Received: 19 February 2021 | Revised: 19 October 2021 | Accepted: 20 January 2022
DOI: 10.1002/oa.3103

RESEARCH ARTICLE

Carbon and oxygen stable isotopic evidence for diverse sheep and goat husbandry strategies amid a Final Bronze Age farming milieu in the Kyrgyz Tian Shan

Taylor R. Hermes[1,2,3] | **Clemens Schmid**[1,2] | **Kubatbek Tabaldiev**[3,4] | **Giedre Motuzaite Matuzeviciute**[3]

[1]Department of Archaeogenetics, Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany

[2]Department of Archaeogenetics, Max Planck Institute for the Science of Human History, Jena, Germany

[3]Department of Archaeology, Vilnius University, Vilnius, Lithuania

[4]Department of Archaeology, Kyrgyz-Turkish Manas University, Bishkek, Kyrgyzstan

Correspondence
Taylor R. Hermes, Department of Archaeogenetics, Max Planck Institute for Evolutionary Anthropology, Deutscher Platz 6, 04103 Leipzig, Germany.
Email: taylor_hermes@eva.mpg.de

Funding information
European Social Fund, Grant/Award Number: 09.3.3-LMT-K-712-01-0002

Abstract

The mountains of Central Asia during the Bronze and Iron Ages are increasingly being reconceived as an important zone for intensive crop cultivation in combination with pastoralist herding. However, very little information is known about how farming practices intersected with livestock husbandry, especially at high-elevation sites. This paper presents the first insights to ancient animal management strategies in the Tian Shan through incremental carbon and oxygen stable isotope analysis of domesticated caprine teeth recovered from the Chap-1 farmstead located at 2000 m.a.s.l. in Kyrgyzstan (1065 to 825 cal BCE). We implemented a fully reproducible analysis of time-series isotope data in the R programming language. Results show subtle but variable manipulation of domesticated caprine diets at subannual scales, suggesting mixed strategies of providing access to a small amount of C_4 plant biomass, in addition to summer movements to high pastures where the overall carbon isotopic composition of graze was depleted in ^{13}C compared with that of the environs of the site or lowland pastures. Nevertheless, caprine dietary intake was overwhelmingly dominated by C_3 plants. Analysis of domesticated caprine birth seasonality reveals off-season fall and winter births, which represent a common strategy employed by ancient producers in Central Asia to improve herd security and extend meat and milk availability. This study illustrates a well-integrated system of agro-pastoralist production that can help clarify the social dynamics underlying food systems in the mountain regions of Central and Inner Asia in the Final Bronze Age. It further reveals the capability for more sedentary agro-pastoralist communities to facilitate wider interregional cultural connections, through limited seasonal herding mobility and investment in highland settlement.

KEYWORDS
agro-pastoralism, birth seasonality, Bronze Age, Central Asia, reproducible research, stable isotope analysis

1 | INTRODUCTION

Archaeologists have long thought that human subsistence in the Bronze Age (3300–1000 cal BCE) of the steppes and mountains of Central Asia had been exclusively based on pastoralism using sheep, goat, cattle, and horses, providing diets rich in meat and dairy (Anthony, 2007; Kohl, 2007; Kuzmina, 1986). However, systematic macrobotanical research at a handful of sites in the mountains of Central Asia over the past decade, combined with direct radiocarbon dating of carbonized seeds, indicates that the earliest pastoralist strategies there were accompanied by wheat, barley, and millet agriculture (Doumani et al., 2015; Frachetti et al., 2010; Motuzaite Matuzeviciute, Hermes, et al., 2020; Yatoo et al., 2020; Zhou et al., 2020). Similar work has further revealed that Central Asian communities of the later Bronze Age and Iron Age (1000 cal BCE–cal CE 200) cultivated an increasingly wide range of plant domesticates as people facilitated subsequent agricultural dispersals and adapted plants for cultivation in highland environments (Motuzaite Matuzeviciute, Tabaldiev, et al., 2020; Motuzaite Matuzeviciute, Mir-Makhamad, & Spengler, 2021; Motuzaite Matuzeviciute, Mir-Makhamad, & Tabaldiev, 2021; Spengler et al., 2013, 2014). Taken together, this research has greatly shifted our understanding of Central Asia, from a domain of nomadic pastoralists to a region with a compelling record for farming (Spengler et al., 2021).

The mountains of Central Asia have emerged as the earliest known intersection for agricultural traditions originally developed in Southwest Asia focused on wheat and barley and traditions from China focused on millets (Frachetti et al., 2010; Liu et al., 2017; Motuzaite Matuzeviciute, Hermes, et al., 2020; Zhou et al., 2020). In addition to these early trans-Eurasian "food globalization" processes (Jones et al., 2011; Liu et al., 2019), dynamic cultural and biological interactions among communities across the wider steppe region appear to have been intensified in the Pamir, Tian Shan, Dzhungar, and Altai Mountains, collectively known as the "Inner Asian Mountain Corridor (IAMC)" (Frachetti, 2012). Critically, human paleogenomic research documents several large-scale gene flow events through the IAMC since the early Bronze Age, which implies a substantial amount of population movements or repeated biological admixture coinciding with the spread of food producing technologies and with the later rise of protracted economic and political networks (Jeong et al., 2020; Narasimhan et al., 2019). However, it remains challenging to reconcile evidence for Bronze and Iron Age agricultural engagements with these dynamic genetic admixtures and material culture exchanges that undoubtedly required regular movements of people across the landscape. This emerging paradox raises important questions about how the management of pastoralist livestock (sheep, goat, cattle, and horse) and herder mobility fit with pervasive crop cultivation. A greater understanding of how domesticated bovids were managed would help clarify how IAMC communities balanced herding and agricultural investments, while further informing on the nature of seasonal mobility patterns.

Here, we investigate subannual scales of animal management through incremental stable carbon and oxygen isotope analysis of tooth enamel bioapatite of domesticated caprines (sheep and goat) recovered from the high-elevation Chap-1 farmstead, dated to the transition between the Bronze and Iron Ages (~1100–800 BCE) located in the Tian Shan mountains of central Kyrgyzstan at 2000 m.a.s.l. This archaeological setting reflects a critical period in Central Asian cultural and institutional dynamics, during which the initial intensification of trans-continental exchange networks occurred amid regionally specific herding practices (Haruda, 2018; Haruda et al., 2019), alongside the proliferation of irrigation agriculture using a complex crop spectrum (Li et al., 2017; Spengler et al., 2014, 2021). A subannual stable isotopic approach focused on herding livestock provides high-resolution temporal records of (1) animal dietary intake, especially of isotopically distinct C_4 plants such as millets, (2) birthing seasons, and (3) vertical mobility. These parameters of animal management are critical components of pastoralist subsistence and help reveal how the ancient people at Chap-1 and those interacting with them shaped their production of food and animal-based commodities. This, in turn, provides a means to understand the interplay of subsistence, residential mobility, and the social mechanisms for how cultural networks across the mountains of Central Asia were built and maintained, while also further illuminating how evidence of high-elevation agricultural systems transforms our understanding of ancient human land use in Central Asia.

2 | ARCHAEOLOGY AND ENVIRONMENT OF CHAP-1

Chap-1 was occupied from 1065 to 825 cal BCE and yielded rich macrobotanical remains of several wheat and barley varieties, foxtail and broomcorn millets, lentils, and peas, in addition to glume bases and rachis internodes, indicating local crop processing (Motuzaite Matuzeviciute, Tabaldiev, et al., 2020; Motuzaite Matuzeviciute, Mir-Makhamad, & Tabaldiev, 2021). Importantly, the zooarchaeological assemblage from Chap-1 demonstrates that animal exploitation was focused on domesticated caprines with smaller components trained on cattle and horses, and more specifically, mortality profiles for caprines show the survival of older animals, suggesting milk and wool production (Ananyevskaya et al., 2021). The ceramic assemblage from Chap-1 shows participation in sprawling cultural networks, which indicates the site's inhabitants were well engaged in communication and exchange with diverse cultural communities in neighboring regions (Luneau et al., 2020; Motuzaite Matuzeviciute, Tabaldiev, et al., 2020).

The Kyrgyz Tian Shan cover nearly the entire area of modern Kyrgyzstan, which provides a highly mosaiced environmental setting and numerous valleys and high-elevation passes that connect to diverse regions of Central Asia. Chap-1 is located in the Kochkor Valley, which extends from Lake Issyk Kul to the southwest for approximately 80 km. Today, the Kochkor Valley is characterized by abundant agricultural fields using terraced and stream irrigation with runoff and snowmelt from the surrounding highlands. While surface water is plentiful in Kochkor Valley, average annual precipitation is only about 232 mm (Böckel & Becker, 2014), which reaches a monthly maximum in July, while winter is characterized by almost zero precipitation (Chupakhin, 1959). The lack of snow accumulation makes an ideal setting for winter pasturing of livestock—an opportunity that attracts herders from neighboring regions today. Moreover, the Kochkor valley and surrounding highlands are devoid of trees. Only the north-facing ranges in the north of the country fall outside of the Tian Shan rain shadow and have forests, which are largely composed of conifers, followed by aspen, birch, willow, and ash (Krever et al., 1998). The vegetation surrounding Chap-1 on the slopes and high terrain is characteristic of steppe environments, indicated by grasses belonging to Pocaceae and *Stipa*, in addition to flowering plants of *Silene*, *Stillaria*, *Fragaria*, and *Potentilla*. In contrast, the well-watered floodplain is dominated by *Chenopodium*, Fabaceae, *Carex*, and *Vaccaria* taxa. The macrobotanical assemblage from the site also contains these wild plant taxa, indicating a similar environment that was highly modified by irrigation and livestock pasturing (Motuzaite Matuzeviciute, Mir-Makhamad, & Tabaldiev, 2021).

3 | MATERIALS AND METHODS

3.1 | Study design and sample selection

Ten mandibular second (M/2) or third molars (M/3) from domesticated sheep and goats were recovered from the well-dated occupational strata of Chap-1 (Motuzaite Matuzeviciute, Tabaldiev, et al., 2020), which met the inclusion criteria of having a crown height greater than 2 cm and having at least one loph with a complete buccal portion (Table S1). Although having comparative isotopic data from domesticated cattle would give a more complete picture of animal management strategies, *Bos* M/2s or M/3s were not recovered from Chap-1 (Ananyevskaya et al., 2021). For a modern comparative dataset from wild bovids, we obtained two mandibular M/2s and M/3s each from two modern Siberian ibex (*Capra sibirica*) from snow leopard kill sites in the Jeti-Oguz nature reserve of Kyrgyzstan (Table S1). Siberian ibex are endemic to the IAMC and provide an important reference for animals that perform vertical migrations, consume wild vegetation, and exhibit natural birth seasonality.

Comparative isotopic data from M/2s of Bronze Age Central Asian domesticated caprines were also reanalyzed from Hermes et al. (2019) for sites Begash and Dali, including one modern sheep from Bayan-Zherek (near Dali), and from Ventresca-Miller et al. (2020) for sites Kent and Turgen, all located in Kazakhstan (Figure 1). These comparative data represent the currently available carbon and oxygen isotopic data generated from incrementally sampled sheep and goat teeth from ancient Central Asia, thus to date providing the most complete regional analysis of intra-annual caprine management. While three bovid species were analyzed in this study, it is unlikely that the general ontogenic scheduling would differ substantially between them (e.g., Zeder, 2006). Moreover, there is no indication that inter-specific metabolic differences in carbon or oxygen isotopic mechanics would generate differences to impede direct comparisons, although research on this topic using controlled feeding would be important for understanding possible dissimilarities between taxa.

3.2 | Isotope mechanics

Bovid M/2s and M/3s develop incrementally, which largely spans the first and second years of life, respectively (Milhaud & Nezit, 1991), and archive intra-annual isotopic inputs with relatively high temporal fidelity (Zazzo et al., 2010). For a discussion on time averaging during enamel formation and also due to sampling method, see Zazzo et al. (2005), Zazzo et al. (2010), and Pederzani et al. (2021: Supplementary Text 7). Sequential measurement of stable carbon and oxygen isotope ratios of enamel bioapatite ($\delta^{13}C_{apa}$ and $\delta^{18}O_{apa}$) along the tooth growth axis provides seasonal records of (1) dietary intake reflecting the relative abundance of ingested C_4 and C_3 plants for

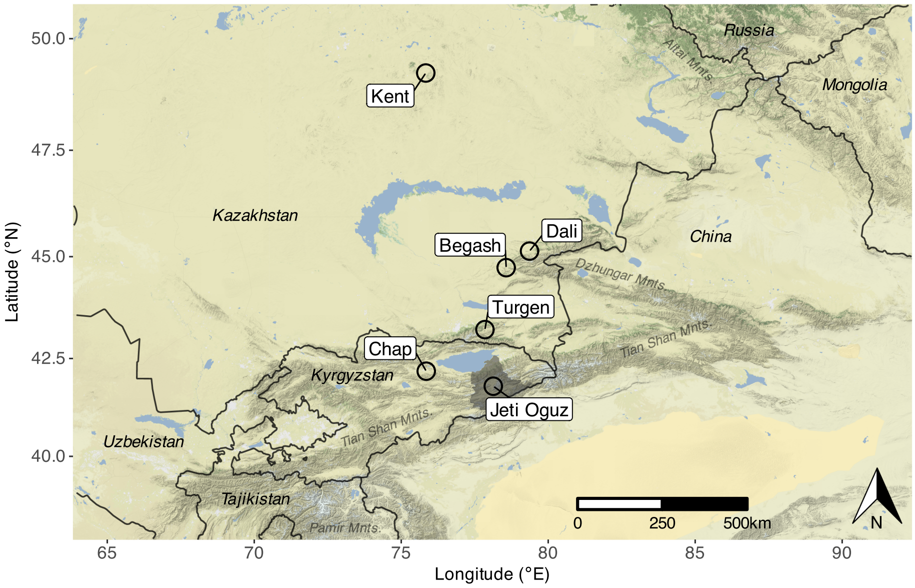

FIGURE 1 Map of the Inner Asian Mountain Corridor showing the location of Chap-1 in relation to other sites providing carbon and oxygen stable isotope data from caprine teeth [Colour figure can be viewed at wileyonlinelibrary.com]

$\delta^{13}C_{apa}$ and (2) ambient environmental temperature via body water for $\delta^{18}O_{apa}$. Due to physiological differences in carbon fixation during photosynthesis, C_4 plants have $\delta^{13}C$ values approximately ranging between −13 and −10‰, and C_3 plants have $\delta^{13}C$ values approximately ranging between −22 and −35‰ (Farquhar et al., 1989). Generally, $\delta^{13}C$ values of C_3 plants are sensitive to a wide range of environmental factors, which for example, can increase $\delta^{13}C$ values by 2–3‰ due to water stress, high salinity soils, and high elevation, while C_4 plants exhibit slight variation in $\delta^{13}C$ due to environment (Tieszen, 1991). Ruminant bioapatite is enriched in ^{13}C by approximately 14.5‰ relative to ingested vegetation (Passey et al., 2005), but a lower fractionation offset of approximately 11.5‰ has been observed in lambs fed a pure C_4 diet (Zazzo et al., 2010).

In particular, the underlying factors for the carbon isotopic variation in plants across elevational gradients are relevant for interpreting vertical mobility of herbivores. Foliar $\delta^{13}C$ values for a single plant taxon increase with higher elevation due to reduced carbon dioxide partial pressure, causing reduced discrimination against ^{13}C during photosynthetic carboxylation (Körner et al., 1988; Wang et al., 2017). However, montane environments in Central Asia are characterized by substantially higher precipitation than the arid lowlands, which occurs in a relatively short growing season (Guan et al., 2022), together causing plants to have low foliar $\delta^{13}C$ values (Tieszen, 1991). Moreover, the effective carbon isotopic pools entering herbivore diets at medium and high elevations are influenced by a substantial reduction in the relative proportion of C_4 to C_3 plants (Körner et al., 1988, 1991). The canopy effect is another contributor to low $\delta^{13}C$ values of understory vegetation, which animals can graze in dense forests (Bonafini et al., 2013). Since forests only occur in Central Asia in the mountains, this reduction in plant $\delta^{13}C$ values is relevant for using carbon stable isotope analysis to infer vertical movements of animals. The canopy effect is caused by a combination of biogenic CO_2 depleted in ^{13}C that is produced by decomposing biomass on the forest floor and also low light intensity for the understory plants resulting in lower CO_2 concentrations in the intercellular spaces relative to atmospheric CO_2 concentrations, correlating to low foliar $\delta^{13}C$ values (van der Merwe & Medina, 1991; Vogel, 1978). Overall, there is less ^{13}C in floral communities in Central Asian highlands relative to lowland environments, which would result in animals that grazed on high-elevation pastures having lower $\delta^{13}C$ values than animals that remained at low elevations.

The oxygen isotope ratios in bioapatite derives from the oxygen isotopic variation in body water, which is influenced by a complex interplay of ingested water, structural oxygen in food, and atmospheric oxygen (Bryant & Froelich, 1995; and for review, see Pederzani & Britton, 2019). Nevertheless, stable isotopic research has shown that marked seasonal environments, such as those in Central Asia, impart a regular oscillation in $\delta^{18}O$ values of precipitation and leaf water that is closely reflected in herbivore tooth enamel bioapatite, such that high $\delta^{18}O_{apa}$ values indicate summer and low $\delta^{18}O_{apa}$ values indicate winter, which can be effectively modelled as a sinusoidal curve (e.g., Balasse et al., 2012; Hermes et al., 2019; Lazzerini et al., 2020; Tornero et al., 2016; Ventresca-Miller et al., 2020). Moreover, time-series of $\delta^{18}O_{apa}$ values from sheep and goat M/2s can be used to model birth seasonality, based on the position of the curve maximum relative to the curve's wavelength, while M/3s exhibit more irregular development over time and are less reliable as temporal indicators of life events when compared between individuals (Balasse et al., 2012), although cattle M/3s have recently been successfully used to infer birth seasonality (Balasse et al., 2021). Time-series of $\delta^{18}O_{apa}$ values have also been argued to be a possible indicator of vertical transhumance, as summer movements from lowlands to highlands, where water sources are more likely to be characterized by relatively lower $\delta^{18}O$ values, would cause a sharp flattening of the $\delta^{18}O_{apa}$ maxima (Hermes et al., 2018)—a pattern also used by Britton et al. (2009) to track caribou migrations between areas of hyperseasonality.

3.3 | Isotopic analysis

Sample preparation for measurement of $\delta^{13}C$ and $\delta^{18}O$ followed Hermes et al. (2019) and was performed at the Bioarchaeology Research Centre of Vilnius University. Selected tooth specimens were sonicated in deionized water and then gently cleaned with a scalpel to remove sediment accretions and cementum. A 1-mm-wide tungsten drill bit was used to incrementally remove enamel powder in bands from the apex to cervix along one loph of the buccal side of each tooth, resulting in an average of approximately 10 samples per tooth (Table S1). Pre-treatment of the sample powder included a soak in 0.1 M acetic acid for 4 h to remove exogenous carbonates, followed by five rinses in Milli-Q ultrapure water and freeze-drying. Bioapatite carbonates were analyzed for $\delta^{13}C$ and $\delta^{18}O$ at the Leibniz Labor, Kiel University with a Finnigan MAT 253 mass spectrometer coupled to a Kiel IV device reacting with 100% orthophosphoric acid at 75°C. Duplicates were run for every 10 samples on average, and two in-house enamel standards were measured 18 times each; analytical precision was 0.079‰ and 0.075‰ for $\delta^{13}C$, and 0.114‰ and 0.132‰ for $\delta^{18}O$ (Table S2). Measurements were calibrated using the carbonate standard NBS 19 ($\delta^{13}C = +1.95‰$ and $\delta^{18}O = -2.2‰$) and expressed relative to the international Vienna PeeDee Belemnite (VPDB) standard in delta notation. $\delta^{13}C_{apa}$ values from modern animals were corrected for the Suess effect by adding 1.5‰ (Keeling, 1979; Suess, 1955).

3.4 | Oxygen isotopic modelling and seasonal inference

We followed Hermes et al. (2019) to fit a cosine function to the $\delta^{18}O_{apa}$ series from each analyzed tooth in order to visualize the isotopic data and estimate birth seasonality, which is an implementation of the method by Balasse et al. (2012) in Microsoft Excel that is used widely (Lazzerini et al., 2020, 2021; Tornero et al., 2015; Ventresca-Miller et al., 2020). In contrast, our method was written as fully reproducible scripts using the R programming language, v. 4.1.0

(R Core Team, 2021). Curve fitting is achieved using non-linear least squares with the following cosine function:

$$\delta^{18}O_m = A\cos\left(2\pi\frac{X - X_0}{z}\right) + M$$

$\delta^{18}O_m$ is the modelled oxygen isotope value. A is the amplitude of the modelled curve in ‰. X is the distance of the sampled tooth increment to the root-enamel junction. X_0 is the offset of the start of the curve, corresponding to the time of year when the tooth began developing. Z is the period of the curve in mm, representing the length of the tooth formed over 1 year. M is the simple mean of the minimum and maximum $\delta^{18}O$ values in ‰. Compared with the approach described by Balasse et al. (2012), our method has several advantages: (1) it is open source and available on any modern computing platform; (2) it can be readily modified to incorporate additional modelling variables and underlying fitting algorithms (e.g., simulating annealing); (3) Numerical output can be easily manipulated in a scripting environment to streamline statistical analysis and graphical output. For example, our approach generates 95% confidence intervals for the curve fitting using bootstrapped values, which then serve as the basis for calculating error in seasonal inferences (e.g., birth seasonality). Our R scripts generate all tables and figures mentioned in this paper. Source code and newly generated isotope data are available at https://github.com/trhermes/isotopes.sheep.goat.tianshan and archived at https://doi.org/10.17605/OSF.IO/UTNYR.

To estimate the time of year using the oxygen isotopic time-series for each analyzed tooth, the period of each sinusoidal curve is used to model a "Julian day" between 1 and 365 for each sampling increment. Measurements of each isotopic increment can then be laid out across the portion of the annual cycle represented in the period of the tooth, which estimates the time of year for carbon isotope values. Estimating birth seasonality similarly uses the position of the maximum for each sinusoidal curve relative to the wavelength of the sinusoidal curve, giving values between 0 and 1 within a probability distribution. Although this study lacks a reference set of modern animals with known birthdates, we can approximate the seasonality of births as follows: spring ≈ 0.13–0.38, summer ≈ 0.38–0.63, fall ≈ 0.63–0.87, winter ≈ 0.87–1 and 0–0.13 (since winter would be split between 0 and 1 values). Isotopic research on modern reference animals may refine these initial birth seasonality classes.

4 | RESULTS

Summary statistics of the newly reported and previously published comparative $\delta^{13}C_{apa}$ and $\delta^{18}O_{apa}$ values are shown in Table 1, and plots of the isotopic values for each newly analyzed tooth are shown in Figure 2. Overall, $\delta^{13}C_{apa}$ values from Chap-1 caprines range between −10.5 and −7‰, which correspond to a diet based almost exclusively on C_3 plants (Table 1). This pattern of dietary intake is further observed for modern Siberian ibex from Jeti-Oguz, which corresponds with the comparative data of one modern domesticated sheep (Bayan-Zherek in Kazakhstan) and also for ancient caprines from Kent (Table 1). In contrast, high $\delta^{13}C_{apa}$ values approaching −3‰ for ancient caprines from Begash and Turgen in the comparative dataset demonstrate the effect of a substantial portion of C_4 plants in the diet (Table 1).

It is important to note that, for each isotopic sequence analyzed here and in the comparative dataset, high $\delta^{13}C_{apa}$ values appear to coincide with low $\delta^{18}O_{apa}$ values, and vice versa (Figure 2; Figures S1–S3). Following Knockaert et al. (2018), we further evaluated this relationship through analysis of the Pearson correlation coefficient between $\delta^{13}C_{apa}$ and $\delta^{18}O_{apa}$ values for each tooth. Out of 40 tooth isotopic sequences in the dataset, 28 exhibit negative correlations between carbon and oxygen isotope values that also yielded p-values greater than or equal to 0.05 (Figure S4; Table S3). Moreover, seasonal changes in dietary intake for Chap-1 caprines, represented by the difference between maximum and minimum $\delta^{13}C_{apa}$ values for each tooth, ranges between 0.4 and 2.8‰ across the 10 analyzed

TABLE 1 Summary statistics of $\delta^{13}C_{apa}$ and $\delta^{18}O_{apa}$ values from teeth of ancient domesticated caprines from Chap-1 and modern wild Siberian ibex from Jeti-Oguz (second and third mandibular molars)

	$\delta^{13}C_{apa}$ (‰)				$\delta^{18}O_{apa}$ (‰)				*n*		
Site	Mean	SD	Min	Max	Mean	SD	Min	Max	Teeth	Increments	MNI
Chap-1	−9.1	0.81	−10.53	−7	−5.37	3.27	−10.76	0.88	10	98	8
Jeti-Oguz (ibex)	−11.02	0.58	−12.17	−9.98	−7.55	2.8	−12.57	−2.59	4	43	2
Bayan-Zherek[a]	−11.07	0.69	−12.38	−10.28	−6.13	3.09	−9.78	−0.92	1	21	1
Begash[a]	−8.49	1.93	−11.17	−3.22	−7.4	3.04	−12.52	−2.03	6	73	6
Dali[a]	−10.05	0.5	−11.17	−9.1	−8.26	3.46	−13	−2.53	2	32	2
Kent[b]	−9.38	0.74	−10.69	−7.66	−8.25	2.96	−14.87	−2.89	10	78	10
Turgen[b]	−9.14	2.14	−11.61	−3.83	−6.5	3.08	−13.68	−1.71	7	43	7

Note: Comparative isotopic data are included.

[a] Previously reported $\delta^{13}C_{apa}$ and $\delta^{18}O_{apa}$ values from caprine second mandibular molars include a modern sheep from Bayan-Zherek and ancient caprines from Begash and Dali (Hermes et al., 2019).

[b] Previously reported $\delta^{13}C_{apa}$ and $\delta^{18}O_{apa}$ values from caprine second molars include ancient caprines from Kent and Turgen (Ventresca-Miller et al., 2020).

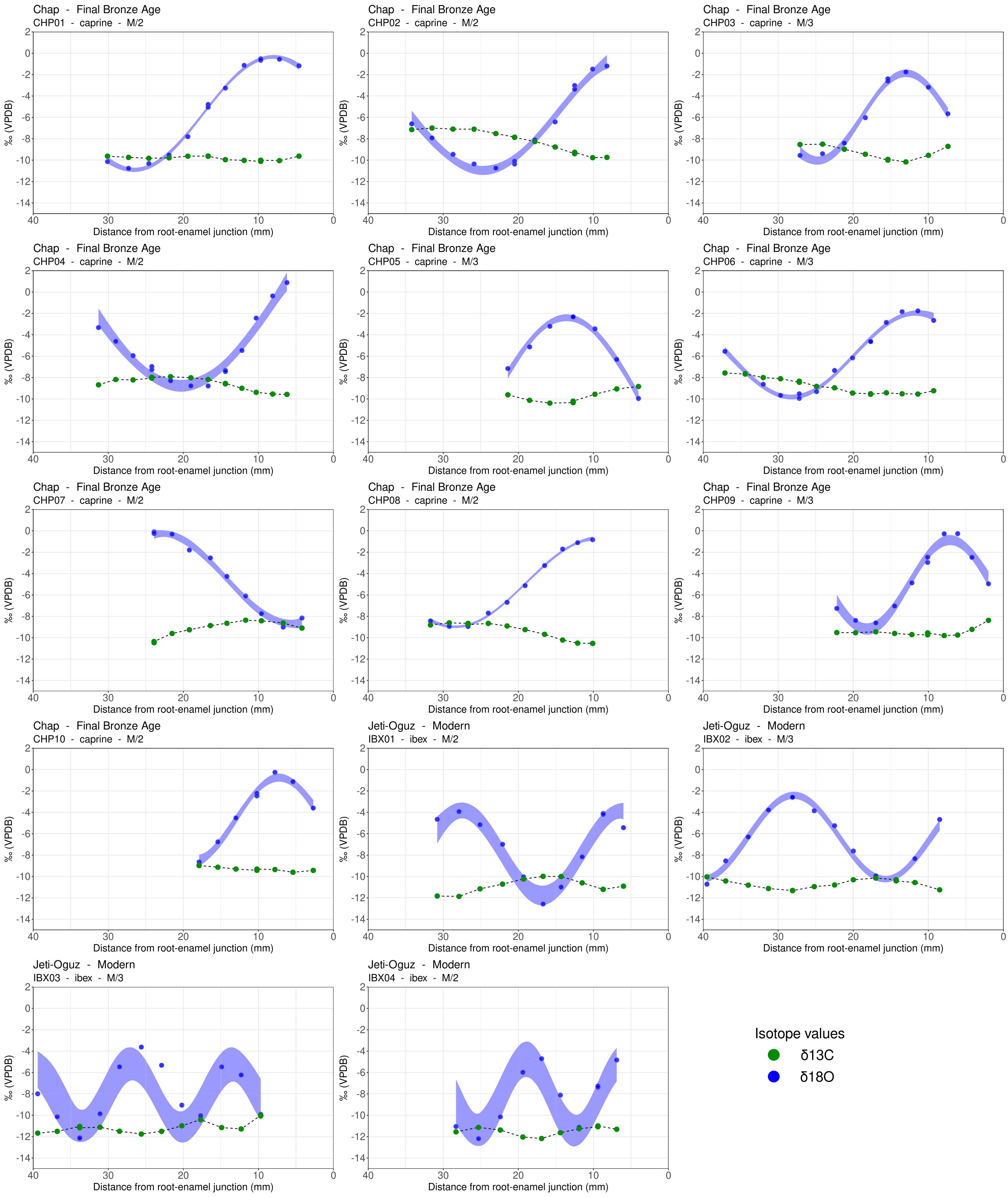

FIGURE 2 Time series plots of $\delta^{13}C_{apa}$ and $\delta^{18}O_{apa}$ values of domesticated caprines from Final Bronze Age layers at Chap-1 and modern Siberian ibex from Jeti-Oguz, Kyrgyzstan [Colour figure can be viewed at wileyonlinelibrary.com]

teeth, while there is a slightly narrower set of individual ranges of $\delta^{13}C_{apa}$ values for Siberian ibex between 1.1 and 1.9‰ (Table S4). For example, teeth CHP01, CHP09, and CHP10 exhibit inter-seasonal stretches of $\delta^{13}C_{apa}$ values that change very little, compared with the inter-seasonal shift in $\delta^{13}C_{apa}$ values visible in the teeth CHP02 and CHP03 (Figure 2). Small seasonal changes in $\delta^{13}C_{apa}$ values in the Chap-1 caprine teeth are broadly similar to that for comparative sites Kent and Bayan-Zherek (Table S4). In contrast, there are prominent seasonal changes in δ^{13}C$_{apa}$ values for Begash and Turgen caprines, of which the teeth with the most change from each site have individual tooth δ^{13}C$_{apa}$ ranges of 5.7 and 4.6‰, respectively (Table S4), which reflects the effect of animals ingesting C$_4$ plants during winter.

We successfully fit cosine functions to the sequences of δ^{18}O$_{apa}$ values for each tooth in the Chap-1 and comparative datasets, except for comparative teeth 5582 and 5583 from Ventresca-Miller et al. (2020) due too few isotope measurements. The modeling performed less well for tooth IBX03, which nearly exhibits three minima in the δ^{18}O$_{apa}$ sequence (Figure 2), likely due to unusually slow tooth development in this Siberian ibex individual, causing this third molar to archive isotopic inputs for an unusually long time of more than 2 years. This effect corresponds to observations made by previous researchers showing a slowdown of molar development in horses (Bendrey et al., 2015; Nacarino-Meneses et al., 2017). In addition, limited research on Iberian ibex (*Capra pyrenaica*) suggests wild goats may have occasional instances of slow molar growth (Vigal & Machordom, 1985); although, more research is needed on a variety of ibex species. Nevertheless, we estimated birth seasonality using data only from the mandibular second molars to avoid irregular developmental schedules for mandibular third molars (Figure 3), and no temporal shifts in tooth growth were visible except for teeth IBX03 and IBX04, from which we excluded one value each closest to the root-enamel junction. Starting with the Siberian ibex, we observe births during the late spring-early summer, which is the natural kidding season for this species (Baskin & Danell, 2003; Heptner et al., 1988), and this is the most common period for births observed in the Chap-1 and comparative datasets (Figure 3). Three of the six caprines from Chap seemingly had off-season births (CHP02, CHP04, and CHP07), in addition to a handful of caprines from Begash ($n = 2$), Kent ($n = 2$), and Turgen ($n = 1$) (Figure 3). Derivations of birth seasonality and Julian days are collated with all isotope data in Table S5.

Finally, the crests of the δ^{18}O$_{apa}$ curves from Chap-1 do not exhibit any detectible flattening that has been previously hypothesized by Hermes et al. (2018) to suggest summer migrations to high-elevation (Figure 2). However, Siberian ibex δ^{13}C$_{apa}$ values corresponding to winter dietary intake are systematically higher than δ^{13}C$_{apa}$ values corresponding to summer dietary intake, giving insight to the change in dietary carbon isotopic variation due to vertical mobility, as these animals routinely occupy alpine environments in summer and descend to lowland valleys in winter (Baskin & Danell, 2003; Heptner et al., 1988).

5 | DISCUSSION

5.1 | Agricultural and pastoralist integration

This study provides initial insight into how sheep and goat husbandry intersected with agriculture at Chap-1 during the final Bronze Age in

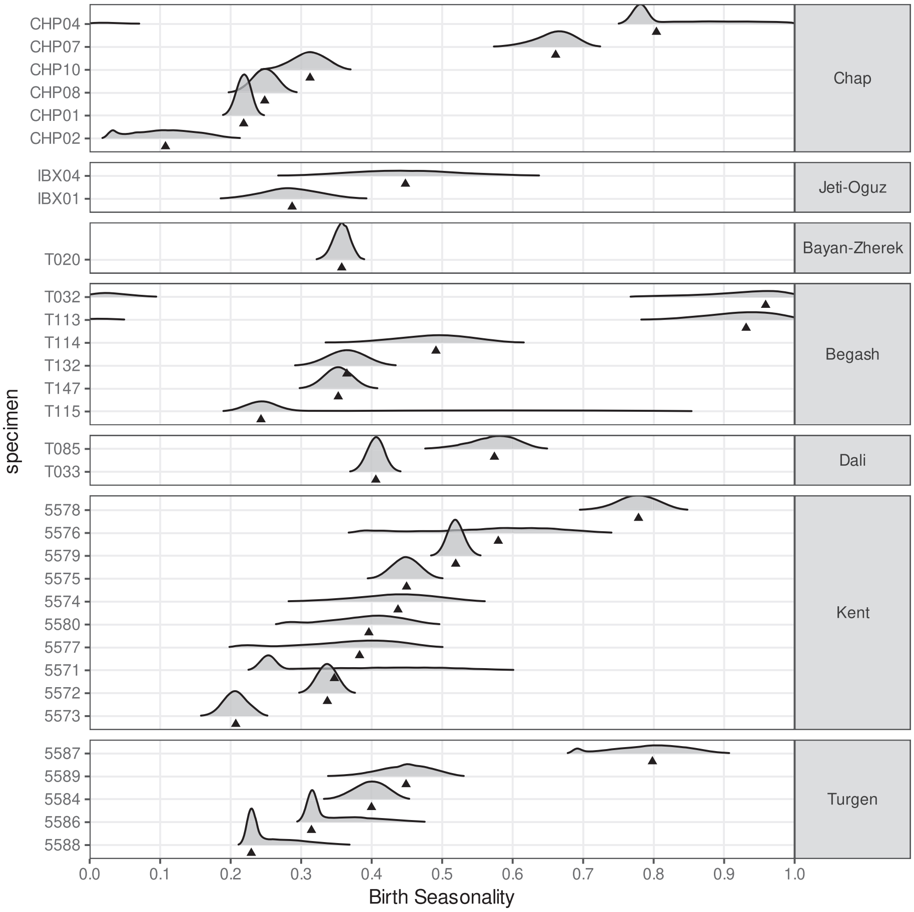

FIGURE 3 Probability distributions of estimated birth seasonality using modelled cosine functions against δ^{18}O$_{apa}$ values from Chap-1 caprines and modern Siberian ibex (Jeti-Oguz), in addition to caprines from comparative sites listed in Table 1. Point estimate for each birth season represents the optimized curve fit. Only data from second mandibular molars were used in the estimations

the Kyrgyz Tian Shan. The relatively wider range of summer-winter $\delta^{13}C_{apa}$ values for individual teeth of domesticated caprines compared with that for Siberian ibex suggests human control of animal diets, likely through flexible strategies that varied from year to year, such as foddering with mixtures of agricultural biproducts, grazing on crop stubble after harvest, and vertical transhumance to summer pastures. Consistent dietary intake between winter and summer suggests that some caprines were closely managed near the site and had regular access to graze and fodder that, in some cases, may have been characterized by unvarying carbon isotopic compositions, perhaps coming from large stockpiles. In contrast, marked change in dietary intake between summer and winter for most analyzed Chap-1 teeth corresponds to that observed for Siberian ibex, which may be the result of vertical mobility to high pastures in summer, where vegetation is characterized by low $\delta^{13}C$ values compared with the more arid lowlands that are affected by the Tian Shan rain shadow. Increased precipitation at higher elevations and rapid plant growth during the short summer season contribute to C_3 vegetation being depleted in ^{13}C compared with that in lowland environments (Tieszen, 1991). Moreover, there is a decreasing relative abundance of C_4 plants at higher elevations (Tieszen et al., 1979), which would further lead to low $\delta^{13}C$ values in summer-forming portions of teeth in caprines herded to higher elevations as the carbon isotopic composition of highland vegetation would be increasingly depleted in ^{13}C.

The seasonal carbon isotopic time-series from Siberian ibex analyzed in this study and from a domesticated sheep documented to have migrated to high pastures in the summer in Hermes et al. (2019) provide additional support that vertical transhumant moves in Central Asia generates a pattern of decreasing $\delta^{13}C_{apa}$ values in summer months. However, this shifting carbon isotopic pattern in domesticated caprines could also be the result of a relatively minor component of winter foddering or stubble grazing with cultivated millet, or the grazing on pastures/fields containing low numbers of wild C_4 plants, such as green foxtail (*Setaria viridis*) and barnyard grass (*Echinochloa* sp.), of which carbonized seeds were recovered from Chap-1 flotation samples (Motuzaite Matuzeviciute, Mir-Makhamad & Tabaldiev, 2021). Overall, the carbon isotopic variability observed in the analyzed teeth of Chap-1 domesticated caprines points toward adaptable strategies for managing animal diets that may have included sedentism, provisioning with a small amount of C_4 plants in combination with more substantial amounts of C_3 wheat and/or barley, and occasional mobility to high-elevation pastures. Thus, we can discern two main processes of integrating caprines into the agricultural milieu at Chap-1: (1) local herding in the surrounds of the site with the possibility of foddering with C_3 crops and (2) infrequent vertical transhumance. A third management strategy would possibly include fall and winter foddering with a relatively low proportion of millets relative to the consumption of natural pastures or C_3 crops. The differentiation of this strategy from vertical transhumance based on seasonal carbon isotopic shifts remains challenging.

It is notable that we did not detect animal diets with large components of C_4 plants, as was evident at Bronze Age Begash (Hermes et al., 2019) and Turgen (Ventresca-Miller et al., 2020). This lack of evidence for foddering with C_4 plants indicates that caprines were not integrated into strategies for the cultivation of millet at Chap-1. Both broomcorn and foxtail millets reflect a minor component of the macrobotanical record at Chap-1, which were found at a relative abundance of 1.9% of the domesticated crops that were dominated by barley (Motuzaite Matuzeviciute, Mir-Makhamad & Tabaldiev, 2021). One possibility could be that cattle were foddered with millet, and the low relative abundance of millets in the macrobotanical record at the site could be explained by different processing of millets compared with wheat and barley. Since cattle teeth were unavailable for this study, future research on the carbon isotopic composition of cattle bone collagen may be able to identify this foddering strategy. However, the low relative abundance of millets at Chap-1 could also be a result of millets growing in fields as weeds and entering the archaeological deposits through the burning of dung from animals that grazed on crop stubble.

5.2 | Manipulation of animal births

Analysis of birth seasonality for domesticated caprines at Chap-1 indicates efforts made by people to facilitate off-season births that extended into the fall and possibly winter. Based on the incremental oxygen isotopic data from Begash, Kent, and Turgen (Hermes et al., 2019; Ventresca-Miller et al., 2020), it is clear that the practical expertise for extending birthing seasons of domesticated caprines was in circulation throughout the wider region since the mid second millennium BCE. An extended birthing season affords producers with fallback offspring if the previous cohort of newborns is killed due to severe winter conditions, such as the deep freezes and snow accumulations caused by the *jut*, provided that recently pregnant ewes can reenter estrus (Ventresca-Miller et al., 2020). Moreover, spaced out birthing seasons also afford producers with extended time periods for harvesting animals for meat and for milking them. Longer lambing seasons can be achieved by the "ram effect," which involves bringing rams into contact with ewes who have been isolated from males for several weeks, causing male pheromones to trigger ovulation within 2–3 days but without the typical physiological signs of estrus (Fabre-Nys et al., 2015). It may be the case that ancient herders in Central Asia had bred and selected animals that had more biological proclivity for off-season births since domesticated sheep and goat first spread into the region during the Neolithic by 6000 BCE (Taylor et al., 2021), and ongoing paleogenomic research may reveal the genetic signatures for such traits in detail. Nonetheless, extended birthing seasons would have demanded a high degree of knowledge about animal reproductive physiology, in addition to a system of record keeping that tracked individual animal contacts with males and tracked the fecundity of ewes. Because the species of the analyzed teeth were not determined with biomolecular methods such as ZooMS (Zooarchaeology by Mass Spectrometry) (Buckley et al., 2010), and could not be reliably differentiated based on dental morphology, the specific goals of production for sheep or goats at Chap-1 cannot be identified. Zooarchaeological research at Chap-1 identified kill-off patterns of caprines (presumably sheep) favoring survivorship of older animals, suggesting a strategy of wool production (Ananyevskaya et al., 2021).

There is the possibility that the three animals showing off-season births at Chap-1 (CHP02, CHP04, CHP07) are not the result of human intent but occurred spontaneously (Fabre-Nys et al., 2015). Tooth CHP07 provides the strongest evidence for a winter birth, as its modelled oxygen isotopic sequence displays a minimum and maximum, while teeth CHP02 and CHP04 show incomplete curve wavelengths (Figure 2). Despite this shortfall, the modelled seasonality of the births represented by these teeth with incomplete wavelengths reflect an off-season clustering with animals from Begash, Kent, Turgen. Thus, taken together, this pattern of off-season births from a limited set of analyzed teeth suggests the practice of manipulating livestock births may have been a relatively common practice in Bronze Age Central Asia. If teeth CHP02 and CHP04 are disregarded, then the presence of one M/2 tooth out of six for Chap-1 still suggests the capability of people to manipulate caprine births, since a random occurrence seems unlikely.

5.3 | Regional perspective

In light of the complex summer and winter cropping systems in place at Chap-1 evidenced from the macrobotanical record (Motuzaite Matuzeviciute, Mir-Makhamad & Tabaldiev, 2021), we can begin to appreciate that the Kochkor Valley at the end of the Bronze Age had a well-integrated system of agro-pastoralist production, the scale of which necessitates discussion. Although the settlement density and stocking rate of the Kochkor Valley in the Bronze Age remains unknown due to a lack of systematic regional survey, a safe assumption can be made that Chap-1 was part of a constellation of farmsteads that likely supported at least dozens of households, if not more. Integrated farming and pastoralism would have shaped complex labor divisions and knowledge systems surrounding crops and animals for the ancient communities living in the valley. We can envision scenarios in which households enter agreements with one another to provide access to pastures and agricultural by-products, and in which some members of households herded animals to highland pastures, facilitating social interactions with summer herders from neighboring regions. In addition to this herding dynamic, animals from the Kochkor Valley may have been herded to lower elevations or vice versa, while crops, dairy products, and other commodities (raw materials or finished crafts) were also likely exchanged. While direct evidence for these channels of communication and exchange remain elusive, we can begin to illustrate how permanent settlement in the fertile highlands of Central Asia would have facilitated dynamic social networks that spread across the wider region, as some people moved with animals while others kept the core of animal management close to farmsteads. Additional research at ancient highland settlements in Central Asia will contribute to a greater understanding of the importance of mountain environments in serving as key corridors of interaction between diverse communities (e.g., Frachetti et al., 2017; Hermes, Doumani Dupuy, et al., 2021; Hermes, Shnaider, et al., 2021; Maksudov et al., 2019).

6 | CONCLUSION

The isotopic evidence for subtle but variable manipulation of domesticated caprine diets using a mixture of strategies, including foddering and vertical transhumance, which were also combined with investment in extending birthing seasons, illustrates a productive and diverse agro-pastoralist subsistence economy in the Kyrgyz Tian Shan during the Final Bronze Age. While this mountain corridor region and Central Asia more broadly has long been thought of as a domain of highly mobile nomadic pastoralists, we should reevaluate this assumption with a growing body of evidence for strongly integrated farming and herding strategies that were well developed in highland environments.

In the context of the abundant and rich macrobotanical record from Chap-1, the occupation of the site must have been year-round, while a section of the community may have been responsible for herding animals to highland pastures or the lowlands on a seasonal basis but retained a strong subsistence connection to an agricultural home base at 2000 m.a.s.l. Thus, when considering how commodities, styles, ideas, and genetic ancestry were transmitted throughout the IAMC since the early Bronze Age, future models for communication and exchange should explicitly factor in such community segments rather than supposing all members of a community were mobile and directly participated in social engagements with neighboring groups. Future research combining human and livestock paleogenomic records for resolving biological admixture and incremental strontium isotopic patterns in human tooth enamel for isolating geographic mobility will greatly help to clarify how communities achieved contact with one another and contributed to dynamic arenas of interaction since the Neolithic. These lines of research are crucial for understanding how agro-pastoralist strategies connecting the lowlands and highlands facilitated community interactions in ancient Central Asia.

ACKNOWLEDGMENTS

This research was funded by the European Social Fund (no. 09.3.3-LMT-K-712-01-0002) under grant agreement with the Research Council of Lithuania (LMTLT). We offer special thanks to Shannon Kachel for collecting Siberian ibex tooth samples during the course of his research on snow leopards. We thank Elina Ananyevskaya for assistance with tooth sampling at the Bioarchaeology Research Centre of Vilnius University. We also thank Nils Andersen of the Leibniz Labor of Kiel University for isotopic measurement. We are grateful to three anonymous reviewers for helping to improve this paper. Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data are available in the text or supporting information.

ORCID

Taylor R. Hermes https://orcid.org/0000-0002-8377-468X
Clemens Schmid https://orcid.org/0000-0003-3448-5715
Kubatbek Tabaldiev https://orcid.org/0000-0002-6679-8030
Giedre Motuzaite Matuzeviciute https://orcid.org/0000-0001-9069-1551

REFERENCES

Ananyevskaya, E., Buckley, M., Chowdhury, M. P., Tabaldiev, K., & Matuzeviciute, G. M. (2021). Specialized wool production economy of prehistoric farmstead of chap I in the highlands of Central Tian Shan (Kyrgyzstan). *International Journal of Osteoarchaeology*, *31*, 18–28. https://doi.org/10.1002/oa.2921

Anthony, D. (2007). *The horse, the wheel, and language: How bronze-age riders from the Eurasian steppes shaped the modern world*. Princeton University Press. https://doi.org/10.1515/9781400831104

Balasse, M., Gillis, R., Živaljević, I., Berthon, R., Kovačiková, L., Fiorillo, D., Arbogast, R. M., Bălăşescu, A., Bréhard, S., Nyerges, É. Á., Dimitrijević, V., Bánffy, E., Domboróczki, L., Marciniak, A., Oross, K., Vostrovská, I., Roffet-Salque, M., Stefanović, S., & Ivanova, M. (2021). Seasonal calving in European prehistoric cattle and its impacts on milk availability and cheese-making. *Scientific Reports*, *11*, 8185. https://doi.org/10.1038/s41598-021-87674-1

Balasse, M., Obein, G., Ughetto-Monfrin, J., & Mainland, I. (2012). Investigating seasonality and season of birth in past herds: A reference set of sheep enamel stable oxygen isotope ratios. *Archaeometry*, *54*, 349–368. https://doi.org/10.1111/j.1475-4754.2011.00624.x

Baskin, L., & Danell, K. (2003). *Ecology of ungulates: A handbook of species in Eastern Europe and northern and Central Asia*. Springer-Verlag. https://doi.org/10.1007/978-3-662-06820-5

Bendrey, R., Vella, D., Zazzo, A., Balasse, M., & Lepetz, S. (2015). Exponentially decreasing tooth growth rate in horse teeth: Implications for isotopic analyses. *Archaeometry*, *57*, 1104–1124. https://doi.org/10.1111/arcm.12151

Böckel, B., & Becker, F. (2014). Viehwirtschaft als Lebensunterhaltungsstrategie im ländlichen Kirgistan und ihre Folgen für die Weidegebiete. In M. Schmidt (Ed.), *Aktuelle Forschungen zu den Mensch-Umwelt-Verhältnissen in Kirgistan* (pp. 66–79). LIT Verlag.

Bonafini, M., Pellegrini, M., Ditchfield, P., & Pollard, A. M. (2013). Investigation of the 'canopy effect' in the isotope ecology of temperate woodlands. *Journal of Archaeological Science*, *40*, 3926–3935. https://doi.org/10.1016/j.jas.2013.03.028

Britton, K., Grimes, V., Dau, J., & Richards, M. P. (2009). Reconstructing faunal migrations using intra-tooth sampling and strontium and oxygen isotope analyses: A case study of modern caribou (*Rangifer tarandus granti*). *Journal of Archaeological Science*, *36*, 1163–1172. https://doi.org/10.1016/j.jas.2009.01.003

Bryant, D. J., & Froelich, P. N. (1995). A model of oxygen isotope fractionation in body water of large mammals. *Geochimica et Cosmochimica Acta*, *59*, 4523–4537. https://doi.org/10.1016/0016-7037(95)00250-4

Buckley, M., Whitcher Kansa, S., Howard, S., Campbell, S., Thomas-Oates, J., & Collins, M. (2010). Distinguishing between archaeological sheep and goat bones using a single collagen peptide. *Journal of Archaeological Science*, *37*, 13–20. https://doi.org/10.1016/j.jas.2009.08.020

Chupakhin, V. M. (1959). *Inner Tian Shan*. Academy of Sciences of Kyrygz SSR.

Doumani, P. N., Frachetti, M. D., Beardmore, R., Schmaus, T. M., Spengler, R. N., & Maryashev, A. N. (2015). Burial ritual, agriculture, and craft production among bronze age pastoralists at Tasbas (Kazakhstan). *Archaeological Research in Asia*, *1-2*, 17–32. https://doi.org/10.1016/j.ara.2015.01.001

Fabre-Nys, C., Kendrick, K. M., & Scaramuzzi, R. J. (2015). The "ram effect": New insights into neural modulation of the gonadotropic axis by male odors and socio-sexual interactions. *Frontiers in Neuroscience*, *9*. https://doi.org/10.3389/fnins.2015.00111

Farquhar, G. D., Ehleringer, J. R., & Hubick, K. T. (1989). Carbon isotope discrimination and photosynthesis. *Annual Review of Plant Physiology and Plant Molecular Biology*, *40*, 503–537. https://doi.org/10.1146/annurev.pp.40.060189.002443

Frachetti, M. D. (2012). Multiregional emergence of Mobile pastoralism and nonuniform institutional complexity across Eurasia. *Current Anthropology*, *53*, 2–38. https://doi.org/10.1086/663692

Frachetti, M. D., Smith, C. E., Traub, C. M., & Williams, T. (2017). Nomadic ecology shaped the highland geography of Asias silk roads. *Nature*, *543*, 193–198. https://doi.org/10.1038/nature21696

Frachetti, M. D., Spengler, R. N., Fritz, G. J., & Maryashev, A. N. (2010). Earliest direct evidence for broomcorn millet and wheat in the central Eurasian steppe region. *Antiquity*, *84*, 993–1010. https://doi.org/10.1017/S0003598X0006703X

Guan, X., Yao, J., & Schneider, C. (2022). Variability of the precipitation over the Tianshan Mountains, Central Asia. Part I: Linear and nonlinear trends of the annual and seasonal precipitation. *International Journal of Climatology*, *42*, 118–138. https://doi.org/10.1002/joc.7235

Haruda, A. (2018). Regional pastoral practice in central and southeastern Kazakhstan in the final bronze age (1300–900BCE). *Archaeological Research in Asia*, *15*, 146–156. https://doi.org/10.1016/j.ara.2017.09.004

Haruda, A. F., Varfolomeev, V., Goriachev, A., Yermolayeva, A., & Outram, A. K. (2019). A new zooarchaeological application for geometric morphometric methods: Distinguishing *Ovis aries* morphotypes to address connectivity and mobility of prehistoric central Asian pastoralists. *Journal of Archaeological Science*, *107*, 50–57. https://doi.org/10.1016/j.jas.2019.05.002

Heptner, V., Nasimovich, A., & Bannikov, A. (1988). *Mammals of the Soviet Union. Artiodactyla and Perissodactyla*. Smithsonian Institution libraries and the National Science Foundation.

Hermes, T. R., Doumani Dupuy, P. N., Henry, E. R., Meyer, M., Maryashev, A. N., & Frachetti, M. D. (2021). The multi-period settlement Dali in southeastern Kazakhstan: Bronze age institutional dynamics along the inner Asian Mountain corridor. *Asian Perspectives*, *60*, 345–381. https://doi.org/10.1353/asi.2021.0004

Hermes, T. R., Frachetti, M. D., Doumani Dupuy, P. N., Maryashev, A., Nebel, A., & Makarewicz, C. A. (2019). Early integration of pastoralism and millet cultivation in bronze age Eurasia. *Proceedings of the Royal Society B*, *286*, 20191273. https://doi.org/10.1098/rspb.2019.1273

Hermes, T. R., Pederzani, S., & Makarewicz, C. A. (2018). Ahead of the curve? Implications for isolating vertical transhumance in seasonal montane environments using sequential oxygen isotope analyses of tooth enamel. In A. Ventresca Miller & C. A. Makarewicz (Eds.), *Isotopic investigations of pastoralism in prehistory* (pp. 57–76). Routledge. https://doi.org/10.4324/9781315143026-5

Hermes, T. R., Shnaider, S. V., Semibratov, V. P., Kungurov, A. L., & Tishkin, A. A. (2021). Revisiting the emergence of pastoralism in the Altai Mountains through interactions between local hunter-gatherer and Afanasievo communities. *Archaeological Research in Asia*, *26*, 100281. https://doi.org/10.1016/j.ara.2021.100281

Jeong, C., Wang, K., Wilkin, S., Taylor, W. T. T., Miller, B. K., Bemmann, J. H., Stahl, R., Chiovelli, C., Knolle, F., Ulziibayar, S., Khatanbaatar, D., Erdenebaatar, D., Erdenebat, U., Ochir, A., Ankhsanaa, G., Vanchigdash, C., Ochir, B., Munkhbayar, C., Tumen, D., … Warinner, C. (2020). A dynamic 6,000-year genetic history of Eurasia's Eastern Steppe. *Cell*, *183*(4), 890–904.e29. https://doi.org/10.1016/j.cell.2020.10.015

Jones, M., Hunt, H., Lightfoot, E., Lister, D., Liu, X., & Motuzaite-Matuzeviciute, G. (2011). Food globalization in prehistory. *World Archaeology*, *43*, 665–675. https://doi.org/10.1080/00438243.2011.624764

Keeling, C. D. (1979). The Suess effect: 13Carbon-14Carbon interrelations. *Environment International*, *2*, 229–300. https://doi.org/10.1016/0160-4120(79)90005-9

Knockaert, J., Balasse, M., Rendu, C., Burens, A., Campmajo, P., Carozza, L., Bousquet, D., Fiorillo, D., & Vigne, J.-D. (2018). Mountain adaptation of caprine herding in the eastern Pyrenees during the bronze age: A stable oxygen and carbon isotope analysis of teeth. *Quaternary International*, *484*, 60–74. https://doi.org/10.1016/j.quaint.2017.05.029

Kohl, P. (2007). *The making of bronze age Eurasia*. Cambridge University Press. https://doi.org/10.1017/CBO9780511618468

Körner, C., Farquhar, G. D., & Roksandic, Z. (1988). A global survey of carbon isotope discrimination in plants from high altitude. *Oecologia*, *74*, 623–632. https://doi.org/10.1007/BF00380063

Körner, C., Farquhar, G. D., & Wong, S. C. (1991). Carbon isotope discrimination by plants follows latitudinal and altitudinal trends. *Oecologia*, *88*, 30–40. https://doi.org/10.1007/BF00328400

Krever, V., Pereladova, O., Williams, M., & Jungius, H. (1998). *Biodiversity and conservation in Central Asia: An analysis of biodiversity and current threats and initial investment portfolio*. World Wide Fund for Nature.

Kuzmina, E. E. (1986). *Drevneishie Skotovodi ot Urala do TyanShana*. Ilim.

Lazzerini, N., Coulon, A., Simon, L., Marchina, C., Fiorillo, D., Turbat, T., Bayarkhuu, N., Noûs, C., Lepetz, S., & Zazzo, A. (2021). The isotope record (δ13C, δ18O) of vertical mobility in incremental tissues (tooth enamel, hair) of modern livestock: A reference set from the Mongolian Altai. *Quaternary International*, *595*, 128–144. https://doi.org/10.1016/j.quaint.2021.04.008

Lazzerini, N., Zazzo, A., Coulon, A., Turbat, T., Marchina, C., & Lepetz, S. (2020). Date of death of domestic caprines assessed by oxygen isotopic analysis of developing molars: Implications for deciphering the calendar of pastoral activities in prehistory. *Journal of Archaeological Science*, *120*, 105163. https://doi.org/10.1016/j.jas.2020.105163

Li, Y., Storozum, M. J., Wang, X., & Guo, W. (2017). Early irrigation and agropastoralism at Mohuchahangoukou (MGK), Xinjiang, China. *Archaeological Research in Asia*, *12*, 23–32. https://doi.org/10.1016/j.ara.2017.09.005

Liu, X., Jones, P. J., Motuzaite Matuzeviciute, G., Hunt, H. V., Lister, D. L., An, T., Przelomska, N., Kneale, C. J., Zhao, Z., & Jones, M. K. (2019). From ecological opportunism to multi-cropping: Mapping food globalisation in prehistory. *Quaternary Science Reviews*, *206*, 21–28. https://doi.org/10.1016/j.quascirev.2018.12.017

Liu, X., Lister, D. L., Zhao, Z., Petrie, C. A., Zeng, X., Jones, P. J., Staff, R. A., Pokharia, A. K., Bates, J., Singh, R. N., Weber, S. A., Matuzeviciute, G. M., Dong, G., Li, H., Lü, H., Jiang, H., Wang, J., Ma, J., Tian, D., … Jones, M. K. (2017). Journey to the east: Diverse routes and variable flowering times for wheat and barley en route to prehistoric China. *PLOS ONE*, *12*, e0187405. https://doi.org/10.1371/journal.pone.0187405

Luneau, E., Ferreras, V. M., Abdykanova, A., Tabaldiev, K., & Motuzaite Matuzeviciute, G. (2020). New studies on Bronze Age ceramics from Northern Kyrgyzstan. In V. P. Nikonorov, L. B. Kircho, & S. YeO (Eds.), *Ancient and medieval cultures of Central Asia (the formation, development and interaction of urbanized and cattle-breeding societies)* (pp. 134–136). Institute for the History of Material Culture.

Maksudov, F., Bullion, E., Henry, E. R., Hermes, T., Merkle, A. M., & Frachetti, M. D. (2019). Nomadic urbanism at Tashbulak: A new highland town of the Qarakhanids. In C. Baumer & M. Novák (Eds.), *Urban cultures of Central Asia from the bronze age to the Karakhanids: Learnings and conclusions from new archaeological investigations and discoveries* (pp. 283–306). Wiesbaden. https://doi.org/10.13173/9783447111690.283

Milhaud, G., & Nezit, J. (1991). Développement des molaires chez le mouton. Études morphologique, radiographique et microdurométrique. *Recueil de Medecine Veterinaire*, *167*, 121–127.

Motuzaite Matuzeviciute, G., Hermes, T. R., Mir-Makhamad, B., & Tabaldiev, K. (2020). Southwest Asian cereal crops facilitated high-elevation agriculture in the central Tien Shan during the mid-third millennium BCE. *PLOS ONE*, *15*, e0229372. https://doi.org/10.1371/journal.pone.0229372

Motuzaite Matuzeviciute, G., Mir-Makhamad, B., & Spengler, R. N. (2021). Interpreting diachronic size variation in prehistoric central Asian cereal grains. *Frontiers in Ecology and Evolution*, *9*, 133. https://doi.org/10.3389/fevo.2021.633634

Motuzaite Matuzeviciute, G., Mir-Makhamad, B., & Tabaldiev, K. (2021). The first comprehensive archaeobotanical analysis of prehistoric agriculture in Kyrgyzstan. *Vegetation History and Archaeobotany*, *30*, 743–758. https://doi.org/10.1007/s00334-021-00827-0

Motuzaite Matuzeviciute, G., Tabaldiev, K., Hermes, T., Ananyevskaya, E., Grikpedis, M., Luneau, E., Merkyte, I., & Rouse, L. M. (2020). High-altitude agro-pastoralism in the Kyrgyz Tien Shan: New excavations of the chap farmstead (1065–825 cal b.c.). *Journal of Field Archaeology*, *45*, 29–45. https://doi.org/10.1080/00934690.2019.1672128

Nacarino-Meneses, C., Jordana, X., Orlandi-Oliveras, G., & Köhler, M. (2017). Reconstructing molar growth from enamel histology in extant and extinct Equus. *Scientific Reports*, *7*, 15965. https://doi.org/10.1038/s41598-017-16227-2

Narasimhan, V. M., Patterson, N., Moorjani, P., Rohland, N., Bernardos, R., Mallick, S., Lazaridis, I., Nakatsuka, N., Olalde, I., Lipson, M., Kim, A. M., Olivieri, L. M., Coppa, A., Vidale, M., Mallory, J., Moiseyev, V., Kitov, E., Monge, J., Adamski, N., … Reich, D. (2019). The formation of human populations in south and Central Asia. *Science*, *365*, eaat7487. https://doi.org/10.1126/science.aat7487

Passey, B. H., Robinson, T. F., Ayliffe, L. K., Cerling, T. E., Sponheimer, M., Dearing, M. D., Roeder, B. L., & Ehleringer, J. R. (2005). Carbon isotope fractionation between diet, breath CO_2, and bioapatite in different mammals. *Journal of Archaeological Science*, *32*, 1459–1470. https://doi.org/10.1016/j.jas.2005.03.015

Pederzani, S., Aldeias, V., Dibble, H. L., Goldberg, P., Hublin, J. J., Madelaine, S., McPherron, S. P., Sandgathe, D., Steele, T. E., Turq, A., & Britton, K. (2021). Reconstructing Late Pleistocene paleoclimate at the scale of human behavior: an example from the Neandertal occupation of La Ferrassie (France). *Scientific Reports*, *11*, 1419. https://doi.org/10.1038/s41598-020-80777-1

Pederzani, S., & Britton, K. (2019). Oxygen isotopes in bioarchaeology: Principles and applications, challenges and opportunities. *Earth-Science Reviews*, *188*, 77–107. https://doi.org/10.1016/j.earscirev.2018.11.005

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Spengler, R. N., Chang, C., & Tourtellotte, P. A. (2013). Agricultural production in the central Asian mountains: Tuzusai, Kazakhstan (410–150 b.c.). *Journal of Field Archaeology*, *38*, 68–85. https://doi.org/10.1179/0093469012Z.00000000037

Spengler, R. N., Frachetti, M. D., & Doumani, P. N. (2014). Late bronze age agriculture at Tasbas in the Dzhungar Mountains of eastern Kazakhstan. *Quaternary International*, *348*, 147–157. https://doi.org/10.1016/j.quaint.2014.03.039

Spengler, R. N., Miller, A. V., Schmaus, T., Matuzevičiūtė, G. M., Miller, B. K., Wilkin, S., Taylor, W. T. T., Li, Y., Roberts, P., & Boivin, N. (2021). An imagined past? Nomadic narratives in central Asian archaeology. *Current Anthropology*, *62*, 251–286. https://doi.org/10.1086/714245

Suess, H. E. (1955). Radiocarbon concentration in modern wood. *Science*, *122*, 415–417. https://doi.org/10.1126/science.122.3166.415-a

Taylor, W. T. T., Pruvost, M., Posth, C., Rendu, W., Krajcarz, M. T., Abdykanova, A., Brancaleoni, G., Spengler, R., Hermes, T., Schiavinato, S., Hodgins, G., Stahl, R., Min, J., Alisher kyzy, S., Fedorowicz, S., Orlando, L., Douka, K., Krivoshapkin, A., Jeong, C., … Shnaider, S. (2021). Evidence for early dispersal of domestic sheep into Central Asia. *Nature Human Behaviour*, *5*, 1169–1179. https://doi.org/10.1038/s41562-021-01083-y

Tieszen, L. L. (1991). Natural variations in the carbon isotope values of plants: Implications for archaeology, ecology, and paleoecology. *Journal of Archaeological Science*, *18*, 227–248. https://doi.org/10.1016/0305-4403(91)90063-U

Tieszen, L. L., Senyimba, M. M., Imbamba, S. K., & Troughton, J. H. (1979). The distribution of C3 and C4 grasses and carbon isotope discrimination along an altitudinal and moisture gradient in Kenya. *Oecologia*, *37*, 337–350. https://doi.org/10.1007/BF00347910

Tornero, C., Balasse, M., Bălăşescu, A., Chataigner, C., Gasparyan, B., & Montoya, C. (2016). The altitudinal mobility of wild sheep at the Epigravettian site of Kalavan 1 (lesser Caucasus, Armenia): Evidence from a sequential isotopic analysis in tooth enamel. *Journal of Human Evolution*, *97*, 27–36. https://doi.org/10.1016/j.jhevol.2016.05.001

Tornero, C., Balasse, M., Molist, M., & Saña, M. (2015). Seasonal reproductive patterns of early domestic sheep at tell Halula (PPNB, middle Euphrates Valley): Evidence from sequential oxygen isotope analyses of tooth enamel. *Journal of Archaeological Science: Reports*, *6*, 810–818. https://doi.org/10.1016/j.jasrep.2015.10.038

van der Merwe, N. J., Medina, E. (1991). The canopy effect, carbon isotope ratios and foodwebs in Amazonia. *Journal of Archaeological Science*, *18*, 249–259. https://doi.org/10.1016/0305-4403(91)90064-V

Ventresca-Miller, A. R., Haruda, A., Varfolomeev, V., Goryachev, A., & Makarewicz, C. A. (2020). Close management of sheep in ancient Central Asia: evidence for foddering, transhumance, and extended lambing seasons during the Bronze and Iron Ages. *STAR: Science & Technology of Archaeological Research*, *6*, 41–60. https://doi.org/10.1080/20548923.2020.1759316

Vigal, C. R., & Machordom, A. (1985). Tooth eruption and replacement in the Spanish wild goat. *Acta Theriologica*, *30*(19), 305–320. https://doi.org/10.4098/AT.arch.85-21

Vogel, J. C. (1978). Recycling of carbon in a forest environment. *Oecologia Plantarum*, *13*, 89–94.

Wang, H., Prentice, I. C., Davis, T. W., Keenan, T. F., Wright, I. J., & Peng, C. (2017). Photosynthetic responses to altitude: An explanation based on optimality principles. *New Phytologist*, *213*, 976–982. https://doi.org/10.1111/nph.14332

Yatoo, M. A., Spate, M., Betts, A., Pokharia, A. K., & Shah, M. A. (2020). New evidence from the Kashmir Valley indicates the adoption of east and west Asian crops in the western Himalayas by 4400 years ago. *Quaternary Science Advances*, *2*, 100011. https://doi.org/10.1016/j.qsa.2020.100011

Zazzo, A., Balasse, M., Passey, B. H., Moloney, A. P., Monahan, F. J., & Schmidt, O. (2010). The isotope record of short- and long-term dietary changes in sheep tooth enamel: Implications for quantitative reconstruction of paleodiets. *Geochimica et Cosmochimica Acta*, *74*, 3571–3586. https://doi.org/10.1016/j.gca.2010.03.017

Zazzo, A., Balasse, M., & Patterson, W. P. (2005). High-resolution δ13C intratooth profiles in bovine enamel: Implications for mineralization pattern and isotopic attenuation. *Geochimica et Cosmochimica Acta*, *69*, 3631–3642. https://doi.org/10.1016/j.gca.2005.02.031

Zeder, M. A. (2006). Reconciling rates of long bone fusion and tooth eruption and wear in sheep (Ovis) and goat (Capra). In D. Ruscillo (Ed.), *Recent advances in ageing and sexing animal bones* (pp. 87–118). Oxford. https://doi.org/10.2307/j.ctvh1ds02.10

Zhou, X., Yu, J., Spengler, R. N., Shen, H., Zhao, K., Ge, J., Bao, Y., Liu, J., Yang, Q., Chen, G., Weiming Jia, P., & Li, X. (2020). 5,200-year-old cereal grains from the eastern Altai Mountains redate the trans-Eurasian crop exchange. *Nature Plants*, *6*, 78–87. https://doi.org/10.1038/s41477-019-0581-y

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Hermes, T. R., Schmid, C., Tabaldiev, K., & Motuzaite Matuzeviciute, G. (2022). Carbon and oxygen stable isotopic evidence for diverse sheep and goat husbandry strategies amid a Final Bronze Age farming milieu in the Kyrgyz Tian Shan. *International Journal of Osteoarchaeology*, *32*(4), 792–803. https://doi.org/10.1002/oa.3103