.

Tütken, T., Knipper, C., Alt, K.W., 2008. Mobilität und migration im archäologischen kontext. Informationspotential von multi-element-isotopenanalysen (Sr, Pb, O). In: Bemmann, J., Schmauder, M. (Eds.), Kulturwandel in Mitteleuropa. Langobarden - Awaren - Slawen. Akten der Internationalen Tagung in Bonn vom 25. bis 28. Februar 2008. Kolloquien zur Vor- und Frühgeschichte 11. Dr. Rudolf Habelt, Bonn, pp. 13–42.

Van der Jagt, I.M.M., Kootker, L.M., Van Kolfschoten, T., Kars, H., Davies, G.R., 2012. An insight into animal exchange in Early Medieval Oegstgeest: a combined archaeozoological and isotopic approach. In: Raemaekers, D.C.M., Esser, E., Lauwerier, R.C.G.M., Zeiler, J.T. (Eds.), A Bouquet of Archaeological Studies. Essays in Honour of Wietske Prummel. Barkhuis, Eelde, pp. 137–149.

Van der Merwe, N.J., Vogel, J.C., 1977. Isotopic evidence for early maize cultivation in New York state. Am. Antiq. 42, 238–242.

Van der Veer, G., 2006. Geochemical soil survey of the Netherlands. Atlas of major and trace elements in topsoil and parent material; assessment of natural and anthropogenic enrichment factors. In: Borchert, J.G., Van Amersfoort, J.M.M., Berendsen, H.J.A., Druijven, P.C.J., Kouwenhoven, A.O., Scholten, H. (Eds.), Netherlands Geographical Studies 347. Koninklijk Nederlands Aardrijkskundig Genootschap, Utrecht.

Veizer, J., 1989. Strontium isotopes in seawater through time. Annu. Rev. Earth Planet. Sci. 17, 141–167.

Viner, S., Evans, J., Albarella, U., Parker Pearson, M., 2010. Cattle mobility in prehistoric Britain: strontium isotope analysis of cattle teeth from Durrington Walls (Wiltshire, Britain). J. Archaeol. Sci. 37, 2812–2820.

Voerkelius, S., Lorenz, G.D., Rummel, S., Quétel, C.R., Heiss, G., Baxter, M., Brach-Papa, C., Deters-Itzelsberger, P., Hoelzl, S., Hoogewerff, J., Ponzevera, E., Van Bocxstaele, M., Ueckermann, H., 2010. Strontium isotopic signatures of natural mineral waters, the reference to a simple geological map and its potential for authentication of food. Food Chem. 118, 933–940.

Vos, P., 2015. Origin of the Dutch Coastal Landscape. Long-Term Landscape Evolution of the Netherlands During the Holocene, Described and Visualized in National, Regional and Local Palaeogeographical Map Series. Barkhuis Publishing, Eelde.

Vos, P., De Vries, S., 2013. 2e generatie palaeogeografische kaarten van Nederland (versie 2.0). Deltares, Utrecht.

Vos, P.C., Bazelmans, J., Weerts, H.J.T., Van der Meulen, H.J.T., 2011. Atlas van Nederland in het Holoceen. Bert Bakker, Amsterdam.

Weerts, H.J.T., Cleveringa, P., Ebbing, J.H.J., Lang, F.D.D., Westerhoff, W.E., 2003. De lithostratigrafische indeling van Nederland – Formaties uit het Tertiair en Kwartair, NITG 03-051-A. Nederlands Instituut voor Toegepaste Geowetenschappen TNO, Utrecht.

Willmes, M., McMorrow, L., Kinsley, L., Armstrong, R., Aubert, M., Eggins, S., Falguères, C., Maureille, B., Moffat, I., Grün, R., 2014. The IRHUM (Isotopic Reconstruction of Human Migration) database — bioavailable strontium isotope ratios for geochemical fingerprinting in France. Earth Syst. Sci. Datas 6, 117–122. http://dx.doi.org/10.5194/essd-6-117-2014.

Wright, L.E., 2005. Identifying immigrants to Tikal, Guatemala: defining local variability in strontium isotope ratios of human tooth enamel. J. Archaeol. Sci. 32, 555–566.

www.bodemdata.nl, last accessed September 2015.

Zwart, M.H., Hooijboer, A.E.J., Fraters, B., Kotte, M., Duin, R.N.M., Daatselaar, C.H.G., Bosma, J.N., 2008. Agricultural practice and water quality in the Netherlands in the 1992–2006 period. RIVM report 680716003/2008, p. 131.