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Isotopic perspectives on pastoral practices in the Eastern European forest-steppe during the Middle Bronze Age

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ABSTRACT

This study investigates the modes of subsistence practices of a Middle Don Catacomb Culture community for which archaeological evidence suggests a reliance on seasonal mobility of humans and their herds. A sequential multi-isotope approach [stable carbon (δ^{13}C), stable oxygen (δ^{18}O), and strontium (^{87}Sr/^{86}Sr)] on tooth enamel of mainly domestic animals (cattle and sheep/goat) from the Middle Bronze Age settlement Ksizovo-1 provides new and important proxy data for the relationships between seasonal mobility and domestic animal husbandry in forest-steppe environments. Stable isotope analyses in the steppe zones of European Russia during the Bronze Age have so far mostly focused on human mobility and diet, with few exceptions. We combine the results of the isotope analysis with the archaeological evidence and use this information to draw conclusions about the organization of the pastoral lifestyles of the community and their herds. Incremental sampling of oxygen and carbon isotope values show a year-round intake of C_3 plant forage and stay in the same ecology, and intra-tooth strontium isotopic variation almost completely corresponds with the local Sr range. The investigated birth periodicity shows different reproductive patterns of cattle and sheep/goat with signs of human interventions in the reproductive cycle. The results suggest small-scale animal movements limited to the regional ecology, which is comparable to the results of other investigations of Bronze Age husbandry practices in steppe environments using isotopic analysis. The study fosters a foundation based on empirical data for the understanding of pastoralist systems in the Eastern European Bronze Age aiming to move beyond the current reliance on hypotheses.

1. Introduction

The role of different forms of animal husbandry in shaping central aspects of past human lifeways and societies has been the subject of archaeological research in a wide range of geographical and temporal contexts (e.g., Cribb, 1991; Khazanov, 1994; Hang and Koster, 1986; Frachetti, 2012; Honeychurch and Makarewicz, 2016; Arbuckle and Hammer, 2019; Salmi and Niinimäki, 2021). Herd composition, degree of mobility, spatial organization of animal husbandry, type of specialization, targeted products and degree of economic integration can influence communities and their social organization. Beyond economic perspectives, animal husbandry has also a bearing on social practices, ritual and symbolic activities, or worldviews of past societies (Russell, 2012; Sykes, 2014; Vandergugten, 2015; Boyd, 2017; Pilaar Birch, 2018).

Isotope analysis of faunal remains provides a basis to directly assess information on these mechanisms, particularly in communities with economies that are based or related to pastoralism (Makarewicz, 2018; Ventresca Miller and Makarewicz, 2018; Lightfoot et al., 2020; Eger, 2022; Janzen, 2022; Szpak, 2022). A geographic area of great interest is the eastern European steppes where pastoralism and mobile lifestyle is suggested to have formed the economic basis of many societies in different prehistoric periods, e.g., during the Bronze and Iron Ages. However, stable isotope analyses in the steppe zones of European Russia during the Bronze Age have so far mostly focused on humans (Shishlina et al., 2012; Gerling, 2015; Schulting et al., 2016; Scheibner, 2016; Shishlina et al., 2018a; Shishlina et al., 2018b; Siliézar et al., 2018; Knipper et al., 2020), with a few exceptions (Kaiser et al., 2020), while in other steppe regions, such as in the Caucasus and Central Asia, stable isotopes are more routinely used on a range of archaeological animal

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remains (Knipper et al., 2008; Hanks et al., 2018; Makarewicz et al., 2018; Chazin et al., 2019; Ventresca Miller et al., 2020; Eger, 2022; Hermes et al., 2022; Samei et al., 2023; Reinhold et al., 2023).

This study investigates how people chose to keep domestic animals in forest-steppe environments of the eastern European Don region during the Middle Bronze Age. The archaeozoological assemblage from the site of Kszizovo-1 (2400–2100 cal BCE) in western Russia provides a rare opportunity to investigate the modes of subsistence practices of a Middle Don Catacomb Culture community that is thought to have relied on the seasonal mobility of humans and their herds. Based on radiogenic strontium and mass-dependent oxygen and carbon isotope analyses obtained from tooth enamel of the major domestic taxa herded at the site (cattle and sheep/goat), this study pursued the following objectives:

1. Explore seasonal movements of herded animals;
2. Identify seasonal and species-specific differences in pastures and forage (and potential foddering);
3. Explore birth periodicity within the herd population.

These data provide important evidence for the coordination of herding activities and zootechnical knowledge. In combination with the archaeological, archaeobotanical and archaeozoological data from the site, the isotopic data informs us about the organization of human pastoral lifestyle and human-herd animal relationships at Ksizovo-1 and provides important insights into animal management in the forest-steppe during the Middle Bronze Age. Our data contribute profoundly to the reconstruction of pastoralist systems in the Eastern European Bronze Age, helping to surpass the current reliance on hypotheses and instead, fostering a foundation based on empirical data (Pustovalov, 1994; Anthony, 2007; Kaiser, 2019).

2. Background

2.1. The Middle Don Catacomb Culture

The term “Catacomb Culture” denotes a cultural horizon defined by its distinct burial constructions, so-called “Catacomb graves”. The archaeological remains of the Catacomb Culture are found across the Eastern European steppe and forest-steppe between the Volga and the Dniester and date to the 3rd millennium BCE (Kaiser, 2019). Within this large distribution area, various regional groups have been distinguished (Popova, 1955; Bratchenko, 1976). One of these regional groups is the Middle Don Catacomb Culture, which is limited to the forest-steppe (Fig. 1). Unlike other Catacomb Culture regional groups, which are known primarily for their burial mounds, more than 200 settlements of the Middle Don Catacomb Culture have been documented in addition to burials (Pryakhin, 1982; Ivashov, 2015). However, due to the ephemeral nature of such sites, the scarcity of archaeological research and the lack of stratigraphic sequences, many questions remain unanswered.

It is generally agreed that the subsistence economy of communities of the Catacomb Culture was primarily based on animal husbandry, with an emphasis on cattle as the main domestic species. However, questions concerning the degrees and diverse forms of pastoralism – such as mobile or semi-mobile lifestyles – remain under scrutiny among archaeologists (Pryakhin, 1982; Ivashov, 2002; Gak and Borisov, 2017; Kaiser, 2019).

Although archaeological settlements are the main source for studying economic activities of the Middle Don Catacomb Culture (Pryakhin, 1982; Ivashov, 2002; Sanzharov, 2004; Antipina, 2011), systematic studies of Bronze Age settlements are rarely conducted in Eastern European archaeology and comparative data are rare. One exception is the Middle Bronze Age site of Rykan-3 (2600–2300 cal BCE), located in the Middle Don forest-steppe, ca. 100 km from Ksizovo-1. The single-layer settlement has been extensively investigated both archaeologically

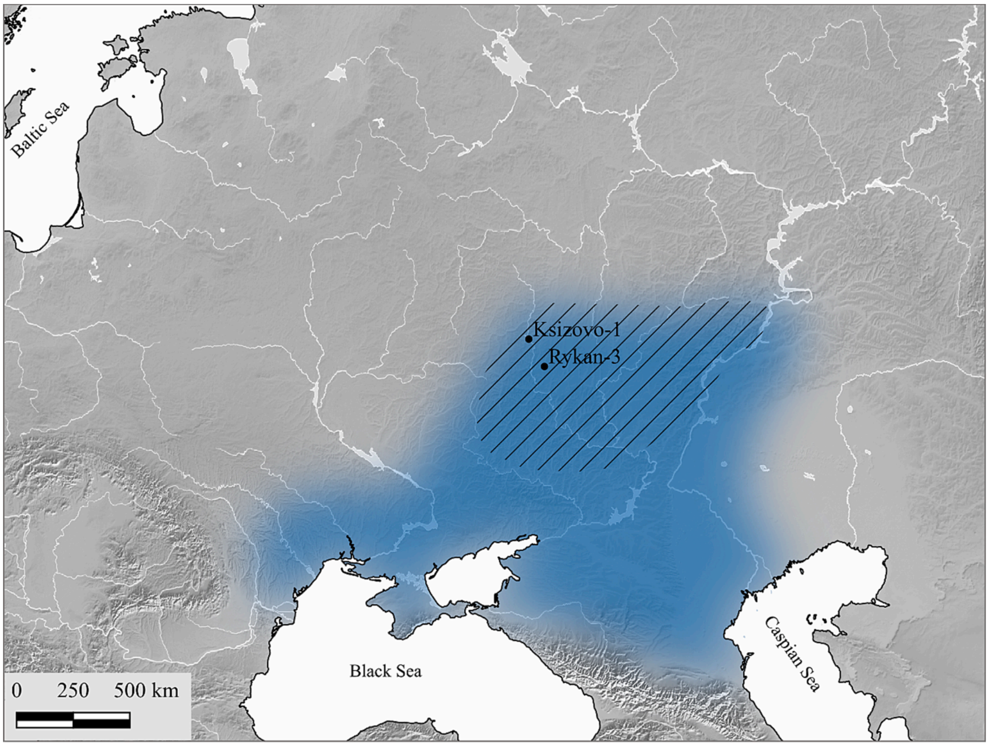

Fig. 1. Approximate distribution of the Catacomb cultural sphere denoted in blue with the area of the regional variant of the Middle Don Catacomb cultural (hatched area) including the settlement sites mentioned in the text. The map was created using QGIS Desktop version 3.22.5 (www.qgis.org), raster and vector map data were obtained from Natural Earth Data (https://www.naturalearthdata.com/). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Gak, 2019) and bioarchaeologically (Gak et al., 2023; Riesenberg, in prep.). Based on comprehensive interdisciplinary research, Rykan-3 is considered a winter camp of a small group of mobile pastoralists who have adapted their lifestyle to the continental climate and environmental conditions of the Middle Don area. Multiproxy analyses highlight the seasonal character of the site, having been repeatedly inhabited over time (Gak and Borisov, 2017; Gak et al., 2023). Similarly, Ksizovo-1 is also considered a temporary settlement, inhabited mainly in winter (Kaiser et al., submitted).

2.2. *The site of Ksizovo-1 during the Middle Don Catacomb Culture*

Ksizovo-1 is a single-layer settlement in a dense group of archaeological sites of the Middle Don Catacomb Culture located in the south of the Lipetsk region, western Russia, at the confluence of the River Snova into the Don (Fig. 2). Radiocarbon dating results of the occupational layer indicate a time span of 2400–2100 cal BCE (Kaiser et al., submitted). The settlement was located on the slope of the first terrace above the flood plain, which today is largely destroyed and continues to be severely eroded by the meandering Snova River. As a result of this process, the inhabited part of the settlement was destroyed, although traces of several residential structures were found when it was rediscovered in the outcrops of the riverbank in 1964 (Pryakhin, 1982). A total area of 640 m^2 was excavated, which is considered the settlement limits. Various archaeological features such as fireplaces, fire pits and pits for other purposes, pottery sherds, and a variety of miscellaneous stone and bone artefacts were recovered. However, no architectural remains or dwellings were found during the excavations, which led to the interpretation of the site as a temporary camp.

Faunal and botanical data from Ksizovo-1 indicate that the Middle Bronze Age community relied primarily on pastoralism, keeping herd animals for meat, with some reliance on wild animals and wild plant resources, such as wild fruits and nuts (Kaiser et al., submitted). Morphological analyses of the archaeozoological remains by Ekaterina Antipina at the Laboratory of Natural Science Methods of the Institute of Archaeology of the Russian Academy of Sciences (IA RAS) showed that the assemblage is comprised of remnants of daily meals and is aggregated from the production activities at the site (Kaiser et al., submitted). Inhabitants primarily relied on a suite of traditional domesticates – cattle (*Bos taurus*), horse (*Equus caballus*), sheep/goats (*Ovis aries/Capra hircus*) and dog (*Canis familiaris*) – for their animal products, including meat, blood, hair, dairy, and bone tools. Wild taxa account for about 14 % of the identified fauna. These include animals that likely lived in nearby forests, such as wild pig (*Sus scrofa ferus*), bear (*Ursus arctos*), and elk (*Alces alces*), as well as taxa that favored freshwater habitats such as beaver (*Castor fiber*).

2.3. *Isotopically relevant information on geology, plants and climatic conditions in the Don forest-steppe*

Located within the Eastern European forest-steppe (Fig. 3), the study area is today part of a transitional ecological zone characterized by broadleaf forest and stands interspersed with grassland steppe [community of fescue (*Festuca* sp.) and feather grass (*Stipa* sp.)] (Bohn and

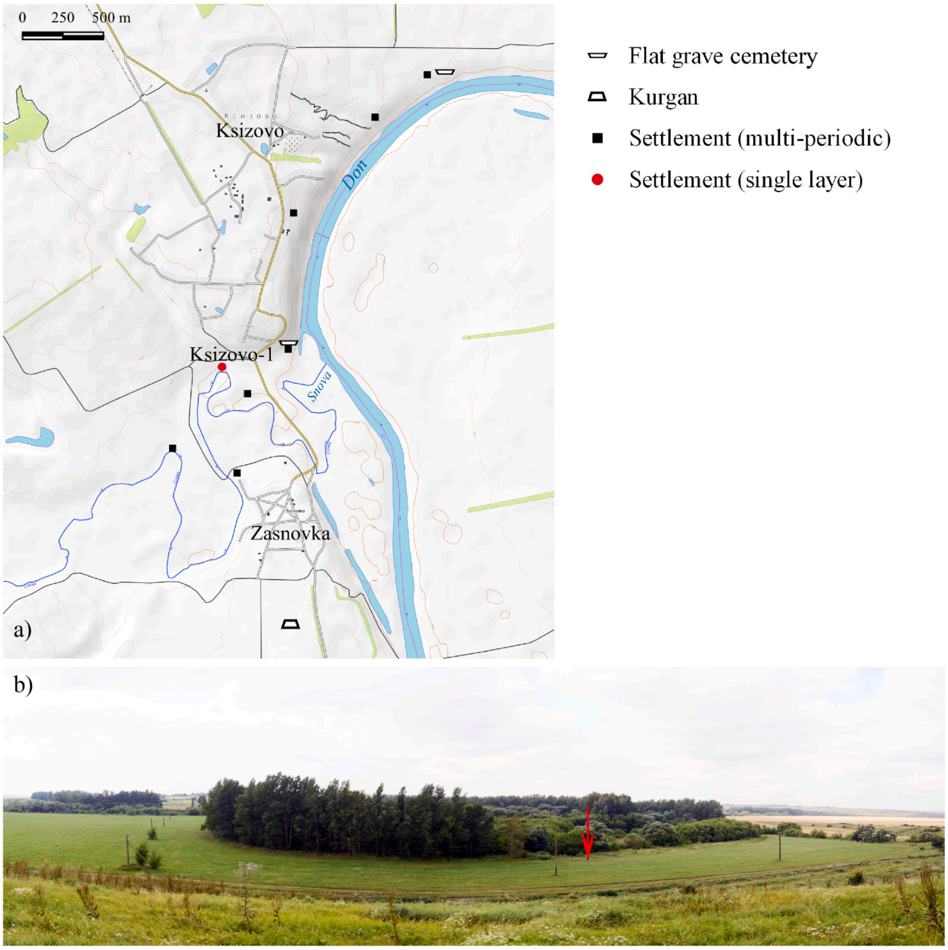

Fig. 2. (A) Location of the single-layer site Ksizovo-1 on the riverbank of the Snova near the modern towns Ksizovo and Zasnovka with a group of multi-periodic settlements and cemeteries of the Middle Bronze Age. Map data: © OpenStreetMap contributors, SRTM | Map display: © OpenTopoMap (CC-BY-SA). (b) View of the site Ksizovo-1 from the north (Photo: E. Gak).

Neuhäusl, 2004; Novenko et al., 2009). Mixed coniferous and deciduous forests expand to the north, while the south is bounded by the grasslands of the Pontic steppe. The environment of Eastern Europe is dominated by C_3 plant vegetation (Kovda et al., 2014), thus they can be expected to make a major contribution to the $\delta^{13}C$ values. In the lower Don region, ca. 500 km away, $\delta^{13}C$ values in archaeobotanical C_3 plants range from ca. –32 ‰ to –23 ‰ (Shishlina et al., 2018b). Natural C_4 vegetation occurs further south and southeast towards the Caspian steppe (Shishlina et al., 2018a). Measured $\delta^{13}C$ values of European C_4 plants range from ca. −16 ‰ to −10.5 ‰ (Pyankov et al., 2010). Contributions by cultivated C_4 plants, such as millet, are not to be expected in accordance with the archaeobotanical material of the site (Kaiser et al., submitted). Moreover, the cultivation of millet did not reach the northern Pontic region before the second quarter of the 2nd millennium BCE (Filipović et al., 2020).

Ksizovo-1 is situated along the upper (left) bank of the Don River, which is part of a section of the Oka-Don lowlands. The Don originates in the Tula Oblast region of western Russia and eventually flows into the Sea of Azov, with numerous tributaries feeding the river along the way. The present-day topography of the area is mostly flat and part of the geological foundation of the Eastern European Plain. Typical soils of the geographic area – chernozems and gray forest soils (Kashirskaya et al., 2020: 495; Potapova et al., 2020: 62) – are formed on rather homogenous geology. Fig. 4 shows the geological substrate of the upper Don forest-steppe. Ksizovo-1 lies within a Palaeozoic Devonian sandstone sequence (sandstone, dolomite, basalt). Outcrops of Mesozoic Cretaceous sandstone and carbonates are found to the west of the site. Cenozoic Pliocene and Miocene clay and sand formations emerge to the East and even further east Mesozoic formations occur. The south(west) edge of the plain is formed by Cenozoic Eocene and Palaeocene sandstone. To the north is the Palaeozoic-Mesozoic formation. Based on predictive modelling using geologies data from across Europe

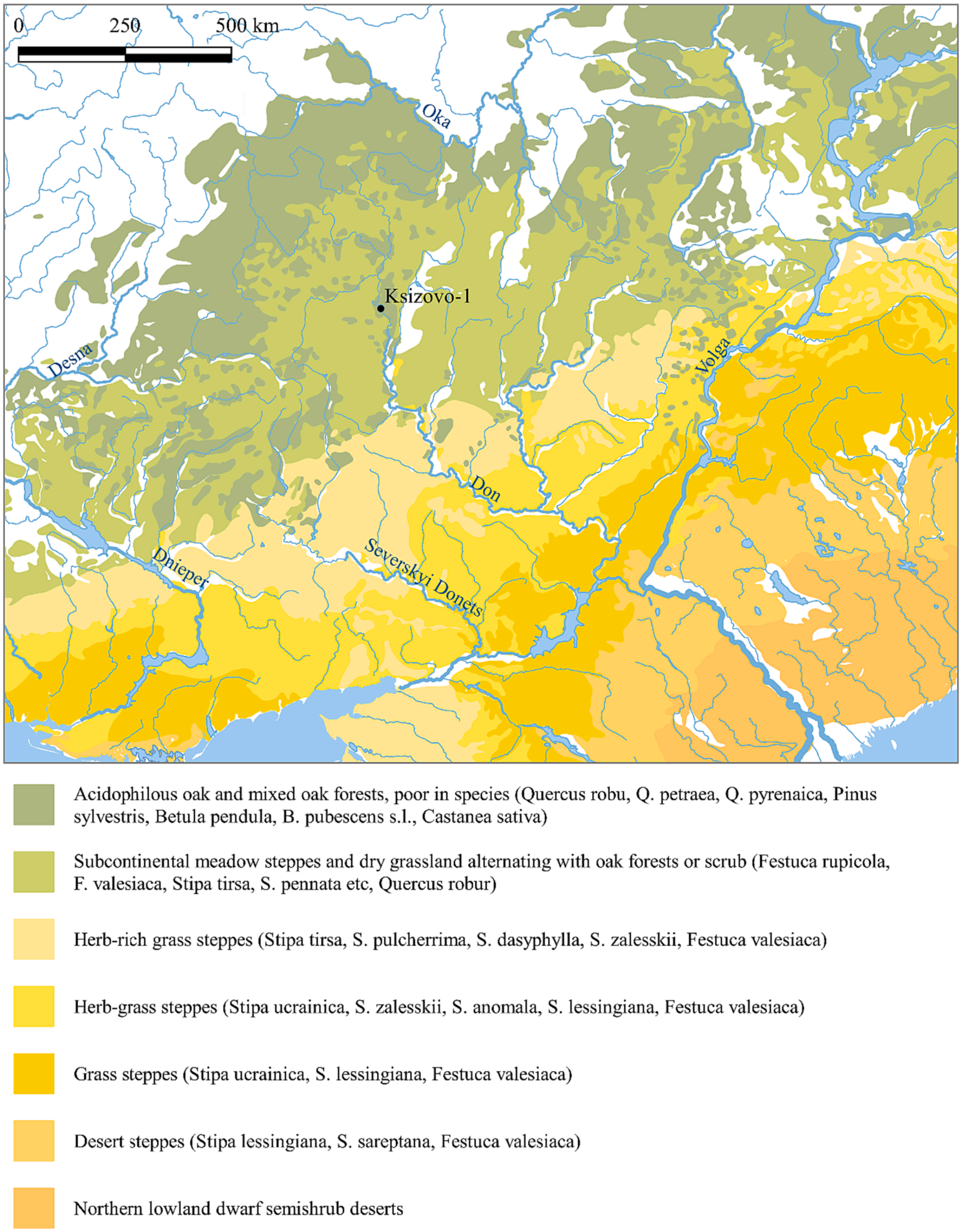

Fig. 3. Natural vegetation map and the location of Ksizovo-1. The map was created using QGIS Desktop, raster and vector map data are provided by the German Federal Agency for Nature Conservation (see also Bohn and Neuhäusl, 2004), and Natural Earth Data (https://www.naturalearthdata.com/).

(Voerkelius et al., 2010) and published Sr data obtained from archaeological human enamel, rodent enamel, and vegetation in the East European steppes (Gerling, 2015; Ventresca Miller et al., 2019; Ventresca Miller et al., 2021), expected Sr isotope ratios are anticipated to fall within the range of ca. 0.707 and 0.709 for Mesozoic, 0.709–0.711 for Cenozoic, and 0.711–0.713 for Palaeozoic geologies.

The sediments in the immediate vicinity of Ksizovo-1 formed under the influence of river floods and erosion due to intensive plowing of the second flood terrace. Today, arable lands occupy up to 85 % of the Lipetsk region (Kurbanova et al., 2023) and forests cover only 8 %. The climate is highly continental, which implies a wide amplitude of seasonal fluctuations in air temperatures. January temperatures average around −6 °C, while July temperatures average + 19 °C. Precipitation rates are low throughout the year with an average of 25 mm in January and 74 mm in July (https://council.gov.ru/en/structure/regions/LIP/, last accessed on 08.06.2023). Snow cover establishes during late November and persists for a period of around three and half months (https://weatherspark.com/y/101446/Average-Weather-in-Lipetsk-Russia-Year-Round, last accessed on 08.06.2023).

2.4. Principles of C, O and Sr isotope analyses on archaeozoological samples

Oxygen isotope values of tooth enamel bioapatite reflect the

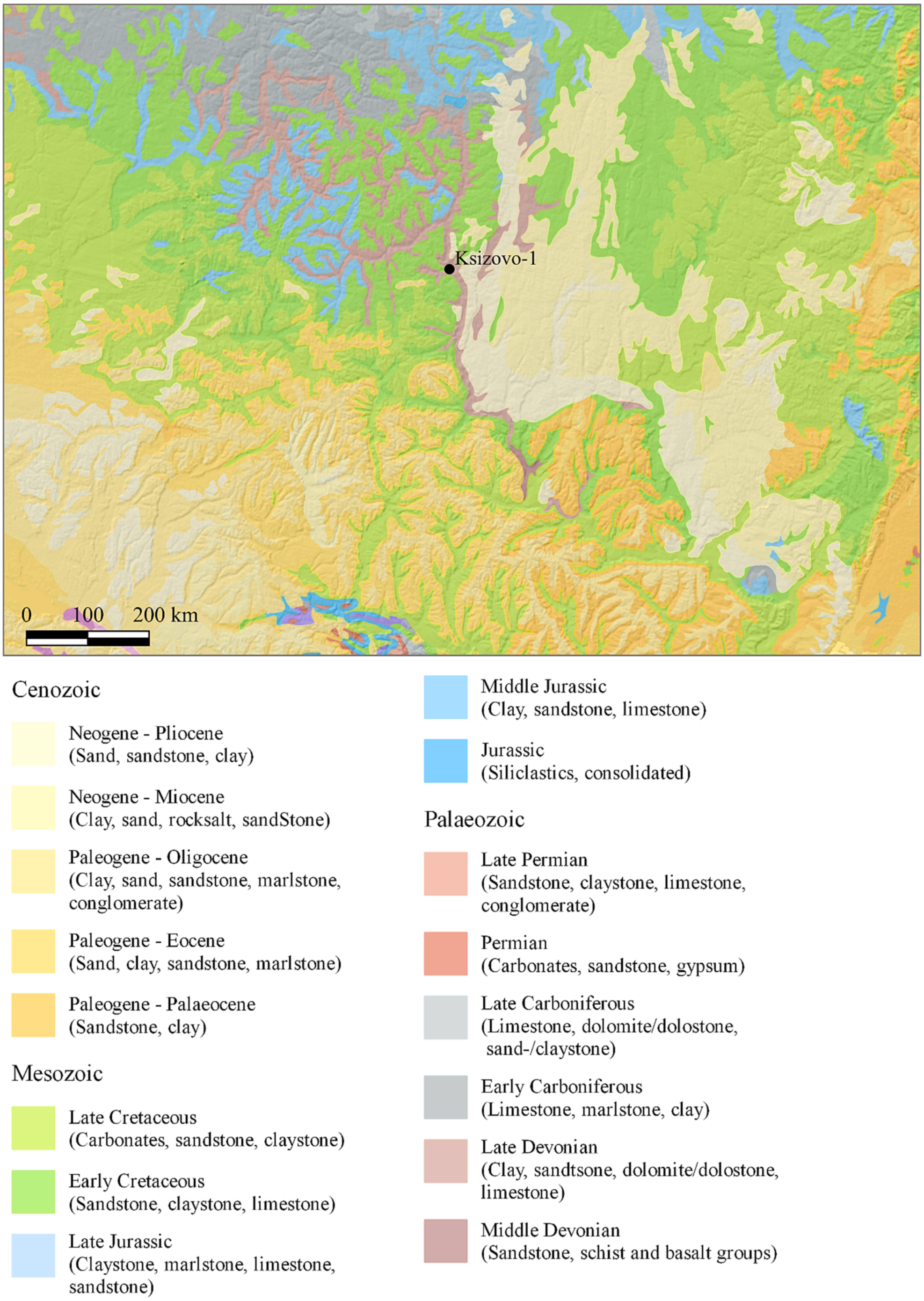

Fig. 4. Map showing the geological substrate of the upper Don forest-steppe and the location of Ksizovo-1. The map was created using QGIS Desktop, raster and vector map data are provided by the Federal Institute for Geosciences and Natural Resources (BGR) (see Asch, 2005).

hydrological conditions experienced by the animals, which for cattle, sheep and goat is related to imbibed water (Bryant and Froelich, 1995; Pederzani and Britton, 2019). Incremental sampling of enamel from herbivores bearing hypsodont teeth, with the oldest sample taken at the apex and youngest samples at the enamel-dentin junction, can track seasonal changes in δ^{18}O values at high resolution. Sinusoidal variation in δ^{18}O values obtained from this method reflects seasonal changes in the oxygen isotope composition of ingested water (Bryant et al., 1996; Fricke and O'Neil, 1996). Low δ^{18}O values reflect the intake of ^{18}O depleted water during winter, whereas high δ^{18}O values reflect the intake of ^{18}O enriched water during summer (Kohn and Welker, 2005). Modelling δ^{18}O values provides additional information on birth seasonality, determining the duration of milk availability for human exploitation (Balasse et al., 2012).

Carbon isotope values of tooth enamel bioapatite reflect the composition of the diet, which for cattle, sheep and goat consists of vegetation including the consumption of C_3 and/or C_4 grasses. The mean δ^{13}C value for C_3 plants is around −27 ‰, while it is around −13 ‰ for C_4 plants (O'Leary, 1988; Tieszen, 1991). The δ^{13}C enrichment from forage to tooth enamel for cattle has been estimated to be approximately 14.6 ‰ (Passey et al., 2005), or more generally for large ruminant mammals to be 14.1 ‰ (Cerling and Harris, 1999). Typical δ^{13}C values of tooth enamel of preindustrial herbivores average at about −13 ‰ for pure C_3 plant consumers and ca. −1 ‰ for pure C_4 plant consumers (Koch, 1998). δ^{13}C values of above −8 ‰ are considered a benchmark of C_4 plant contribution (Cerling et al., 1997). Ecological properties related to climatic conditions and forest habitats cause minor variations within the δ^{13}C spectrum of C_3 plants (Drucker et al., 2008; Kohn, 2010; Diefendorf et al., 2010).

Sequential sampling of herbivore teeth can be expected to show seasonal changes in vegetation of free ranging animals in temperate climates, with parallel patterns in δ^{13}C and δ^{18}O. Conversely, providing the herd population with fodder or moving them between grazing areas during an annual cycle can change the natural pattern (Makarewicz, 2014, 2017, 2018; Winter-Schuh et al., 2018; Groot et al., 2021). No clear co-variation between δ^{13}C and δ^{18}O sequences or damped δ^{13}C curves could indicate the provision of fodder due to limitations of grazing areas (Henton et al., 2014; Towers et al., 2017; Hirose et al., 2021; Eger et al., 2022).

Strontium isotope ratios (^{87}Sr/^{86}Sr) have the potential to provide a means of linking the archaeological animals to their geographic – i.e., geological – origin. There is a relation between the geological substrates on which the animals lived while their teeth mineralized and the strontium composition in the soil as well as the bioavailable strontium ingested via plant consumption (Bentley, 2006; Lewis et al., 2017). Since the soils of the geographic area in the Don forest-steppe consists of relatively homogeneous geology, there are only a few potential strontium inputs to the animals consumed at Ksizovo-1 (cf. section 2.3).

3. Materials and Methods

A multi-isotope approach (δ^{13}C, δ^{18}O, ^{87}Sr/^{86}Sr) was applied to sequentially sampled cattle and caprine tooth enamel.

Tooth enamel in second and third cattle molars forms in the first two life years (Brown et al., 1960), with some additional months until enamel mineralization is completed (Balasse, 2002). Second molars cover ca. the first 1 to 12 months, while the third molar provides isotopic insights into the time between ca. 9/10 to 23/24 months (Knipper, 2011, fig. 8.4). Tooth enamel in sheep has similar mineralization rates. Second molars mineralize between 1 and 12 months, and third molars mineralize between ca. 10 to ca. 22 months (Zazzo et al., 2010). While there is an ongoing discussion about time averaging during tooth enamel formation (Zazzo et al., 2010; Pederzani et al., 2021), sequential measurements of stable carbon and oxygen isotope, along with strontium isotope ratios, provide seasonal records of dietary intake that reflect environmental, ecological, and geological conditions.

The material consists of 14 teeth of herbivores, 7 of cattle, 7 of caprine (sheep or goat) from Ksizovo-1. These include three lower second molars and four lower third molars from cattle and one lower and three upper second molars as well as three lower third molars from sheep/goat. The determination of whether the molars belonged to different individuals was made by evaluating tooth size and wear. However, despite exhibiting different characteristics, we cannot entirely rule out the possibility that the teeth may belong to the same individuals. Studies using maxillary teeth for intra-tooth sequential analysis and their investigation of the isotopic composition are rare with some exceptions (e.g., Balasse et al., 2003, 2017, 2020; Chase et al., 2014; Gerling et al., 2017; Hirose et al., 2021; Makarewicz, 2017; Makarewicz and Pederzani, 2017). Upper molars from domestic ruminants have begun to receive specific attention, see Balasse et al., 2020 and Morandi et al., 2021. Such investigations are of particular importance in the context of isotopic studies involving archaeological dentition, especially when teeth of lower jaws are less well preserved or absent in the faunal assemblages and only maxillary teeth are available. However, the majority of existing research has primarily centered on lower molars. This focus led analysts to predominantly select those archaeological teeth to ensure data comparability, contributing to the existing research gap. As cited in Makarewicz and Pederzani (2017), a few studies report the timing of eruption for upper teeth of sheep/goat to be slightly offset compared to the lower teeth, likely occurring within a few months of lower tooth eruption times (Bullock and Rackham, 1982; Silver, 1963; Vigal and Machordom, 1985). Thus, it is important to note that minor variations in temporal patterns of tooth formation between mandibular and maxillary dentition may have implications for interpretations and comparability of shape and change points in isotopic sequences (Makarewicz and Pederzani, 2017).

The baseline of bioavailable strontium was established using tooth enamel of 2 omnivore wild pigs, 1 beaver, and 1 bear as well as 3 dentin samples of cattle/caprine of Ksizovo-1. Tooth enamel and bone of a wild pig from Solovevka, a Middle Don Catacomb Culture burial site ca. 7 km to the south, served as another baseline source.

Sampling was conducted by E. Antipina at the facilities of the RAS. Mechanical and chemical preparation were conducted at the laboratory facilities of the Integrative Prehistory and Archaeological Science, Department of Environmental Sciences, University of Basel, and followed established procedures (see Gerling, 2015; Gerling et al., 2017). Stable and strontium isotope analysis were conducted at the mass spectrometry facilities at Aquatic and Isotope Biogeochemistry, Department of Environmental Sciences, University of Basel, and at the School of Ocean and Earth Science, University of Southampton, National Oceanography Centre Southampton, respectively.

Teeth were cleaned ultrasonically in ultra-pure (deionized) water and air-dried. The surface of the enamel was then cleaned using a dental drill and a diamond-coated burr. Enamel was sequentially sampled by drilling powder of transversal slices (with a width of ca. 1 mm) along the growth/mineralization axis of the tooth, from the apex (i.e., the oldest part) to the enamel-root junction (ERJ, i.e., youngest part). Powder was collected in 1.5 ml Eppendorf tubes.

For carbon and oxygen isotope analysis, ca. 1.5 mg of the powdered tooth carbonate samples were weighed into 12 ml exetainers (Labco Limited, Lampeter, UK) without any pretreatment (cf. Pellegrini and Snoeck, 2016) and transferred to the mass spectrometry facilities in the Aquatic and Isotope Biogeochemistry, Department of Environmental Sciences, University of Basel. The carbon and oxygen isotope compositions were determined using a Gasbench II coupled to a Delta V Advantage mass spectrometer (ThermoFisher Scientific, Bremen, Germany). Carbon and oxygen isotopic ratios were calibrated using international carbonate isotope standards NBS 18, NBS 19 and USGS 44 and reported in δ-notation as δ^{13}C and δ^{18}O relative to VPDB (Vienna Pee Dee Belemnite). The analytical reproducibility of δ^{13}C and δ^{18}O, respective to the three isotopic standards, is $\leq \pm$ 0.10 ‰. The analytical reproducibility of δ^{13}C and δ^{18}O of each sample is $\leq \pm$ 0.15.

For strontium isotope analysis, ca. 6–15 mg of the powdered tooth enamel samples – taken from the sampling points of suggested winter minima and summer maxima based on the $\delta^{18}O$ data – were weighed into Teflon beakers and dissolved in 1 ml 7 M HNO_3, dried down and redissolved in 2 ml 3 M HNO_3. Aliquots representing 3 mg of enamel were then subject to ion exchange chromatography under clean-lab conditions. Strontium was separated using 70 µl of Eichrom Sr spec resin (50–100 µm) columns, the resin was first cleaned with alternate washings of 3 ml 3 M HNO_3 and 3 ml ultrapure water. Following conditioning with 1.5 ml 3 M HNO_3 the samples were loaded as 0.5 ml aliquots. Samples were washed with 2.2 ml 3 M HNO_3 before strontium was eluted in 1.5 ml ultrapure water. After strontium separation, samples were sent to National Oceanography Centre, University of Southampton, for mass spectrometry. $^{87}Sr/^{86}Sr$ was analysed using a ThermoFisher TRITON Thermal Ionization Mass Spectrometer (TIMS). Samples were loaded onto Ta filaments with a Ta activator solution and run at an ^{88}Sr beam of 2 V. The standard international reference material NIST SRM 987 was run alongside the samples; the long-term $^{87}Sr/^{86}Sr$ average of SRM 987 for this instrument is 0.710243 ± 0.000021 (2σ) ($n = 303$). The average column blank was 0.2 ng. Three replicates of NIST SRM 987 samples, that had been through the column chemistry, averaged 0.710237 ± 0.000009 (2σ).

The analysis of the archaeological comparative material, i.e., tooth enamel of wild boar, beaver and bear, dentin of cattle/caprine and bone of wild boar, followed the same analytical protocols with the exception that one sample per specimen was taken as vertical enamel slice of 10–15 mg in a distance of ca. 10 mm from the apex of the tooth or as bulk sample of 20–30 mg from dentin and bone using a dental drill and a diamond-coated saw and burr. After sampling, surfaces were cleaned mechanically and ultrasonically. Sample treatment then followed the procedure described above. Statistical analyses were carried out using XLSTAT in Excel.

Additionally, we used the $\delta^{18}O$ sequences in this study to evaluate the results for birth seasons using the method developed by Balasse et al., (2012a) and Balasse et al., (2012b). Only lower molars showing roughly sinusoidal seasonal variation in $\delta^{18}O$ values were included. By using an equation derived from a cosine function, the $\delta^{18}O$ curves are modelled to obtain the x_0/X ratio, which normalizes the position (distance to enamel-root junction) of the maximum $\delta^{18}O$ value (x_0) to the periodic cycle corresponding to the crown length formed potentially over a year (X). This technique eliminates differences in tooth size between individual animals. The x_0/X ratio defined for each modelled $\delta^{18}O$ sequence may be directly compared between the individual animals. The distribution of x_0/X within a herd population reflects the duration of the birth period (Balasse et al., 2021).

4. Results

4.1. Oxygen and carbon isotopes

The results of stable carbon and oxygen obtained from 14 sequentially sampled cattle and sheep/goat from Ksizovo-1 are presented in Table 1 and Fig. 5.

All 14 specimens show sinusoidal or partly sinusoidal variation in $\delta^{18}O$ values along the growth/mineralization axis of the tooth enamel, reflecting seasonal changes in the oxygen isotope composition of ingested water due to differences in temperature. (Probably) full seasonal cycles are exhibited by five cattle (KS1−1, −3, −4, −5, −6) and three sheep/goat (KS1−8, −9, −15) teeth. The amplitude of intra-tooth oxygen isotopic change in this sample varies between 2.3 and 4.0 ‰ in cattle and tends to be higher in sheep/goat with amplitudes between 3.7 and 4.5 ‰ ($\delta^{18}O$ −11.0 to −2.1 ‰). The $\delta^{18}O$ values in enamel carbonate from the five cattle specimens with full seasonal cycles are very consistent and vary between −10.3 to −6.1 ‰, with minimum winter season $\delta^{18}O$ values of −10.3 to −9.6 ‰ and maximum summer season $\delta^{18}O$ values of −8.8 to −6.1 ‰. The $\delta^{18}O$ values in the cattle teeth that are unlikely to show full seasonal cycles (KS1−2, −7) fall in the same range.

The $\delta^{18}O$ values in enamel carbonate from the three sheep specimens with complete seasonal cycles are highly variable, which is, however, only due to the individual KS1−9. This specimen shows substantially higher $\delta^{18}O$ values, pointing to stays in regions with ^{18}O enriched drinking water. Excluding KS1−9, the $\delta^{18}O$ values in enamel carbonate of the two sheep/goat specimens with complete seasonal cycles are also consistent, ranging between −11.0 and −6.5 ‰, broadly corresponding to the cattle range. The specimens show minimum winter season $\delta^{18}O$ values of −11.0 and −10.5 ‰ and maximum summer season $\delta^{18}O$ values of −6.8 and −6.5 ‰. Similar to the cattle specimens, $\delta^{18}O$ values in sheep/goat teeth, which are unlikely to show a complete seasonal cycle (KS1−10, −16, −17, −20), fall in the same range. Despite KS1−9, all $\delta^{18}O$ values are within the expected ranges for the region (Gerling, 2015; Kaiser et al., 2020).

Carbon isotope values in tooth enamel carbonate from the cattle and sheep/goat from Ksizovo-1 are less variable and very consistent. This indicates an exclusive and consistent contribution of C_3 vegetation to each diet. The amplitude of intra-tooth carbon isotopic change in this sample varies little, between 0.6 and 1.2 ‰ in cattle and between 0.3 and 1.3 ‰ ($\delta^{13}C$ −13.3 to −10.5 ‰) in sheep/goat. The $\delta^{13}C$ values in enamel carbonate from the five cattle specimens with complete seasonal cycles are very consistent and vary between −12.2 to −10.8 ‰, with minimum winter season $\delta^{13}C$ values of −12.2 to −11.5 ‰, with maximum summer season $\delta^{13}C$ values of −12.0 to −10.8 ‰. The $\delta^{13}C$ values in the teeth from cattle that are unlikely to show complete seasonal cycles (KS1−2, −7) fall in the same range.

The $\delta^{13}C$ values in enamel carbonate from the three sheep specimens with complete seasonal cycles are also very consistent, ranging between −13.3 and −10.5 ‰, which is slightly broader than the cattle range. The specimens show minimum winter season $\delta^{18}O$ values of −13.3 to −10.8 ‰ and maximum summer season $\delta^{18}O$ values of −12.0 to −10.5 ‰. Similar to the cattle specimens, the $\delta^{13}C$ values of teeth from sheep/goat that are unlikely to show complete seasonal cycles (KS1−10, −16, −17, −20) fall in the same range. Overall, the $\delta^{13}C$ range is consistent with a terrestrial C_3-dominated ecosystem of the European forest-steppe.

While an initial cluster of teeth – i.e., KS1−1, −3, −4, −5, (cattle), KS1−8, −10, −15, −16, −20 (sheep/goat) – exhibit $\delta^{13}C$ values that correspond to expected natural seasonal fluctuations and follow the seasonal pattern of $\delta^{18}O$ values, a second cluster – i.e., KS1−6 (cattle), KS1−9, −17 (sheep/goat) – exhibits no discernible seasonal trend in carbon isotopes. A third cluster, KS1−2, −7 (cattle), displays a pattern of inverse cyclical variation between $\delta^{13}C$ and $\delta^{18}O$ values.

No statistical differences can be detected in carbon and oxygen isotopic mean values nor in the amplitudes between cattle and sheep/goat. Comparing second and third molars, the amplitudes of intra-tooth carbon isotopic change in cattle M2 (mean = 3.6 ± 0.5 ‰, n=3) differs to M3 (mean = 2.6 ± 0.4 ‰, n=4), which is statistically significant ($t(5) = 2.99$, $p = 0.03$). Second molars also exhibit lower mean $\delta^{18}O$ values (mean = -8.3 ± 0.2 ‰, n=3) compared to third molars (mean = -8.8 ± 0.2 ‰, n=4), which is statistically significant ($t(5) = 3.42$, $p = 0.019$).

4.2. Strontium isotopes

Strontium isotopic results obtained for 14 sequentially sampled cattle and sheep/goat from Ksizovo-1 together with archaeological comparative data from Ksizovo-1 and Solovevka are reported in Table 2 and Fig. 6.

The $^{87}Sr/^{86}Sr$ ratios exhibited in cattle and sheep/goat tooth that are suggested to correspond with winter and summer dietary intake range from 0.70944 to 0.71022 (n=31) and averaging at 0.70997 ± 0.00017 (1σ). Cattle $^{87}Sr/^{86}Sr$ ratios range between 0.70944 and 0.71022 (n=17), averaging at 0.70993 ± 0.00017 (1σ), and sheep/goat $^{87}Sr/^{86}Sr$ ratios range between 0.70969 and 0.71021 (n=14), averaging at 0.71001 ± 0.00016 (1σ).

Table 1

Results from stable carbon (δ^{13}C), oxygen (δ^{18}O) and strontium (^{87}Sr/^{86}Sr) isotope analyses of cattle and sheep/goat molars from Ksizovo-1, including four δ^{13}C and δ^{18}O values of comparative archaeological samples. Both δ^{13}C and δ^{18}O values are reported relative to VPDB. ERJ = enamel root junction. Mean values are arithmetic averages of all values measured in a tooth. Δ = values indicate intra tooth amplitude (difference between maximum and minimum values).

	ERJ (mm)	δ^{13}C (‰)	δ^{18}O (‰)	^{87}Sr/^{86}Sr		ERJ (mm)	δ^{13}C (‰)	δ^{18}O (‰)	^{87}Sr/^{86}Sr		ERJ (mm)	δ^{13}C (‰)	δ^{18}O (‰)	^{87}Sr/^{86}Sr
KS1-1, Cattle, lower M2					*KS1-2, Cattle, lower M2*					*KS1-3, Cattle, lower M3*				
1	34.5	−11.37	−9.87		1	29	−13.26	−6.77	0.71004	1	36	−11.47	−8.92	
2	31	−11.92	−10.13	0.70944	2	26	−13.21	−7.10		2	33	−11.80	−8.26	
3	27.5	−12.47	−9.64		3	22.5	−12.55	−7.51		3	29	−11.53	−7.82	
4	24	−12.09	−8.94		4	19.5	−12.42	−7.95		4	25.7	−11.35	−7.31	0.71009
5	20.5	−11.83	−7.86		5	16	−12.34	−8.17		5	22	−11.35	−7.93	
6	17	−11.17	−6.91		6	12.5	−12.22	−8.90		6	18.6	−11.45	−8.49	
7	13.5	−10.94	−6.07	0.70982	7	9	−12.23	−9.35		7	15.6	−11.47	−8.82	
8	10	−11.1	−6.79		8	4.9	−12.05	−9.79	0.70987	8	12.05	−11.62	−9.33	
9	6.5	−11.25	−7.02		9	1.9	−12.27	−9.78		9	8.5	−11.86	−9.66	
10	3	−11.16	−7.76							10	5.5	−12.25	−9.59	
										11	2.5	−12.13	−10.27	0.71003
	Mean	−11.53	−8.10			Mean	−12.50	−8.37			Mean	−11.66	−8.76	
	Min	−12.47	−10.13			Min	−13.26	−9.79			Min	−12.25	−10.27	
	Max	−10.94	−6.07			Max	−12.05	−6.77			Max	−11.35	−7.31	
	Δ	1.53	4.06			Δ	1.21	3.01			Δ	0.91	2.96	
KS1-4, Cattle, lower M3					*KS1-5, Cattle, lower M2*					*KS1-6, Cattle, lower M3*				
1	51	−11.93	−9.05		1	41.7	−11.69	−9.88		1	48.5	−12.29	−9.34	
2	47.5	−12.03	−8.78	0.70990	2	38.2	−11.81	−10.12	0.70998	2	45	−12.46	−9.33	
3	44	−12.03	−9.43		3	34.8	−11.60	−8.43		3	41.5	−12.10	−9.80	0.71000
4	40.5	−12.17	−9.97		4	32	−11.45	−7.71		4	38	−11.95	−9.62	
5	37	−12.22	−10.28		5	28.7	−11.41	−7.50		5	34.5	−12.56	−9.37	
6	33.5	−12.21	−10.31	0.70993	6	25.4	−10.84	−6.42	0.70988	6	31	−12.08	−8.55	
7	29.5	−12.16	−9.43		7	21.5	−10.61	−6.73		7	26.9	−12.27	−7.92	
8	25.5	−11.74	−9.04		8	17.5	−10.86	−7.34		8	22.8	−12.27	−7.37	
9	21.5	−11.50	−8.65		9	13.5	−11.13	−8.27		9	19.2	−11.65	−6.95	0.70988
10	17.5	−11.81	−8.34		10	9.75	−11.58	−9.07		10	15	−11.71	−7.84	
11	13.5	−11.49	−8.04	0.70991	11	6.5	−11.78	−9.66		11	10.8	−11.73	−8.33	
12	9.5	−11.23	−8.41		12	2.5	−11.65	−10.22	0.70998	12	6.6	−11.69	−9.24	
13	5.5	−10.72	−8.98							13	3	−11.54	−9.55	0.70976
	Mean	−11.79	−9.13			Mean	−11.37	−8.45			Mean	−12.02	−8.71	
	Min	−12.22	−10.31			Min	−11.81	−10.22			Min	−12.56	−9.80	
	Max	−10.72	−8.04			Max	−10.61	−6.42			Max	−11.54	−6.95	
	Δ	1.49	2.28			Δ	1.20	3.80			Δ	1.02	2.85	
KS1-7, Cattle, lower M3					*KS1-8, Sheep/Goat, lower M3*					*KS1-9, Sheep/Goat, lower M3*				
1	36.3	−11.68	−8.54		1	27	−11.57	−10.96	0.70996	1	14	−11.20	−7.50	
2	32.8	−11.65	−8.60	0.71022	2	23.5	−12.39	−10.78		2	11	−10.82	−6.34	0.70969
3	29.8	−11.49	−7.88		3	20	−11.76	−8.87		3	8	−10.94	−2.81	
4	25.8	−11.43	−7.95		4	16.8	−11.54	−6.92		4	5	−10.53	−2.12	0.70985
5	21.8	−11.46	−8.30		5	13.5	−10.80	−6.49	0.71019	5	2	−10.71	−5.15	
6	17.3	−11.67	−8.34		6	10	−10.31	−7.49						
7	13.8	−11.17	−8.89		7	6.5	−10.77	−8.28						
8	11.3	−11.26	−9.12		8	2.5	−11.13	−9.96						
9	6.8	−10.81	−9.20	0.71010										
10	3.3	−10.78	−10.07											
	Mean	−11.34	−8.69			Mean	−11.28	−8.72			Mean	−10.84	−4.79	
	Min	−11.68	−10.07			Min	−12.39	−10.96			Min	−11.20	−7.50	
	Max	−10.78	−7.88			Max	−10.31	−6.49			Max	−10.53	−2.12	
	Δ	0.90	2.20			Δ	2.08	4.47			Δ	0.67	5.38	
KS1-10, Sheep/Goat, upper M2					*KS1-15, Sheep/Goat, lower M3*					*KS1-16, Sheep/Goat, lower M2*				
1	15.1	−10.81	−10.81		1	25.8	−12.15	−7.14		1	17.1	−12.52	−8.64	0.71021
2	8.5	−11.86	−10.93	0.70981	2	24.3	−12.34	−7.51		2	14.2	−12.65	−9.51	
3	5.2	−11.41	−9.59		3	21.3	−12.52	−9.22		3	11.1	−12.99	−9.80	
4	1.9	−11.09	−6.42	0.71000	4	18.4	−12.93	−10.07		4	8.1	−12.67	−9.93	0.71013
					5	15.3	−13.29	−10.51	0.71008	5	5.4	−12.04	−8.94	
					6	12.4	−13.55	−10.48						
					7	9.1	−13.19	−9.06						
					8	6.3	−12.89	−8.52						
					9	3.2	−11.98	−6.81	0.71014					
	Mean	−11.29	−9.44			Mean	−12.76	−8.81			Mean	−12.57	−9.36	
	Min	−11.86	−10.93			Min	−13.55	−10.51			Min	−12.99	−9.93	

(*continued on next page*)

Table 1 (*continued*)

ERJ (mm)	δ^{13}C (‰)	δ^{18}O (‰)	^{87}Sr/^{86}Sr	ERJ (mm)	δ^{13}C (‰)	δ^{18}O (‰)	^{87}Sr/^{86}Sr	ERJ (mm)	δ^{13}C (‰)	δ^{18}O (‰)	^{87}Sr/^{86}Sr
Max	−10.81	−6.42		Max	−11.98	−6.81		Max	−12.04	−8.64	
Δ	1.05	4.51		Δ	1.57	3.70		Δ	0.95	1.29	

	ERJ (mm)	δ^{13}C (‰)	δ^{18}O (‰)	^{87}Sr/^{86}Sr		ERJ (mm)	δ^{13}C (‰)	δ^{18}O (‰)	^{87}Sr/^{86}Sr
KS1-17, Sheep/Goat, upper M2					*KS1-20, Sheep/Goat, upper M2*				
1	19	−12.58	−8.40	0.71013	1	20.59	−12.37	−8.45	0.70990
2	16	−12.50	−7.60		2	15.04	−12.30	−7.51	
3	14	−12.72	−6.65		3	10.18	−12.24	−6.89	
4	11	−12.36	−6.12		4	6.96	−11.83	−5.74	0.70995
5	8	−12.29	−5.17	0.71014	5	3.98	−11.47	−6.59	
6	5	−12.33	−5.24						
	Mean	−12.46	−6.53			Mean	−12.04	−7.04	
	Min	−12.72	−8.40			Min	−12.37	−8.45	
	Max	−12.29	−5.17			Max	−11.47	−5.74	
	Δ	0.43	3.23			Δ	0.90	2.71	

The ^{87}Sr/^{86}Sr ratios of the comparative samples range from 0.70988 to 0.71025 (n=9) averaging at 0.71007 ± 0.00026 (2σ). Following a conventional approach, this gives a range of 0.70981 to 0.71033 for ^{87}Sr/^{86}Sr that we suggest represents the biologically available Sr at Ksizovo-1. All but 3 data points (cattle KS1−1 and KS1−6, sheep/goat KS1−9; all winter Sr values) match the local Sr range.

Intra-tooth strontium isotopic variation is mainly low, i.e., <0.0001 (KS1−3, −4, −5, −25, −16, −17, −20), suggesting geologically restricted annual mobility. Only few specimens showed intra-tooth shifts >0.0002 (KS1−1, −6, −8, −10). Higher intra-tooth variation coincides with winter ^{87}Sr/^{86}Sr ratios outside the local Sr range in 3 specimens (KS1−1, −6, −10). Taken together, this suggests potential seasonal changes in pastures.

Fig. 7 (Sr−C) shows that local Sr values are largely consistent with local C_3 vegetation. The Sr isotopic winter value outliers KS1−1 and KS1−9 are not outliers with respect to δ^{13}C. KS1−4, in turn, is an outlier in terms of δ^{13}C, indicating forage differences but showing no seasonal movement between geologies. In addition, KS1−6 is interesting concerning a concentration of (regional) movement and varying seasonal forage. Fig. 7 (Sr−O) illustrates the similarity between winter minimum δ^{18}O values and summer maximum δ^{18}O values in both cattle and sheep/goat. The Sr isotopic winter outlier KS1−9 is also a significant outlier in terms of δ^{18}O, whereas KS1−1 does not show any differences.

Double analysis of winter minima (KS1−5, KS1−6)/summer maxima (KS1−4) in cattle enamel showed similar δ^{13}C and δ^{18}O values and ^{87}Sr/^{86}Sr ratios (Table 1, Fig. 7).

4.3. *Modelling of δ^{18}O sequences (Balasse method)*

Results from the modelling of the δ^{18}O sequences (Table 3) show that the length of tooth crown formation over one year (X) varies between 39.65 and 43.27 mm for cattle and between 14.62 and 37.41 mm for sheep/goat, indicating inter-individual variations in annual tooth growth rate. Pearson's R-values between 0.96 and 0.99 for cattle and between 0.98 and 1.00 for sheep/goat confirm the similarity between the δ^{18}O values and the modelled data. The location of the maximum δ^{18}O value in the tooth crowns (x_o) varies from 11.86 to 25.71 mm from ERJ for cattle and from 6.00 to 33.42 mm for sheep/goat.

Births of the five cattle individuals fall within two sequential segments of the year (2nd and 3rd quarters, defined by $x_0/X = 0.25$ to 0.50 and 0.50 to 0.75) (Fig. 8), indicating a slightly extended season of calving. The analysis of the three sheep/goat molars suggest lambing was also not limited to a single narrow period. The birth of two individuals (KS1−8, KS1−9) falls within the same segment of the year (second quarter, defined by $x_0/X = 0.25$ to 0.50), while the birth of the third individual (KS1−15) occurs in the fourth segment (x_0/X quarter = 0.75 to 0.50). The distance between the birth seasons of sheep/goat of about two quarters of the year is also directly reflected in the δ^{18}O curves running almost in opposite directions.

5. Discussion

5.1. *Quality of the biologically available strontium isotope baseline and indications of limited mobility*

Determining a valid range of the biologically available strontium isotope at the archaeological site is crucial for identifying isotopic outliers and distinguishing between varying herding practices. The quality of suitable sample material to establish the local biologically available strontium isotope baseline has been intensively discussed in recent decades (e.g., Price et al., 2002; Bentley, 2006; Montgomery, 2010; Maurer et al., 2012). In addition to collecting baseline samples from the investigated sites, creating regional or supra-regional isoscapes is essential to understand faunal movement (Holt et al., 2021). Due to availability and the current political situation, our baseline sampling was limited to the archaeological fauna of the excavations at the site. By using archaeological samples as a baseline, a potential anthropogenic and environmental influence, e.g., by modern fertilizers, leading to a change in the ^{87}Sr/^{86}Sr values of the baseline samples can be avoided (Bentley, 2006; Andreasen and Thomsen, 2021). However, wild pig, bear and beaver are not ideal baseline samples, since they are not locally restricted and have relatively large ^{87}Sr/^{86}Sr ranges. Specifically, wild pigs and bear feed on mixed rather than exclusively herbivorous diets, probably leading to a more varied range of ^{87}Sr/^{86}Sr. Neither dentin nor bone are ideal proxies for the biologically available strontium at the site. Due to their porosity and susceptibility to contamination, they are subject to diagenesis and accumulate Sr from the burial or site environment (Budd et al., 2000; Chiaradia et al., 2003). Consequently, their ^{87}Sr/^{86}Sr values are heavily influenced by the ^{87}Sr/^{86}Sr values in soils and are less varied than what can be considered as biologically available. Despite these limitations and based on the consistencies in the geology and between the baseline samples, the established range of biologically available Sr is considered as a valid proxy for distinguishing 'locally constant' vs. 'seasonally mobile' herding.

Intra-tooth strontium isotope data suggests that both cattle and sheep/goat experienced very limited seasonal mobility during the period of tooth formation, i.e., early in life. However, patterns of movement between different geologies may be obscured by possible long-term averaging of strontium in cattle and sheep/goat tooth enamel due to retention of Sr in metabolic body pools and delayed incorporation into body hard tissues such as tooth enamel (Montgomery et al., 2010). Hence, mobility between geologies with similar ^{87}Sr/^{86}Sr values – in this study, Cenozoic and Mesozoic geologies, representing various sections of the forest steppe in the Ksizovo region – may not necessarily be detected through sequential enamel sampling techniques along the growth axis of the tooth. However, mobility between Cenozoic and

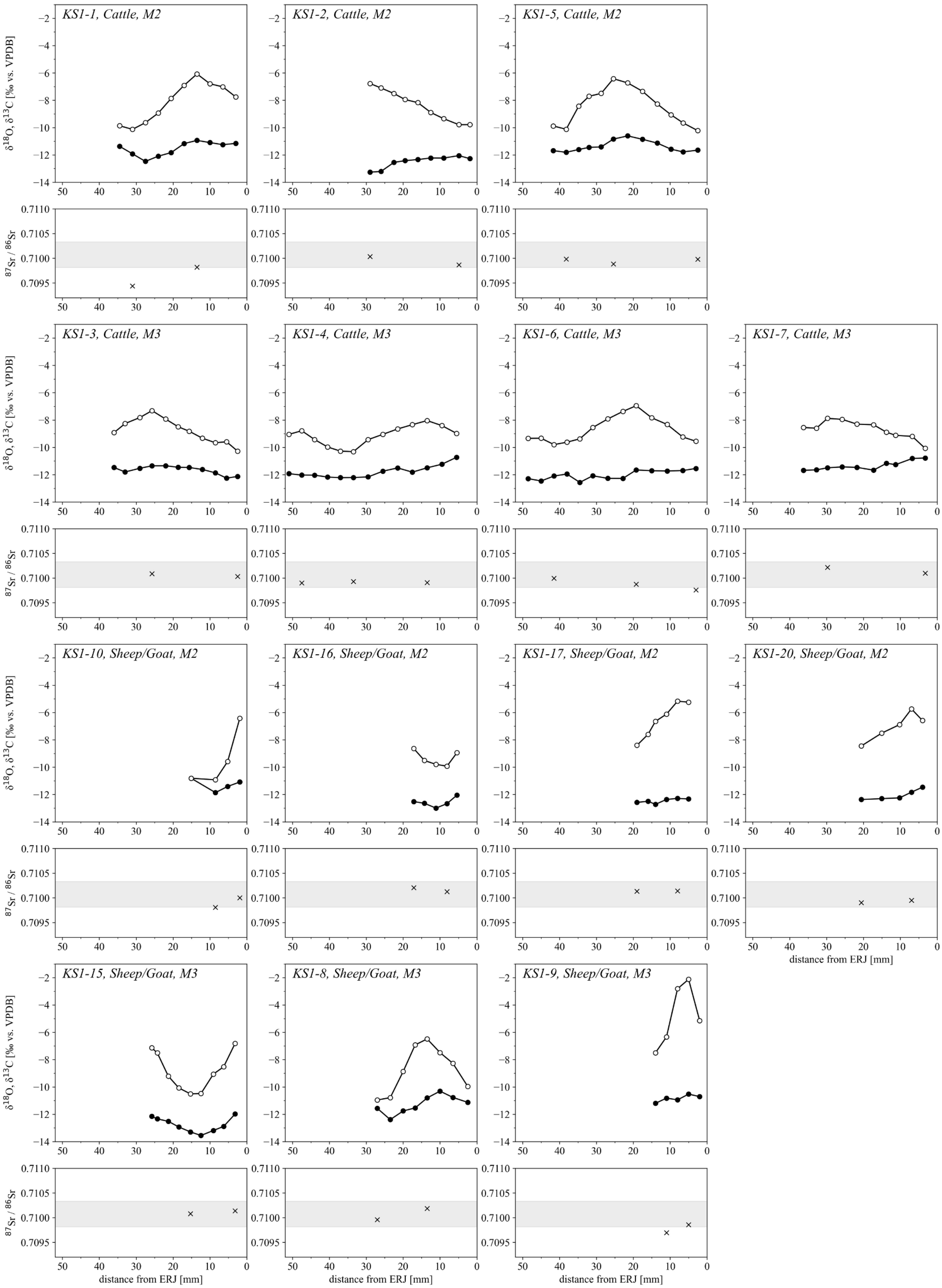

Fig. 5. Tooth enamel sequential isotope data of cattle and sheep/goat from Ksizovo-1: $\delta^{13}C$ and $\delta^{18}O$ values (black and white circles, respectively) for second and third molars (M2 and M3) representing ca. 1 annual cycle, and $^{87}Sr/^{86}Sr$ ratios (black dashes). The $^{87}Sr/^{86}Sr$ range of comparative faunal samples used as baseline data (cf. Table 2, mean ± 2 s.d., shaded in grey) is indicated.

Table 2
Strontium isotope data of cattle and sheep/goat tooth enamel as well as of comparative archaeological samples from the faunal assemblage of the Ksizovo-1. Sequentially sampled molars (KS1-1–KS1-10, KS1-15–KS1-17 and KS1-20), cf. Table 1.

ID	Species	Skeletal element	$^{87}Sr/^{86}Sr$	2σ
KS1-1	*Bos taurus*	lower M2	0.70944	0.00001
			0.70982	0.00001
KS1-2	*Bos taurus*	lower M2	0.71004	0.00001
			0.70987	0.00001
KS1-3	*Bos taurus*	lower M3	0.71009	0.00001
			0.71003	0.00001
KS1-4	*Bos taurus*	lower M3	0.70990	0.00001
			0.70993	0.00001
			0.70991	0.00001
KS1-5	*Bos taurus*	lower M2	0.70998	0.00001
			0.70988	0.00001
			0.70998	0.00001
KS1-6	*Bos taurus*	lower M3	0.71000	0.00001
			0.70988	0.00001
			0.70976	0.00001
KS1-7	*Bos taurus*	lower M3	0.71022	0.00003
			0.71010	0.00002
KS1-8	*Ovis aries/Capra hircus*	lower M3	0.70996	0.00001
			0.71019	0.00001
KS1-9	*Ovis aries/Capra hircus*	lower M3	0.70969	0.00001
			0.70985	0.00001
KS1-10	*Ovis aries/Capra hircus*	upper M2	0.70981	0.00001
			0.71000	0.00002
KS1-15	*Ovis aries/Capra hircus*	lower M3	0.71008	0.00001
			0.71014	0.00001
KS1-16	*Ovis aries/Capra hircus*	lower M2	0.71021	0.00002
			0.71013	0.00001
KS1-17	*Ovis aries/Capra hircus*	upper M2	0.71013	0.00001
			0.71014	0.00001
KS1-20	*Ovis aries/Capra hircus*	upper M2	0.70990	0.00001
			0.70995	0.00001
KS1-6	*Bos taurus*	lower M3 (dentin)	0.71017	0.00001
KS1-10	*Ovis aries/Capra hircus*	upper M2 (dentin)	0.71010	0.00001
KS1-11	*Sus scrofa f.*	lower M3	0.70993	0.00001
KS1-12	*Sus scrofa f.*	upper M2	0.70988	0.00001
KS1-14	*Castor fiber*	upper M1	0.71025	0.00001
KS1-18 (Solovevka)	*Sus scrofa f.*	lower M1 (dentin)	0.71003	0.00001
		Mandible (bone)	0.71002	0.00001
KS1-19	*Ursus arctos*	lower P2	0.71025	0.00001
KS1-20 (Solovevka)	*Ovis aries/Capra hircus*	upper M2 (dentin)	0.71000	0.00001

Palaeozoic geologies, such as movements between river valleys and the forest steppe, will lead to identifiable intra-tooth $^{87}Sr/^{86}Sr$ variability.

We identified a minimal difference between the $^{87}Sr/^{86}Sr$ values of wild pig enamel (regarded as typical of the forest-steppe environment) and the $^{87}Sr/^{86}Sr$ values of cattle and sheep/goat dentin/bone and beaver enamel (regarded as characteristic for the river valley of the Ksizovo region), which might count as an indication of identifiable intra-tooth $^{87}Sr/^{86}Sr$ variability of different geologies. In the absence of modern baseline samples from the archaeological site and its surroundings, as well as a more profound archaeological baseline, this observation cannot be further investigated.

Another consideration is the potential long-term average of dietary intake leading to averaged $^{87}Sr/^{86}Sr$ values that may not be directly comparable to sequential oxygen and carbon isotope data obtained from enamel (Montgomery et al., 2010). The delayed incorporation of strontium isotope values into enamel may result in poor recognition of seasonal movements between different geologies, leading to misinterpretation of winter and summer pastures.

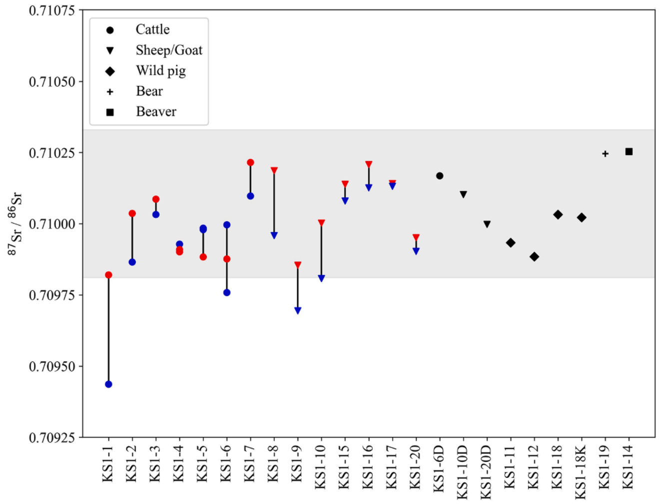

Fig. 6. $^{87}Sr/^{86}Sr$ isotope ratios of samples from Ksizovo-1. Red colour indicates $^{87}Sr/^{86}Sr$ ratio measured at the highest $\delta^{18}O$ value, and blue colour indicates $^{87}Sr/^{86}Sr$ ratio measured at the lowest $\delta^{18}O$ value. The range of the baseline data (mean ± 2 s.d., shaded in grey) is indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.2. Implications for herd management based on birth periodicity of cattle and sheep/goat

Studies on cattle birth periodicity in prehistoric Europe demonstrate seasonal calving prevailed during the sixth to fourth millennia BCE. They were usually concentrated within an annual three-month period (Balasse et al., 2021). In traditional, pre-modern flocks in Europe, calving and lambing took place in spring (Shamanov, 1972; Ebersbach, 2002; Antipina, 2017). The five cattle teeth modelled in this study suggest a longer birthing season spanning more than three months, while the three caprine teeth indicate births in two opposite seasons. A prolongation in the duration of the birth period or multi-season reproduction was demonstrated for prehistoric sites in Europe dating from the 6th to the 3rd millennium BCE (Balasse et al., 2017; Hadjikoumis et al., 2019; Tornero et al., 2020; Chazin, 2021; Messana et al., 2023), indicative of human interventions in the reproductive cycle of the animals and intense animal husbandry strategies. Multiple birthing seasons or a longer birthing period suggest a deliberate extension of the time during which animals can be milked. Some information on age composition of domestic animals was obtained from the fragmented dental material of the osteological collection (Kaiser et al., submitted). However, remains of cattle or sheep/goats younger than half a year could not be determined; on the one hand, this could be an indication that calving and lambing took place elsewhere than directly at the site and supports the assumption of the site's use as a winter camp. On the other hand, this observation can be biased by the poor taphonomic condition of the faunal material.

First indications for prolonged birthing seasons of cattle illustrate that herd organization and reproduction were manipulated by herders. This might be due to the increasing interest in the intensification of dairying (Scott et al., 2022). Two different birth seasons of sheep/goat does add to this impression, however, albeit indicated by only one caprine individual, making a more nuanced interpretation difficult.

5.3. Middle Bronze Age economy in the forest-steppe

The economy of the Bronze Age steppe communities, the Yamnaya and Catacomb cultures in particular, is thought to have been based on specialized cattle and sheep/goat husbandry accompanied by seasonal mobility (Kaiser, 2019: 13). However, archaeological evidence of the

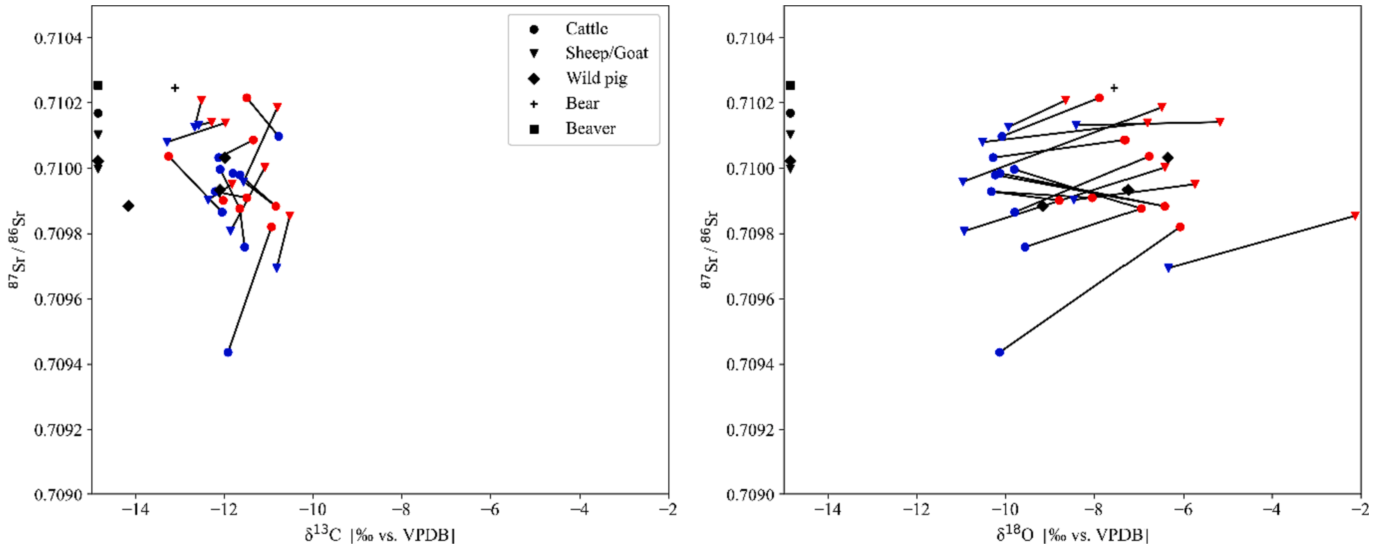

Fig. 7. Plot of carbon, oxygen isotope vs. strontium ratios (y-axis) for cattle and sheep/goat teeth as well as the reference samples of wild pigs, beaver, and bear (left: ^{87}Sr/^{86}Sr vs. δ^{13}C, right: ^{87}Sr/^{86}Sr vs. δ^{18}O). The red colour indicates ^{87}Sr/^{86}Sr ratio measured at the highest δ^{18}O value, and the blue colour indicates ^{87}Sr/^{86}Sr ratio measured at the lowest δ^{18}O value. ^{87}Sr/^{86}Sr ratios of the baseline data obtained from dentine and bone are plotted at the y-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Results from the modelling of δ^{18}O sequences of sequentially sampled cattle and sheep/goat molars from Ksizovo-1.

Specimen	X (mm)	A (‰)	x_0 (mm)	M (‰)	x_0/X	r (Pearson)
M2						
KS1-1 (cattle)	39.65	1.87	11.86	−8.21	0.30	0.99
KS1-5 (cattle)	41.56	1.78	23.17	−8.38	0.56	0.97
M3						
KS1-3 (cattle)	43.27	1.16	25.71	−8.85	0.59	0.97
KS1-4 (cattle)	43.13	0.99	14.82	−9.15	0.34	0.96
KS1-6 (cattle)	41.64	1.28	20.33	−8.53	0.49	0.98
KS1-8 (sheep/goat)	28.41	2.23	12.80	−8.78	0.45	0.98
KS1-9 (sheep/goat)	14.62	2.90	6.00	−4.73	0.41	1.00
KS1-15 (sheep/goat)	37.41	2.73	33.42	−7.83	0.89	0.99

economic basis of these Bronze Age steppe societies is scarce. While numerous Catacomb Culture graves are known across the steppes and forest-steppes, settlement structures are rare, largely due to the poor state of research and the focus on excavations of burial mounds (Kaiser, 2019: 281). Based on profound archaeological and bioarchaeological research, N. Shishlina established a mobility model for the Bronze Age in the North Caucasian and Caspian steppes. In this model, small-scale and year-round mobility of humans and animal herds for the Early Bronze Age (Yamnaya) is contrasted with larger-scale mobility involving seasonal movement cycles of several hundred kilometres in the subsequent Middle Bronze Age, corresponding to the Catacomb Culture in this region, due to increases in both aridity and herd sizes, as well as decreasing pasture productivity (Shishlina et al., 2012; Shishlina et al., 2014; Shishlina et al., 2018b). Stable carbon and nitrogen isotope data obtained from bone collagen samples of domestic cattle, sheep/goat and horses from Middle Bronze Age Catacomb Culture contexts in the Caspian steppes confirmed Shishlina's hypothesis. The data indicate seasonal movement cycles that include the exploitation of various ecological steppe environments and stretch across vast areas (Shishlina, 2012; Shishlina et al., 2018b). These climatic and ecological developments, however, seem to have affected the semi-desert steppes in particular and probably led to higher mobility compared to the forest-steppes, because isotope studies in other areas of the Eurasian steppe zones do not confirm these trends. Bulk stable carbon and nitrogen isotope data obtained from bone collagen of domestic animals from Bronze Age contexts in the northern Caucasus foreland (Knipper et al., 2020) point to seasonal herding cycles limited to the same ecology. Pastoral husbandry strategies restricted to the local ecologies were also attested by sequentially analysed sheep from Turgen and Kent, Bronze and Iron Age contexts in Kazakhstan (Ventresca Miller et al., 2020). Very similar patterns to those in Ksizovo-1 were recorded from sequentially analysed domestic animals at the Early Bronze Age site of Generalka 2 located in the Dnieper valley, Ukraine (Kaiser et al., 2020). Limited

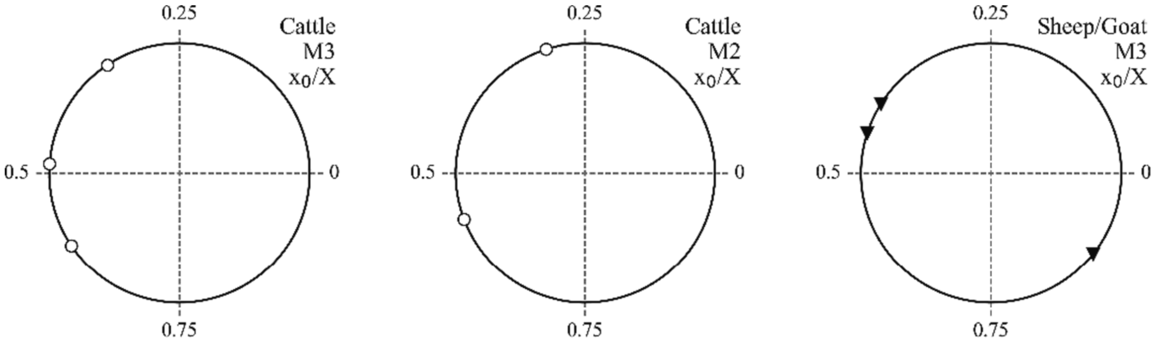

Fig. 8. Distribution of cattle and sheep/goat birth based on the normalized data set (x_0/X) from modelled δ^{18}O lower M3 and M2 teeth.

seasonal variation in carbon isotope compositions, pointing to a predominantly C_3 plant-based diet, seasonal oxygen isotope values following sinusoidal patterns consistent with expected $\delta^{18}O$ values for the region, and very low intra-annual variability in strontium isotope ratios were interpreted as an indication for limited, small-scale mobility. Notably, $\delta^{13}C$ and $\delta^{18}O$ values are within the same range as the Ksizovo-1 data or slightly higher, corresponding to differences in vegetation cover, temperature and precipitation between forest steppe and grass-steppe. All published isotope data that can be used as a comparison are located considerable distances (i.e., several hundred kilometres away) from Ksizovo-1. Isotope data from more proximal sites are subject to an ongoing PhD thesis by M. Riesenberg at the Free University of Berlin, who is investigating herding management of domestic animals in the western Eurasian steppes during the Bronze Age (Riesenberg, in prep.).

Despite the results from the Caspian steppes, these data suggest small-scale animal movements limited to the regional ecology. Multi-isotope data obtained from cattle and sheep/goat from Ksizovo-1 point in the same direction: limited seasonal regional mobility without crossing ecological borders. Seasonal movement of domestic animal herds is indicated by (1) the low number of Sr isotopic outliers, (2) O and C isotopic patterns mostly consistent with expectations for the forest-steppe region, and (3) small intra-tooth variation. These are in contrast to larger intra-tooth variation that may indicate long-distance movements due to wider ranges of $\delta^{18}O$ values in meteoric water and to greater proportions of C_4 vegetation in the dry steppe region further south/southeast. The interpretation of small-scale mobility is supported by the abundance of known Catacomb Culture settlements in the middle Don region (Pryakhin, 1982; Kaiser, 2019: 39). For some of these settlements, a seasonal occupation is proposed, particularly those located in floodplains, as they are seasonally flooded in spring (Gak and Borisov, 2017). Seasonal settlement or temporal camps point to a certain level of mobility, but do not necessarily have to be accompanied by large-scale movements.

Similar $\delta^{18}O$ and $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ ratios in cattle enamel, presumably corresponding to successive winters and summers, may be considered indicative of repetitive seasonal movement cycles and repeated visits to seasonal camps or settlement sites and pastures (as suggested by Shishlina, 2008; Shishlina et al., 2012 for the Bronze Age in the Caspian steppes). Repeated visits to the same location might be indicated by the presence of several (multi-periodic) settlements in the Ksizovo microregion.

Three specimens show no discernible seasonal trend in carbon isotopes, in contrast to natural seasonal variation with higher $\delta^{13}C$ values in plants in summer and lower values in winter (Flanagan and Farquhar, 2014). This may indicate human-influenced foddering during winter, as suggested, for example, for Late Bronze Age horses in Central Asia (Makarewicz et al., 2018). Winter stabling of animals is suggested for the Late Bronze Age, i.e., the second half of the 2nd millennium BCE, in the Eastern European steppe, based on sickle finds used for hay harvesting (Boroffka and Mantu-Lazarovici, 2011). While in the earlier Bronze Age periods, i.e., the Yamnaya and Catacomb Cultures, animals were kept outside year-round (Bunyatyan, 2003: 275-276). For the Don region, Gak and Borisov (2017) argue that winter settlements or camps are likely to have been located in the river valleys due to their more sheltered location (see also Shishlina, 2001, 2008; Kaiser, 2019: 280). The $^{87}Sr/^{86}Sr$ data do not fully support the archaeozoologically based interpretation of Ksizovo-1 as a temporal winter camp/settlement (Kaiser et al., submitted), as the only $^{87}Sr/^{86}Sr$ values not matching the range of biologically available Sr are those corresponding to $\delta^{18}O$ winter values.

Two isotopic outliers, KS1−1 ($^{87}Sr/^{86}Sr$), and KS1−9 ($\delta^{18}O$), may count as examples of animals originating in other geological and ecological settings. Non-local origins of animals related to human migration are likely in Catacomb Culture contexts due to archaeological evidence of higher mobility and migrations of Catacomb Culture communities within the steppe zone (Kaiser, 2019: 280). There are, however, certainly other explanations for non-local origins, such as exchange or trade. Since these specimens are not consistent with the local isotopic range for only one element investigated, this observation remains speculative and needs further investigation.

6. Conclusion

Despite the restricted data set, this study has resulted in novel findings for the Bronze Age animal economy in the Western Eurasian forest-steppe. The obtained data points towards herding practices that are indicative of small-scale movements within the local ecology, reflecting similar results of other studies on Bronze Age husbandry practices in steppe environments using isotopic analysis. Our case study serves as a proxy to approach the debate on the subsistence economy of communities of the Catacomb Culture, particularly in the Upper Don course, from an isotopic perspective. Further work in this ecoregion, including the creation of isoscapes, is needed to contextualize the results of this study; however, each study site and data set adds information on the investigations of past subsistence practices and the herding organization of domestic animals. Understanding the history of animal husbandry is important for revealing factors that drove Bronze Age communities in the western Eurasian forest-steppe that intersects with aspects of dairying, pastoralism, and the degree of mobility.

CRediT authorship contribution statement

Claudia Gerling: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Funding acquisition, Visualization, Writing – original draft, Writing – review & editing. **Jana Eger:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Funding acquisition, Visualization, Writing – original draft, Writing – review & editing. **Evgenii Gak:** Funding acquisition, Project administration. **Elke Kaiser:** Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is included in the text manuscript.

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