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Preliminary strontium isotope ($^{87}Sr/^{86}Sr$) baselines for the Bjäre Peninsula and Halland in southern Sweden

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During the last decade, the application of strontium isotope analysis ($^{87}Sr/^{86}Sr$) has increased rapidly. The understanding of the strontium isoscape and the construction of a strontium isotope baseline in southern Scandinavia are biased toward Denmark and southwestern to eastern Scania. We report the results of new baseline samples in Halland and the Bjäre Peninsula, adding to the rich strontium isotope library that exists for southern Scandinavia. We add nuance to the previous divisions of Scania, in which the Bjäre Peninsula is not well represented. The results show that the Bjäre Peninsula is characterized by relatively low $^{87}Sr/^{86}Sr$ values gathered in the preliminary baseline 0.7100 ± 0.0024 (2σ, $n = 8$), similar to that of southwest Scania and Zealand in Denmark. There is a greater variation and higher values among the Halland samples. Together with previously published faunal samples, a preliminary $^{87}Sr/^{86}Sr$ baseline for Halland is 0.7122 ± 0.0055 (2σ, $n = 24$). We apply these baseline results to archaeological cases, both human and animal, from recent excavations in the Bjäre Peninsula. The results imply that there was a certain degree of mobility and interaction across the landscape in this region of southern Scandinavia in prehistory.

KEYWORDS

strontium isotope analysis, archaeology, Bjäre, Halland, archaeological mobility studies

1 Introduction

The archaeological application of strontium isotope ($^{87}Sr/^{86}Sr$) analysis has majorly impacted the study of movement, mobility, interaction, and communication in prehistory (Slovak and Paytan, 2012; see Kristiansen, 2022). The basis of the archaeological understanding of mobility is now transferred from being object-based to being based on the research subjects themselves, that is, the remains of the humans and animals inhabiting the past. The uptake of $^{87}Sr/^{86}Sr$ into organic tissues (bone, teeth, etc.) is directly related to the local bioavailable strontium ratios. However, for $^{87}Sr/^{86}Sr$ analysis to provide meaningful information on migration, local $^{87}Sr/^{86}Sr$ "baselines," that is, reference values, are needed for any geographical area. The understanding of the $^{87}Sr/^{86}Sr$ ratio variation in southern Scandinavia has significantly increased since the surge in strontium-related studies in the last few decades. Published baseline studies exist for Scania (e.g., Ladegaard-Pedersen et al., 2021; Boethius et al., 2022), western Sweden (e.g., Blank et al., 2018; Klassen et al., 2020), and Denmark (e.g., Frei et al., 2019). The $^{87}Sr/^{86}Sr$ strontium isotope mapping is cumulative, meaning that adding data increases the knowledge of local strontium isotopic variations and bioavailable strontium (e.g., Holt et al., 2021). The majority of $^{87}Sr/^{86}Sr$ in Scania is based primarily on samples from the southern and eastern parts. The northwest Scania, including the Bjäre Peninsula, is less sampled and thus less understood.

This article aims to fill this gap in the strontium isoscape map by presenting new baseline data from the Bjäre Peninsula and Halland. We contextualize the data by relating it to the baseline frames that exist for Scania and Halland. Like Ladegaard-Pedersen et al. (2021), we base the discussion on descriptive statistics rather than modeling approaches. We also incorporate earlier published $^{87}Sr/^{86}Sr$ reference values from Halland in our analysis (Klassen et al., 2020), presented in Supplementary Table S1. Finally, the aim is to apply this improved baseline archaeologically, with strontium isotope analyses on human and animal remains from recent excavations in Bjäre.

The Bjäre Peninsula constitutes the northwestern outpost of Scania, bordering the region of Halland to the north (Figure 1). Bjäre and parts of Halland lie on the Sveconorwegian orogen. Bjäre is covered by a granitoid to syenotoid migmatitic gneiss (1.7 Ga). This is also the case for Halland, with the addition of granite (1.7–1.0 Ga) and small spots of mainly amphibolite (1.7–0.9 Ga). The northernmost part of Halland consists of granitoid (1.6–1.5 Ga) and metamorphic bedrock, which extends northward above Lake Vänern. We also see areas of granite, syenitoid, and metamorphic equivalents (approximately 1.36–1.27 Ga) and gabbro, diorite, ultrabasic rock, dolerite (1.6–1.3 Ga), and metamorphic rocks. The intersection between Bjäre and Halland, that is, the bay interconnecting them, is Cretaceous sedimentary cover rock consisting of limestone, sandstone, and clay.

The similarity in bedrock across Halland and Bjäre and inland northern Scania indicates that most of these areas, disregarding any sea spray or marine effects, should hypothetically contain similar $^{87}Sr/^{86}Sr$ ratios. However, soil variation is often a more important consideration of bioavailable strontium (Wilhelmson, 2017, p. 199). The soil types are more heterogeneous in Bjäre, dominated by till with spots of exposed bedrock across the peninsula, while along the south coast and the "tip" of the peninsula are postglacial sand/gravel deposits (Figure 1). Halland, by comparison, is dominated by postglacial sand, with spots of fluvioglacial deposits, exposed bedrock, and clay/silt.

2 Material and methods

Leaves from two different plants from seven locations in Halland and three in Bjäre (Table 1) were sampled for the $^{87}Sr/^{86}Sr$ analysis. Three leaves were each collected from Lokal 18, Lokal 21, and Ängelbäcksstrand on Bjäre (Figure 1). We chose both coastal and inland locations to capture possible sea-spray effects or any marine variation (Figure 1). The preliminary strontium baseline is established on descriptive statistics of the isotopic results, as well as earlier published baseline $^{87}Sr/^{86}Sr$ values from Klassen et al. (2020). We have excluded samples from Klassen et al. (2020, p. 414), which we consider possibly unrepresentative of the local signal, such as modern minks, which probably were feralized from mink industries with an unknown food supply. Furthermore, we do not include humans and domestic animals, for example, pigs, sheep, and goats, that could hypothetically have a high degree of mobility (e.g., Meiri et al., 2017). This is a more conservative approach than the contextual one put forward by Klassen et al. (2020); however, we believe it is more robust in establishing the local $^{87}Sr/^{86}Sr$ baseline.

2.1 Strontium isotope analysis

The samples were processed in the isotope geochemistry clean laboratory at the Department of Earth, Marine and Environmental Sciences, University of North Carolina at Chapel Hill. Plant material (including leaves/twigs and grass) was dried in an oven at approximately 50°C overnight and then ashed in a Thermo® box (muffle) furnace at 550°C for 4 h. Bone and enamel were abraded with a Dremel, whereupon the best-preserved section was selected and lightly crushed. Approximately 8–10 mg of the sample was dissolved in distilled 3.5 M HNO_3. Strontium was isolated using ion-exchange column chromatography with EiChrom Sr-Spec™ resin using 3.5 M HNO_3 to wash the columns and quadruple distilled water to elute the strontium. H_3PO_4 was added to the sample and evaporated to dryness. The Sr samples were loaded on Re filaments with TaF_5 and analyzed in triple-dynamic multi-collector mode with $^{88}Sr = 3$ V (10^{11} Ω resistor) on either a VG Sector-54 thermal ionization mass spectrometer (TIMS) or IsotopX Phoenix X62 TIMS. All data are normalized to $^{86}Sr/^{88}Sr = 0.1194$, assuming exponential fractionation behavior. Data are reported relative to a value for SRM NBS-987 of $^{87}Sr/^{86}Sr = 0.710250$, with long-term external error of 0.000020 (2σ).

3 Results and analysis

The $^{87}Sr/^{86}Sr$ results from the plants (Table 1) are summarized for each area as the sample mean (x) ± 2σ (Wilhelmson, 2017, p. 198), generating a preliminary single-proxy baseline for Bjäre of 0.7100 ± 0.0024 (2σ, $n = 8$) and Halland 0.7124 ± 0.0058 (2σ, $n = 15$). The $^{87}Sr/^{86}Sr$ ratios of plants show that Bjäre provided lower values than Halland. The $^{87}Sr/^{86}Sr$ variation is narrower in Bjäre (0.7082–0.7115) compared to Halland (0.7087–0.7177), which could be due to relatively fewer samples or a more homogeneous makeup of bioavailable strontium. The lower $^{87}Sr/^{86}Sr$ values in Bjäre and Halland, compared to, for example, northeast Scania, probably indicate a certain degree of sea-spray effect, as these regions are closer to seawater $^{87}Sr/^{86}Sr$ values of approximately 0.70918 (McArthur et al., 2001). Klassen et al. (2020) found that $^{87}Sr/^{86}Sr$ values from faunal samples were least radiogenic along the southern Halland coast (minimum 0.7087) and most radiogenic inland (maximum 0.7189). The lowest $^{87}Sr/^{86}Sr$ values in that study were from three rodent crania (0.7087, 0.7098, and 0.7099), collected from coastal sites in Halland, leading Klassen et al. (2020) to infer that sea spray must be affecting strontium ratios in western Sweden in general. In our plant data, we do not fully observe the sea-spray effect among the samples from the coastal settlements, especially Ängelbäcksstrand (Wil 20–22) and Skummeslöv (Wil 11–12). The latter is located on younger sedimentary rocks than in most of Bjäre and Halland (Figure 1), so this is somewhat surprising. The effect of sea spray on bioavailable strontium seems

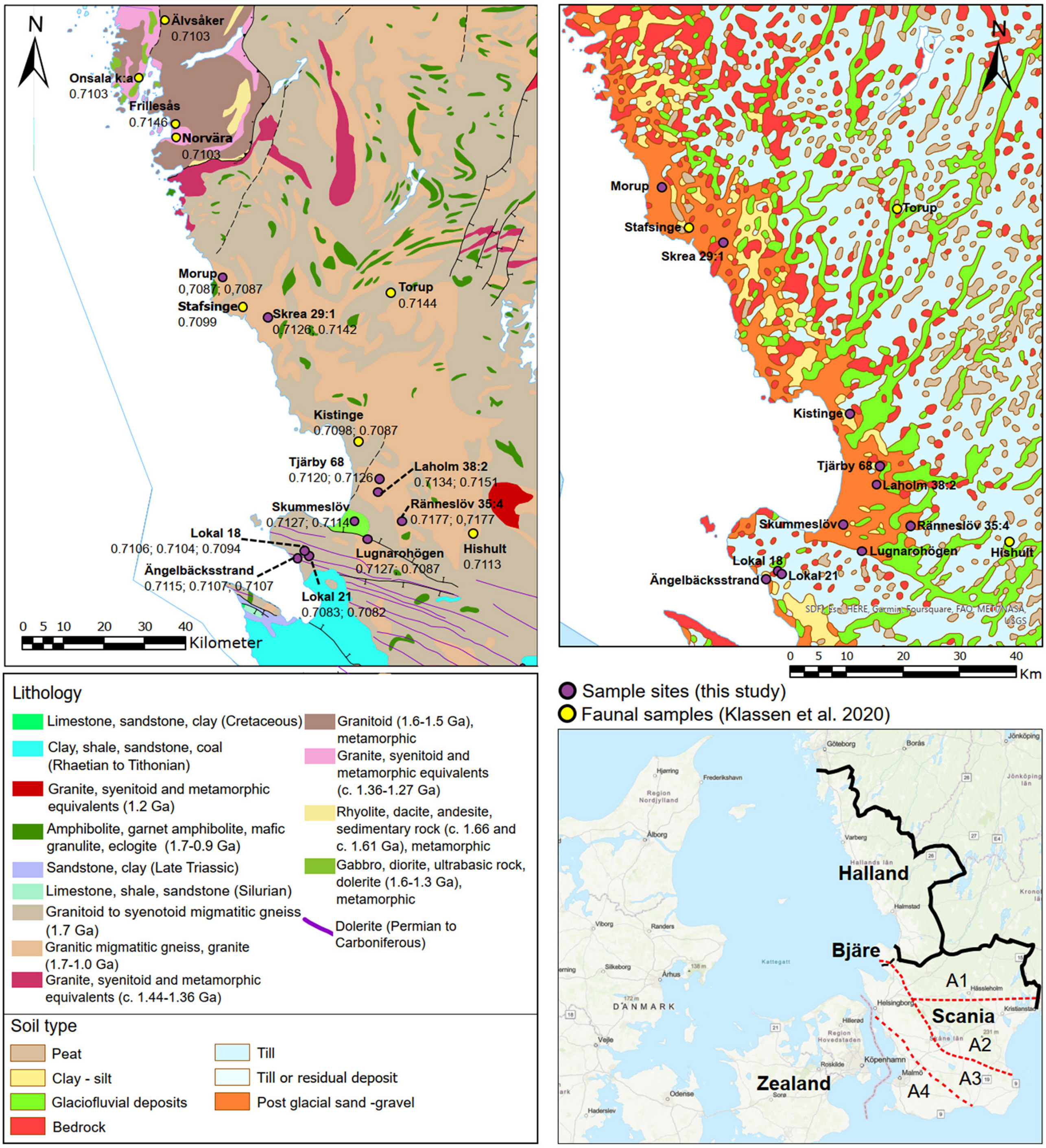

FIGURE 1
Geological map of northeastern Scania and Halland in Scandinavia. **Left**: Bedrock geology with measured flora and fauna $^{87}Sr/^{86}Sr$ values. **Right**: Soil-type geology. Faunal $^{87}Sr/^{86}Sr$ values (yellow dots) are from Klassen et al. (2020:414; Supplementary Table S1). Geological maps from "Jordarter 1:25,000-1:100,000" and "Berggrund 1:1 miljon" © Sveriges geologiska undersökning. **Lower right**: Map of southern Scandinavia, with highlighted areas of interest, including the strontium isotope areas (A1-4) suggested by Ladegaard-Pedersen et al. (2021). Maps made with ArcGIS vs 3.0.0 © ESRI.

to vary locally, especially as geological soil formation is complex, due to the idiosyncratic ways the ice retreated during the Late Glacial (see Klassen et al., 2020, p. 416). At Skummeslöv, located on limestone (Figure 1), the soil type is similar to most of the gneissic and granitic Halland coast (postglacial sand/gravel). This may have an averaging effect on the bioavailable strontium in the whole area. The till from which the Bjäre samples were taken is similar to most of inland western Sweden in this area, so this may be one explanation for why the values are not as low as expected.

TABLE 1 $^{87}Sr/^{86}Sr$ values from modern plants on Bjäre and in Halland.

Region	Sampled site	Sample ID	Material	$^{87}Sr/^{86}Sr$
Halland	Laholm 38:2	Wil 1	Plant leaves (*Betula*)	0.71339
Halland	Laholm 38:2	Wil 2	Plant leaves (*Ulmus*)	0.71513
Halland	Morup	Wil 3	Plant leaves (*Betula*)	0.70870
Halland	Morup	Wil 4	Plant leaves (*Quercus*)	0.70866
Halland	Skrea 29:1	Wil 5	Plant leaves (*Prunus*)	0.71255
Halland	Skrea 29:1	Wil 6	Plant leaves (*Betula*)	0.71423
Halland	Ränneslöv 35:4	Wil 7	Plant leaves (*Salix*)	0.71768
Halland				0.71769
Halland	Ränneslöv 35:4	Wil 8	Plant leaves (*Sorbus aucuparia*)	0.71584
Halland	Lugnarohögen	Wil 9	Plant leaves (*Malus*)	0.71272
Halland	Lugnarohögen	Wil 10	Plant leaves (*Prunus*)	0.70874
Halland	Skummeslöv 26:1	Wil 11	Plant leaves (*Sorbus intermedia*)	0.71273
Halland	Skummeslöv 26:1	Wil 12	Plant leaves (*Castanea*)	0.71136
Halland	Tjärby 68	Wil 13	Plant leaves (*Quercus*)	0.71197
Halland	Tjärby 68	Wil 14	Plant leaves (*Sorbus intermedia*)	0.71260
Bjäre	Lokal 18	Wil 15	Plant leaves	0.71055
Bjäre	Lokal 18	Wil 16	Plant leaves	0.71035
Bjäre	Lokal 18	Wil 17	Grass	0.70939
Bjäre	Lokal 21	Wil 18	Plant leaves	0.70834
Bjäre	Lokal 21	Wil 19	Grass	0.70820
Bjäre	Ängelbäcksstrand	Wil 20	Plant leaves	0.71151
Bjäre	Ängelbäcksstrand	Wil 21	Grass	0.71073
Bjäre	Ängelbäcksstrand	Wil 22	Plant leaves (*Rosa*)	0.71066
	Summary		Halland	Bjäre
	Number		15	8
	Minimum		0.70866	0.70820
	Maximum		0.71769	0.71151
	Mean		0.71293	0.70997
	Standard deviation		0.00290	0.00120
	Median		0.71272	0.71045
	Interquartile range		0.00302	0.00155
	Confidence interval 95%*		0.00147	0.00083

*$\alpha = 0.05$.

To contextualize our modern plant $^{87}Sr/^{86}Sr$ values from Halland, we turn to previous baseline samples as reported by Klassen et al. (2020), particularly those deriving from bone or teeth of smaller mammals (Supplementary Table S1). These values show a slightly lower $^{87}Sr/^{86}Sr$ baseline of 0.7111 ± 0.0041 (2σ, $n = 9$) than the plants. Integrating Klassen et al.'s faunal samples from Halland with our plants generates a multiproxy baseline for Halland of 0.7122 ± 0.0055 (2σ, $n = 24$). Klassen et al. (2020) provided one value from a hare, 0.7101, from Hallands Väderö, an islet outside the tip of Bjäre. This fits into the Bjäre baseline range proposed earlier (0.7100 ± 0.0024).

Like Bjäre, most of northern and middle Scania, down to the Ringsjö lakes and a few kilometers east of the city Hässleholm, is located on a granitic to syenotoid migmatitic gneiss. This area of Scania constitutes the largest part of "Area 1" as delineated by Ladegaard-Pedersen et al. (2021) in their division of Scania in terms of bioavailable strontium through a multiproxy approach, using plants, water, and soil leachates (see Figure 1). The strontium baseline for this area is 0.7184 ± 0.0061 (2σ, $n = 16$; Ladegaard-Pedersen et al., 2021). For the east of Scania, "Area 2," covering the southern part of the previously mentioned gneiss bedrock to the eastern Scanian coastline, the calculated baseline was 0.7140 ± 0.0043 (2σ, $n = 48$; Ladegaard-Pedersen et al., 2021). Using these baselines, both areas are described with more radiogenic $^{87}Sr/^{86}Sr$ values than those we observe in Bjäre and Halland. The Bjäre $^{87}Sr/^{86}Sr$ values are most similar to southwest Scania, Ladegaard-Pedersen et al. (2021)'s "Area 3 + 4," with an $^{87}Sr/^{86}Sr$ baseline of 0.7110 ± 0.0030 (2σ, $n = 39$). This is also comparable with many Danish baselines (Frei et al., 2019; Klassen et al., 2020), excluding the Bornholm region.

4 Archaeological applications

4.1 The Bjäre excavations in 2021

In advance of the construction of new water pipes along the southern coast of Bjäre, contract archaeology investigations were conducted following standard Swedish heritage legislation. Several localities were investigated as part of this project (Svensson and Liahaugen, forthcom). Archaeologically, the Bjäre Peninsula is understudied, so this project resulted in new information concerning almost all archaeological periods on a large diversity of site types. The preservation of organic material is generally poor in this part of Scania, and in addition, the osteological material, most suitable for chemical analysis, was often heavily burned and fragmented. The features with preserved bone material predominantly consisted of pits from the pre-Roman Iron Age and Late Iron Age–medieval periods. Materials from three investigated sites were the subjects of the current analysis.

4.2 Sampled specimens

Seven bones and teeth from humans and other animals were sampled for $^{87}Sr/^{86}Sr$. Three samples are from three separate humans, retrieved from cremation pits of different kinds: B1 and B7, both skull fragments, derived from contexts dated to the 10th century CE, and B2, a human long bone fragment, recovered from a cremation pit dated to Late Neolithic/Early Bronze Age. The other four samples were derived from cattle or sheep/goats. One adult cattle tooth (P3–) and one burned bone from a sheep/goat were recovered from the same Viking Age pit as one of the human samples (B2). One sheep/goat burned long bone and one adult cattle tooth (M1–) were recovered from pits dated to the pre-Roman Iron Age. The cattle sample was retrieved from a cooking pit. The samples, archaeological information, and $^{87}Sr/^{86}Sr$ results are presented in Table 2. The laboratory procedures for the $^{87}Sr/^{86}Sr$ analysis follow the outlined methodologies in the Material and Methods section. Four samples were derived from burned bone. Bone remodels through life, meaning that the $^{87}Sr/^{86}Sr$ is indicative of the lived environment on average (e.g., Wolska, 2020). Two samples are from teeth, both from cattle, from which slaughter ages have also been estimated.

TABLE 2 $^{87}Sr/^{86}Sr$ values from archaeological samples in Bjäre.

Sample ID	Area	Feature (find no.)	Context	Chronology	Taxa	Material	$^{87}Sr/^{86}Sr$	2σ abs.
B1	15	64,312 (740)	Cremation grave	Late Neolithic/ Early Bronze Age	*Homo sapiens*	Long bone (burned)	0.71461	0.00001
B2	18	81,785 (241)	Cremation grave	Viking Age (10th century CE)	*Homo sapiens*	Skull roof (burned)	0.71371	0.00001
B3	18	81,785 (200)	Cremation grave	Viking Age (10th century CE)	*Bos taurus*	P3– (tooth) from mandible (aged >3 yr)	0.71152	0.00001
B4	18	81,785 (224)	Cremation grave	Viking Age (10th century CE)	*Ovis/ Capra*	Radius (burned)	0.71271	0.00001
B5	21	40,466 (84)	Pit	Pre-Roman Iron Age	*Ovis/ Capra*	Metatarsal (burned)	0.71422	0.00001
B6	21	41,761 (76)	Cooking pit	Pre-Roman Iron Age	*Bos taurus*	M1– (tooth) from mandible (aged >34–43 months)	0.71574	0.00001
B7	–	1,596 (24)	Cremation grave	Viking Age (10th century CE)	*Homo sapiens*	Skull roof (burned)	0.71094	0.00001

The archaeological information regarding B1–B6 derives from Svensson and Liahaugen (forthcom) and B7 from Macheridis (2024). Area is equivalent to Swedish *Lokal* (Figure 1). Death age estimations have been retrieved from Macheridis (2024).

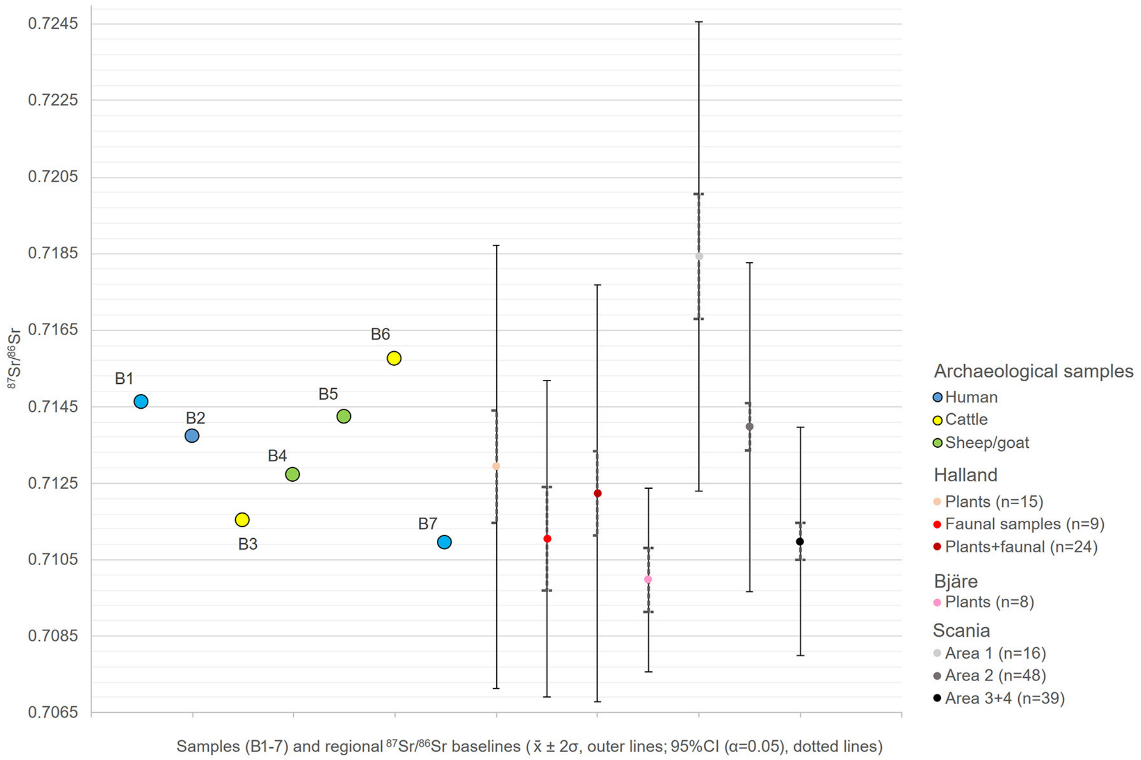

FIGURE 2
$^{87}Sr/^{86}Sr$ results from archaeological samples (B1–7) together with multi- and single-proxy baselines, here as the sample mean ± 2σ, combined with confidence interval (95% CI), from areas in Scania (Ladegaard-Pedersen et al., 2021, p. 23) and from Halland (Supplementary Table S1; Klassen et al., 2020, p. 414).

4.3 The human remains

Three samples from human remains yielded $^{87}Sr/^{86}Sr$ ratios. B1, representing an individual living during the Late Neolithic/Early Bronze Age, yielded the ratio 0.7146. B2, representing a human living in the 10th century CE, produced the ratio 0.7137. Both can be fitted within all baseline values from Halland (0.7087–0.7177; Table 1, Supplementary Table S1). Using the sample mean (x) ± 2σ, gives an even wider range (0.7122 ± 0.0055; Figure 2). If we complement the commonly used x ± 2σ, with the confidence interval (CI) of the mean, the most likely range for bioavailable strontium can be distinguished. In the case of Halland, the CI, at a confidence level of 95%, would be 0.7111–0.7133 ($\alpha = 0.05$, $1\sigma = 0.0027$, $n = 24$). B1 and B2 have higher $^{87}Sr/^{86}Sr$ values than the 95% CI but are well within the Halland baseline, as proposed earlier. Although we cannot exclude coastal Halland as lived environs for these individuals, as these regions fit within the proposed Halland $^{87}Sr/^{86}Sr$ baseline, it is perhaps more probable that they lived most of their lives further inland, in Halland or north/east Scania, as suggested by the 95% CI (Figure 2). More reference values may change this interpretative framework, but currently, only one sample, B7 from 10th century CE, reflects a likely local coastal $^{87}Sr/^{86}Sr$ ratio, 0.7109. This person may also have lived somewhere along the Scanian west coast or western Denmark (excluding Bornholm), but a local provenience on Bjäre is perhaps more reasonable.

4.4 Bovidae as mobility indicators

Cattle and sheep/goats were among the other archaeological specimens examined in this study. Starting with the cattle, their known death ages let us contextualize the $^{87}Sr/^{86}Sr$ values temporally. B3, the third premolar in the mandible (P3–), belonged to an animal that died after 3 years of age. This tooth, however, is formed earlier in life, between 6 and 18 months, following Brown et al. (1960, p. 21). We use the longer enamel maturation period of approximately 6 months compiled by Kohn (2004). This means that the $^{87}Sr/^{86}Sr$ value is an average of the geological background for this animal between 0.5 to approximately 2 years of age. The $^{87}Sr/^{86}Sr$ value 0.7115 (Figure 2) is close to the Bjäre Peninsula ratios, meaning that this animal may have lived most of its life in this area.

B6 is the first mandibular molar from a mandible belonging to an animal slaughtered aged 34–43 months. It was retrieved from a pre-Roman Iron Age cooking pit. For cattle, the first molar's crown is 1/3 formed *in utero* and completed at 2–3 months. Using the enamel maturation period of large bovids, the $^{87}Sr/^{86}Sr$ value of the first molar approximately reflects the prenatal period and the first 8–9 months of life. The $^{87}Sr/^{86}Sr$ value of 0.7157, is indicative of it not being bred on Bjäre but rather from zones with higher $^{87}Sr/^{86}Sr$ values, most probably inland toward the east, such as inland Halland or northeastern Scania. The two sheep/goat bones (B4, B5) also showed relatively high $^{87}Sr/^{86}Sr$ values, 0.7127 and 0.7142, indicating a lived-in environment outside of Bjäre (Figure 2). These results support the *a priori* assumption of this article that domesticated mammals can move distances and that they are therefore likely not suitable for constructing strontium isotope baselines.

5 Conclusion

This short communication presents new strontium isotope data from the Bjäre Peninsula and Halland in southern Sweden. Based on plant data, we suggest 0.7100 ± 0.0024 (2σ, $n = 8$) as a specific $^{87}Sr/^{86}Sr$ baseline for Bjäre. The results indicate that the Bjäre Peninsula is affected by marine sea-spray effects, as the values are lower than values from inland localities with similar geological backgrounds. There is a greater $^{87}Sr/^{86}Sr$ variation in Halland, with generally higher $^{87}Sr/^{86}Sr$ values. Together with previously published faunal samples, we suggest a revised strontium isotope baseline for Halland to 0.7122 ± 0.0055 (2σ, $n = 24$). We applied these baselines to seven archaeological samples from human, cattle, and sheep/goat remains, dating to the Late Neolithic/Early Bronze Age, pre-Roman Iron Age, and the late Viking Age, retrieved from recent excavations in the southern part of Bjäre. The results from both human and animal samples are interesting for the discussion of mobility and interaction. Several samples yielded $^{87}Sr/^{86}Sr$ values indicative of provenience outside of Bjäre, which highlights the potential of studying mobility, communication, and interaction in this area through isotopic analysis. This research is incremental and can be added to the recent surge of studies, increasing the understanding of bioavailable $^{87}Sr/^{86}Sr$ in southern Scandinavia. Importantly, more studies refining and modifying our suggested $^{87}Sr/^{86}Sr$ baseline will surely follow in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and the institutional requirements. The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

SM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft, Writing—review & editing. MS: Data curation, Investigation, Methodology, Writing—original draft, Writing—review & editing. AS: Project administration, Resources, Writing—review & editing. HW: Investigation, Writing—review & editing. ÅB: Investigation, Writing—review & editing. PW: Investigation, Writing—review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fearc.2024.1379055/full#supplementary-material

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