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Isotope ratio study of Bronze Age samples from the Eurasian Caspian Steppes

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Abstract

This paper presents result of the isotope study of human, faunal and plant archaeological samples from Bronze Age kurgans and graves of the Eurasian Steppes. Isotope data reveal a very broad range of $\delta^{13}C$ and $\delta^{15}N$ values for the Bronze Age cultures. The more ancient a sample is in age, the lower are its $\delta^{13}C$ and $\delta^{15}N$ values. Stable isotope values of plants, animal and humans are very sensitive to climate change. Annual precipitation and temperature were key factors driving the overall isotope trend. The data obtained helped us propose two fodder models for domesticated animals and three diet models for humans. $\delta^{13}C$ and $\delta^{15}N$ values in animal bones indicate that different pastures were used by local mobile groups. Some archaeological plant samples dating to the period of aridization are characterized by very high ^{15}N values. These were probably included in animal fodder, which was reflected in the isotope ratio of domesticated animals. Humans had a mixed diet, which is why regular patterns of changes in the isotope ratios of carbon and nitrogen are more subtle. There is a small group of humans from North Caucasus who consumed mainly vegetable foods (C_3 plants) and the flesh/milk of domesticated animals. The diet system characteristic for the humans whose main area of occupation was the steppe included the flesh/milk of herbivores, river and lake aquatic foods, and wild C_3 plants. The third group of humans consumed marine food. The isotope data we have obtained demonstrate that the human diet system changed due to changes in economy, nature of exploited local food resources, and climate.

Keywords

Stable isotopes, collagen, diet, Bronze Age, Eurasian Caspian Steppes

Introduction

Isotope analysis of archaeological and contemporary samples plays an important role in the investigation of the main components of ancient human subsistence (Buchachenko, 2007). Isotopes help researchers to more precisely define the chronology of ancient populations (Cook et al., 2002); they are used in ecological studies (Lecolle, 1985), and they provide unique information on the diet system, which forms part of the human technological base (Iacumin et al., 1998; Richards et al., 2003; Shishlina et al., 2009; Hollund et al., 2010).

Dietary information can be obtained from $\delta^{13}C$ and $\delta^{15}N$ values of human and faunal bone collagen (Lanting and van der Plicht, 1998; Richards et al., 2003). Carbon and nitrogen constitute part of the trophic food chain. Investigations of such chains have revealed that isotope values in bone collagen of humans (as consumers) deviate from values for constituents of the diet by 5‰ for carbon and 3–4‰ for nitrogen (Iacumin et al., 1998). Differences in $\delta^{13}C$ and $\delta^{15}N$ values point to differences in diet systems, which can be reconstructed for different population groups (Lanting and van der Plicht, 1998; Thompson et al., 2005; Jay and Richards, 2006; Keenleyside et al., 2009).

The ranges of isotope values determined for major sources of organic matter are shown in Table 1. Bone collagen isotope values, therefore, can help us ascertain what main food products humans consumed during the last 10–20 years of their lives; i.e. whether they subsisted mainly on vegetable foods, or a mixed diet with vegetable food and meat; what proportion of their diet consisted of marine and river/lake products; or what proportion of C_3 and C_4 plants.

One difficulty associated with the reconstruction of ancient diet is that the ^{13}C and ^{15}N values associated with a specific dietary component can be influenced by the local environment. It can be argued that

Table 1 | Ranges of isotope values for major sources of organic matter

Organic matter source	$\delta^{13}C_{VPDB}$, ‰	$\delta^{15}N_{air}$, ‰
Human (mixed diet)	–22 to –15	7 to 14
Human (marine diet)	–15 to –13	17 to 18
Animals (herbivore)	–23 to –20	3 to 9
Fish from lake (littoral)	–22 to –12	9 to 12
Fish from lake (pelagic)	–24 to –20	7 to 13
Terrestrial plants C3	–27 (–32 to –22)	–10 to 10
Terrestrial plants C4	–13 (–16 to –9)	–10 to 10

aridization of climate caused a decrease in precipitation, leading to changes in vegetation and processes of water preservation, as well as the deposit of ^{15}N-depleted wastes, such as urea. These factors can lead to an increase in $\delta^{15}N$ in human and animal collagen in the arid areas (Schwarcz et. al., 1999). It is therefore necessary to take into account ecological characteristics of the region in question as well as data obtained through different approaches.

The area of investigation

The Caspian Steppes are adjacent to the North Caucasus, the Volga and the Don Rivers. They comprise an area of wormwood and gramineous Eurasian and Kazakhstan steppes, or a southern sub-zone of dry steppes, transitional to semi-deserts (Lavrenko, 1991; Bobrov, 2002). The climate is continental and arid. Summer are hot and dry; snow cover in winter is thin, and sometimes frost is severe. Average temperatures are –4––5°C in January and +25.5–+26°C in July; average annual temperature is +10°C. Average annual rainfall is between 180 and 350 mm. The average snow cover over much of the region is 3–8 cm, up to 10–11 cm in the north. The environment, i.e. landscape, climate, hydrology, and vegetation, differs in the river valleys, in the upper part of the watershed plateau, and the open steppe. Research into the regional palaeoclimate has revealed frequent and sometimes very dramatic climate changes during the period 4000–2000 calBC (Demkin et al., 2002; Shishlina, 2008).

The cultural context

Starting in the Eneolithic Age and throughout the Bronze Age, the Caspian Steppes represent a distinct cultural province that developed a mobile pastoralism (Shishlina, 2008). The Eneolithic population was the first to exploit steppe landscapes, at the end of the fifth millennium BC. The Steppe Majkop population penetrated into the steppe from the North Caucasus area at the end of the first half of the fourth millennium BC. Then the Yamnaya culture population settled on the steppe, opening a new period of its exploitation. In the subsequent period the cultural situation changed and we see a mosaic of cultures emerging. Open steppe southern boundaries and developed river routes are linked with the spreading of a new Steppe North Caucasus population. During a relatively short period multiple cultural groups, i.e. the Late Yamnaya, Early Catacomb and Steppe North Caucasus, must have coexisted. At the end of this period the East Manych Catacomb population appeared. The last cultures that appeared at the end of the

Table 2 | Chronology of the cultures analyzed

Culture	Time interval
Eneolithic	4300–3800 calBC
Majkop	3500–3000 calBC
Yamnaya	3000–2500 calBC
Early Catacomb	2700–2400 calBC
Steppe North Caucasus	2500–2300 calBC
East Manych Catacomb	2500–2200 calBC
Lola and Krivaya Luka	2200–2000 calBC

second millennium BC were the Lola and Krivaya Luka cultures. Table 2 provides data on the chronology of the cultures. The time interval covered is 4300–2000 calBC.

Method and objects

The main source for the historical reconstruction of the lives the first pastoralists living in the region in question is that of funerary sites, i.e. kurgans (burial mounds) and graves. Many organic materials, such as human and animal bones, wood, plant remains, fibres and seeds, have been preserved in these sites due to specific arid conditions of soils and the depth to the ground water.

To conduct the study, we collected samples from the kurgan burial grounds located in the Caspian Steppes, the Lower Volga and the Don regions and the North Caucasus (Fig. 1).

The following types of samples were analyzed in the project ($\delta^{13}C$ and $\delta^{15}N$ isotope analysis):

- human and animal bones of the Bronze Age;
- archaeological plant remains dating to the Bronze Age.

Most isotope ratio measurements were performed at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, with the use of isotope Mass Spectrometer DELTA Plus XP (ThermoFinnigan), connected to the Flash EA element analyzer. Each sample was measured in triplicate, the analytical error was ± 0.2‰ for $\delta^{13}C$ and ±0.2–0.3‰ for $\delta^{15}N$. The rest of the measurements were performed at Oxford University and Groningen University.

The objective of this paper is to demonstrate that a traditional archaeological source preserves very important chemical information and to discuss the results of the study of samples from Bronze Age sites in that context. The focus will be on:

- possible components of the diet system of the Bronze Age population, which exploited steppe areas of the Caspian Steppes, Don River valleys and the North Caucasus;
- domesticated animal fodder in these areas in the Bronze Age.

An additional task is to study archaeological plants and reconstruct a vegetation pattern and ascertain the ratio of C_3 to C_4 plants.

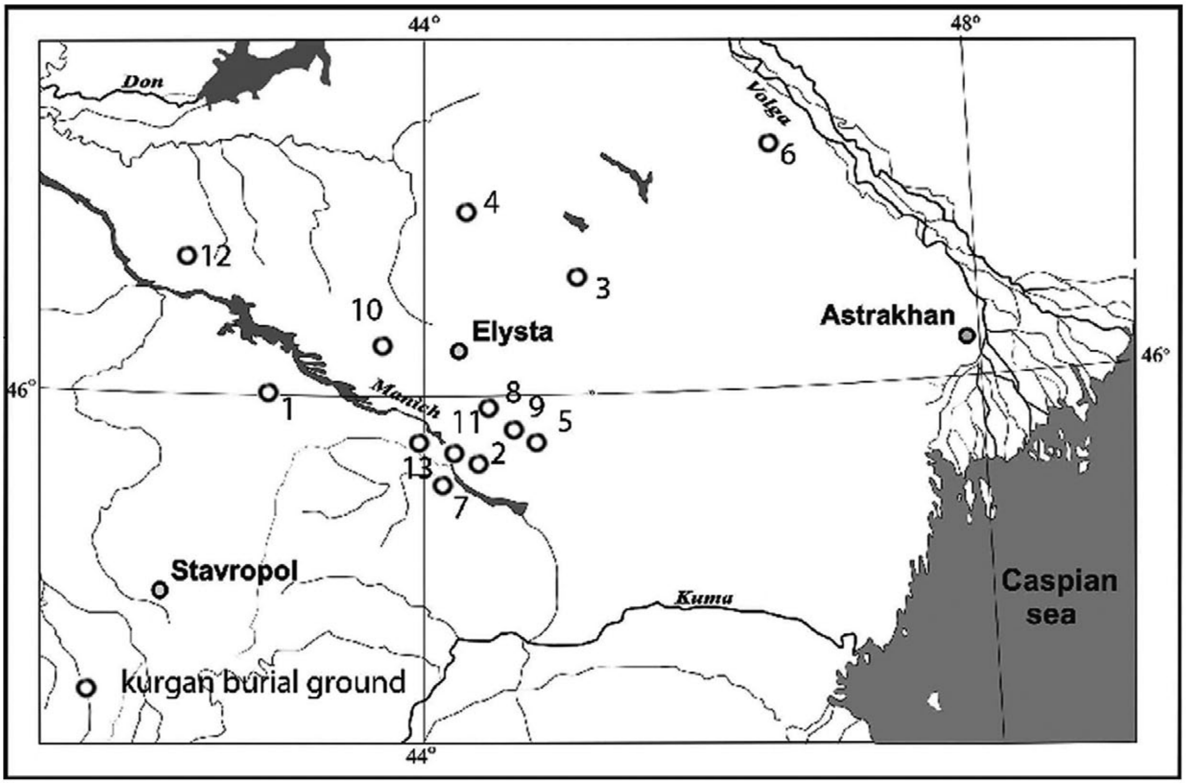

Fig. 1 | Caspian Steppes archaeological sites. 1 Baga-Burul; 2 Zunda-Tolga and East Manych, 3 Chilguir, 4 Yergueni, 5 Mandjikiny; 6 Krivaya Luka; 7 Chogray; 8 Khar-Zukha; 9 Mu-Sharet; 10 Temrta, Ulan and Sukhaya Termista; 11 Ostrovnoy; 12 Shakhaevskaya; 13 Sharakhalsun

Results

In order to examine the reliability of radiocarbon dates obtained for the region in question, we started by measuring $\delta^{13}C$ in human and animal bone collagen (Shishlina et al., 2007). The addition of $\delta^{15}N$ values helped launch an study of diet models proposed for humans. Isotope ratios were also measured in animal bone collagen (Shishlina, 2008; Shishlina et al., 2009). Over the past years, 96 human, 65 animal, 2 fish and 1 dolphin archeological samples have been subjected to analysis. Almost all data have already been published (Shishlina et al., 2009): they are presented again here in Tables 3 and 4 (see appendix).

Animal stable isotope values vary and they can be divided into two groups based on differences in the average values of $\delta^{13}C$ and $\delta^{15}N$. The first group (n=44) is characterized by a ^{13}C range from –24.1 to –17.3‰ and $\delta^{15}N$ from +4 to +10‰, with average values of –20.7‰ and +7.0‰, respectively. The second group (n=18) is characterized by a $\delta^{13}C$ range from –21.5 to –14.2‰ and $\delta^{15}N$ from +9.9 to +14.9‰, with average values of –17.9‰ and +12.4‰.

Human stable isotope values also show large variations. The values obtained fall into three groups. The first group (n=6) is characterized by a $\delta^{13}C$ range from –20.7 to –18.4‰ and $\delta^{15}N$ from +8.9 to +10.5‰, with average values of –19.6‰ and +9.7‰. The second group (n=64) is characterized by a $\delta^{13}C$ range from –22.2 to –17.5‰ and $\delta^{15}N$ from +9.4 to +17.1‰, with average values of –19.9‰ and

Table 5 | Isotope values of archaeological plants of the Bronze Age

Site name	Sample	Species	$\delta^{13}C$, ‰	$\delta^{15}N$, ‰
Yamnaya culture period: 3000–2500 calBC				
Mu-Sharet 1	kurgan 5, grave 3	seeds of Amaranths	–26.5	+6.4
Early Catacomb culture period: 2700–2400 calBC				
East Manych, Left Bank, III	kurgan 29, grave 8	plant mat, reed?	–24.3	+15.6
Mandjikiny 1	kurgan 14, grave 6	seeds (*Lithosperpum officinale*)	–26.6	+13.0
Mandjikiny1	kurgan 14, grave 6	plant mat, gramineous plants	–24.6	+13.9
Temrta 1	kurgan 1, grave 2	plant mat, reed?	–25.2	+1.9
Temrta 1	kurgan 1, grave 2	plant mat, reed	–28.6	+4.6
Ulan IV	kurgan 3, grave 14	plant mat, reed?	–25.9	+6.5
Ulan IV	kurgan 3, grave 15	plant mat, reed?	–25.4	+13.0
Ulan IV	kurgan 3, grave 15	plant mat, reed?	–25.48	+10.3
Steppe North Caucasus culture period: 2700–2400 calBC				
Kislovodsk	tomb 3	karakas seeds	–19.6	+1.5
East Manych, Left Bank, III	kurgan 12, grave 13	reed?	–24.0	+11.8
East Manych and West Manych Catacomb cultures period: 2500–2200 calBC				
Mandjikiny 1	kurgan 14, grave1	reed	–23.9	+17.4
Mandjikiny 1	kurgan 14, grave 1	plant mat, stem of reed	–25.7	+21.1
Yergueni	kurgan 10, grave 2	reed	–25.4	+19.1
Shakhaevskaya	kurgan 4, grave 35	gramineous plants from the pot	–27.2	+5.6
Shakhaevskaya	kurgan 4, grave 32	seeds (Lithospermum officinale)	–22.6	+9.6
Sharakhalsun-6	kurgan 3, grave 4	plant mat, reed stem	–28.0	+11.9
Lola culture period: : 2200–2000 calBC				
Ostrovnoy,	kurgan 3, grave 39	seeds of winter-cress,	–22.6	+10.7

+13.3‰. The third group (n=18) is characterized by a $\delta^{13}C$ range from –18.2 to –15.3‰ and $\delta^{15}N$ from +11.1 to +18.4‰, with average values of –16.8‰ and +14.8‰.

Archaeological plant samples: An additional pilot isotope study was conducted into archaeological Bronze Age plants. $\delta^{13}C$ values for C_3 and C_4 plants differ greatly. The average value of C_3 plants, which are predominant in the steppe zone, is around –26‰; the average $\delta^{13}C$ value for C_4 plants is around –12‰. Table 5 shows the isotope data obtained for archaeological samples of reed, some seeds and gramineous plants. All samples have values appropriate for C_3 plants.

It is worth mentioning that some of the reed samples obtained from different areas are characterized by very high $\delta^{15}N$ values. Two samples of wild gramineous plants, attributed to C_3 plants, and are characterized by a very high value of nitrogen as well.

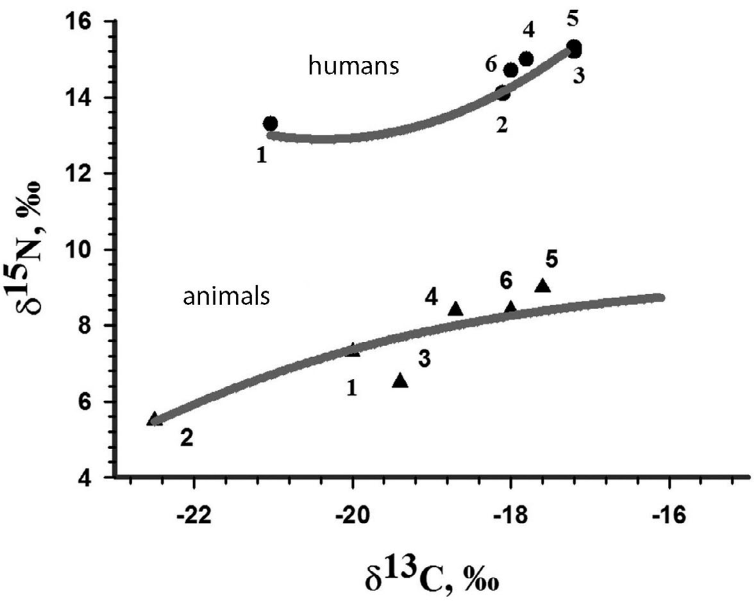

Fig. 2 | Average values of $\delta^{13}C$ and $\delta^{15}N$ for humans and animals from analyzed cultures. 1 Eneolithic, 2 Majkop, 3 Yamnaya, 4 Early Catacomb, 5 East Manych Catacomb, 6 Lola and Krivaya Luka

Discussion

The results demonstrate a very broad range of $\delta^{13}C$ and $\delta^{15}N$ values for Bronze Age cultures of the area under discussion. The greater the age of the sample, the lower are the values of $\delta^{13}C$ and $\delta^{15}N$. Stable isotope values obtained show a positive correlation of $\delta^{13}C$ and $\delta^{15}N$ ratios (see Fig. 2) with average values for cultures and demonstrate the same trend both for animals and humans.

Our data also helped us to propose two fodder models for domesticated animals (Fig. 3) and three diet models for humans (Fig. 4).

Model 1, for domesticated animal fodder (isotope group 1), is based on the use of pastures with the predominance of C_3 plants (a period of Eneolithic, Steppe Majkop and Yamnaya cultures with mild and humid climate; it is assumed that such pastures existed in some areas during the Catacomb and Lola cultures as well).

Model 2, for domesticated animal fodder (isotope group 2), is based on the use of pastures with mixed C_3 and C_4 plants typical for the period of aridization.

Thus variations in isotope data are characteristic for domesticated animals, especially animals that date back to the period of aridization, i.e. around 2300–2200 calBC. The large range in the isotope values for Bronze Age herbivores was identified by Hollund and colleagues (2010) for the North Caucasus as well. Several sheep dating to this time (Baga-Burul; Zunda-Tolga-1, Chilguir, Yergueni) have a very high $\delta^{15}N$ value (from +10.39 to +13.72‰) and a very high $\delta^{13}C$ value (from –16.74 ‰ to –14.27). Similarly high values for $\delta^{15}N$ in animal bone samples have been reported for a faunal collection dated to the Majkop North Caucasus culture (Hollund et al., 2010).

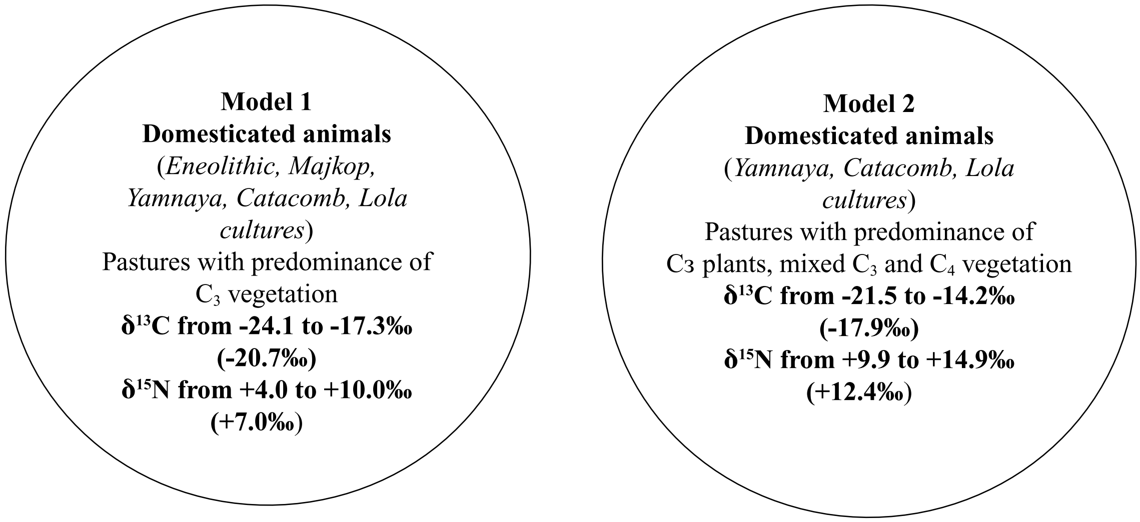

Fig. 3 | Models of domesticated animal fodder in Eneolithic-Bronze Age

Throughout all ages the life of ancient populations was closely linked to sources of water. This link necessarily became substantially stronger in pastoral economies. While an individual does not need more than tow litres of water per day for personal consumption, in a pastoral economy with a mobile life style the population is forced to return to sources of water once or twice a day in order to water their animals.

Changes in pasture vegetation might also be responsible for differences in isotope values in animal bone collagen. One scenario is that of the occurrence of extremely severe droughts, resulting in disastrous wind erosion, an increase in the concentration of water-soluble components in soils and the deflation of the upper horizon of soils in watershed areas. Plant remains in soil samples taken from kurgan profiles and primary graves provide information about the local vegetation during the time of kurgan construction and the existence of various cultures. Soil samples associated with Early Catacomb culture (2700–2400 calBC) have been shown to contain pollen and phytoliths of numerous plants: wormwood (*Artemisia*), leguminous plants (*Fabaceae*), grass plants (*Poaceae*), goosefoot (*Chenopodiaeceae*), lily (*Liliaceae*), and dicotyledonous mixed grasses (*Silenaceae, Asteraceae, Polygonaceae*). This vegetation is typical for a mixed grass steppe. Samples for Catacomb culture (2500–2200 calBC) contained pollen and phytoliths of *Artemisia, Chenopodiaeceae, Asteraceae*. So here we see local vegetation changing to semi-desert landscapes with a predominance of wormwood-fescue associations. The Lola and Krivaya Luka cultures (2200–2000 calBC) existed in a desert with a predominance of wormwood associations (Shishlina, 2008). A vegetation change of this kind could well have altered the forage plant isotope values, which would be reflected in the isotope values in domesticated animal bone collagen.

We believe that such values could have been caused by climate change and the concomitant long distance migrations necessitated by the stress on domesticated animals associated with the lack of pasture and the fact that water resources are scattered all over environmental niches of the Steppe and the North Caucasus. Some C_4 plants started growing in certain steppe areas and were gradually incorporated into sheep fodder. As noted in the introduction, a high $\delta^{15}N$ value may characterize C_3 plants in an arid climate, i.e. in Egypt (Thompson et al., 2005) or in Anatolia (Richards et al., 2003).

The isotope data obtained for archaeological plants also vary. Such plants respond to the climate change in a way similar to that seen in human and animal bones, enabling us to elaborate the proposed models of the animal fodder system. Data confirm findings on the predominance of C_3 plants in the region in question. This observation is in agreement with pollen and phytoliths obtained from the archaeological context (Shishlina, 2008) and with the description of vegetation from contemporary pilot pastures (Novikova, 2001). It is possible that some C_4 plants were present in the animal fodder but if so their proportion was very low.

However, some archaeological plants have a very high $\delta^{15}N$ isotope value. Several archaeological sheep bone collagen samples also yield very high nitrogen values. These were probably caused by the inclusion of plants with a high nitrogen value in the animals' fodder, although fractionation within the sheep, when under drought stress, may also be a factor.

A great deal of moisture evaporates from large masses of leaves and stems of reed. The high value of nitrogen in the archaeological samples might be a signal of stressed plants suffering from a lack of water during drought. Reed is used as winter fodder for domesticated animals. In 1988 we saw reed being cut in Lake Deed-Khulsun to be preserved as winter fodder. Almost the entire population of Kormovoye village was engaged in preparing reed for winter animal fodder, which is traded across the Republic of Kalmykia. We took samples from the lake in 2008. Local pastoralists whom we interviewed confirmed that they cut reed and used it as animal fodder.

One of the main requirements for Kazakh winter pastures is proximity to sources of reed and cane (Masanov, 1995). Apparently, reed and cane were used as winter fodder for domesticated animals in the Bronze Age as well, especially in times of drought when pasture was inadequate during summer and winter seasons. That is probably the reason that archaeological samples reveal a high value of nitrogen in animal bone collagen. Sheep bones with a high level of nitrogen were found in graves containing mats made of reed (Shishlina, 2008). Kurgan burial grounds containing such finds were located not far from rivers with reed banks. Sheep with a high nitrogen value date from the period of aridization.

Aridization had an impact on all components of the landscape, i.e. vegetation, soil, water resources. Dry-steppe and semi-desert species appeared. They produced much less biomass per square kilometre than their predecessor plants did. Winter precipitation rate dropped; intensity of heavy showers in summer grew, leading to erosion processes. Climate changes caused a change in vegetation which led to changes in the isotope values in animal bone collagen. In addition, human management may have brought about overgrazing, causing degradation of soil and vegetation. Animals have a direct impact on plant cenosis, as they eat terrestrial parts of plants (overgrazing), destroy the upper part of soils with their hooves, and leave droppings. A substantial share of the mineral elements contained in the plants that animals eat get back into soil via droppings. Hence, a large amount of organic matter rich with nitrogen that appears on the soil surface improves soil microbiological activity and vital functions of soil mesofauna. The impact of animal droppings on soil and plants is defined not only by their amount but by their chemical composition, physical properties, and shape, as well as by their distribution pattern across the surface. Sheep droppings are especially rich in the minerals important for plants. The largest source of the nitrogen and potassium input to pastures is animal urine. Concentrated urine can burn plants and is the main reason for a drastic increase in their alkalinity. Sheep droppings are distributed across the soil surface evenly and do not have an adverse mechanical impact on plants. During their decomposition, mineral elements contained in droppings gradually get back into the soil (Masanov, 1995). Recent studies have shown the impact of manuring on nitrogen isotope ratios on plants (Bogaard et al., 2007).

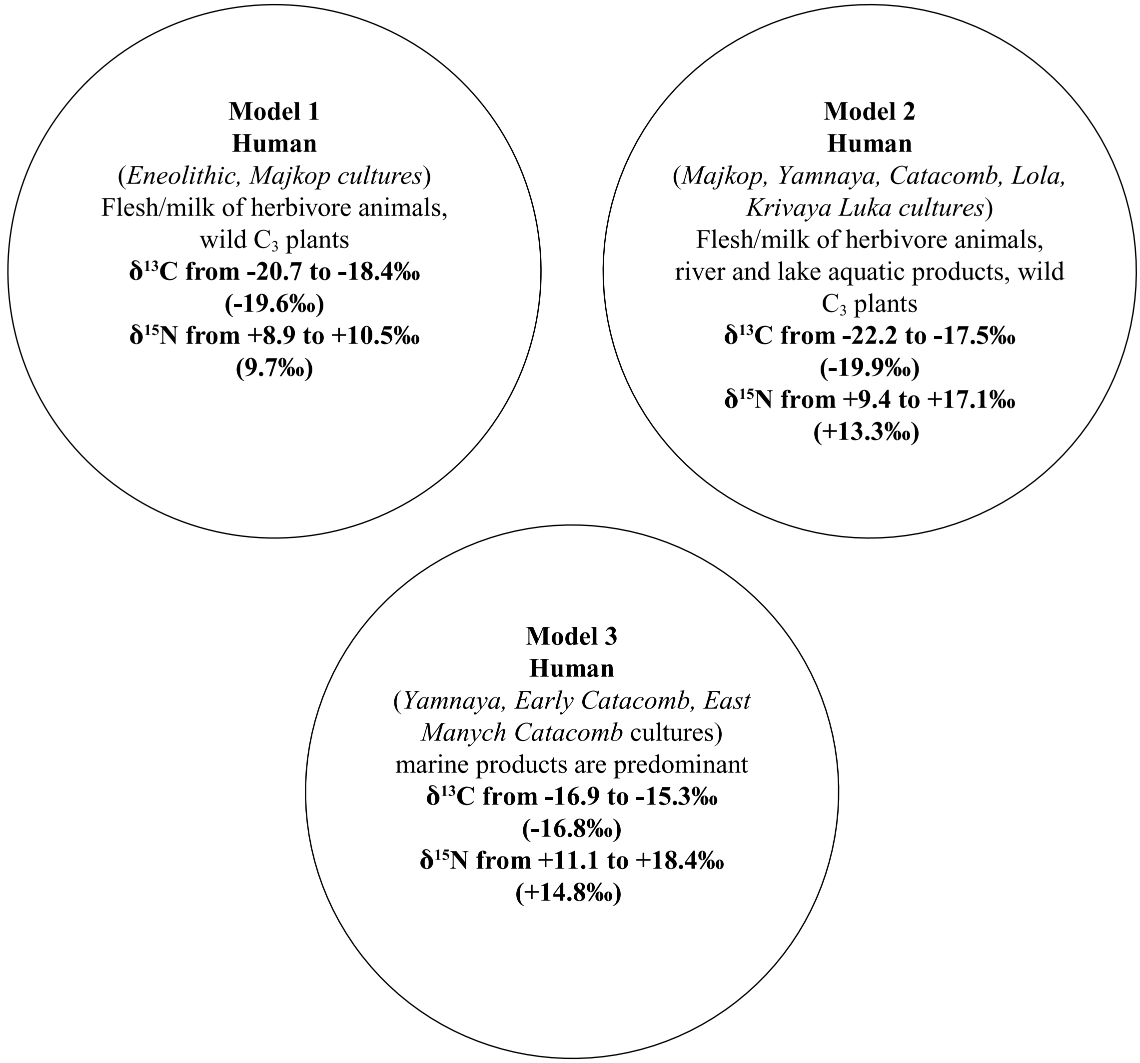

Fig. 4 | Models of human diet obtained for Eneolithic and Bronze Age cultures

It is also possible that degradation of pastures led to appearance of xerophytes and a decline in pasture productivity. Animals destroyed the upper part of the soil with their hooves and this led to the change in vegetation pattern (Dinesman and Bold, 1992). The result of this is the change of economy and, first of all, pastoral routes.

Data obtained for humans with a mixed and multicomponent diet system form the basis for discussing three diet system models (Fig.4).

Model 1 is characteristic for several representatives of the Eneolithic and Steppe Majkop cultures (Khvalynsk, Nalchik, Mandjikiny) who ate mostly vegetable food, resulting in lower values for $\delta^{13}C$ and $\delta^{15}N$ (isotope group 1).

Model 2 is based on the consumption of large quantities of aquatic resources (fish, mollusks, water plants) and wild C_3 plants (isotope group 2). It was the most widespread and developed economy in the steppe environment associated with mobile pastoralists of the Eneolithic-Bronze Age. Stress (as discussed above) caused by the struggle to survive and the aridity of climate increased values of the nitrogen isotope ratio in human collagen. This means that population groups of the Khvalynsk, Majkop, Yamnaya, Catacomb, Lola and Krivaya Luka cultures made use of all food resources in the exploited areas of the Volga, Don, the Caspian Steppes and steppes of the North Caucasus areas.

This interpretation of isotope data is confirmed by certain archeological finds: sheat-fish (*Silurus glanis*) bones and special fishing tools, i.e. hooks and harpoons found at Eneolithic sites (Agapov et al., 1990); finds of river fish bones and shells of edible molluscs (like pearl oysters) in the Yamnaya, Early Catacomb and Catacomb burials; imprints of knotless net preserved on the bottom of clay pots of the Yamnaya and Catacomb cultures (Orfinskaya et al., 1999), the bones of pike uncovered at the Catacomb Rykan site (excavation of E.I.Gak in the Voronezh region). The increasing wetness of the climate led to abundance of water reservoirs, i.e. steppe rivers and lakes, with a lot of fish.

Model 3 is based on the consumption of seafood (Isotope Group 3). This group, for example, includes an old man from a Chilguir Caspian Plain grave and three females aged 14–17 and 45–50 years from the Middle and South Yergueni Hills (Mandjikiny-2, Khar-Zukha and Mu-Sharet-4). The diet system of these individuals was based on marine food. Seasonality data obtained from these graves indicate that these people were seasonal pastoralists and apparently moved from one pasture to another. Possibly, the two young women aged 14–17 were born somewhere near the coastlines of the Caspian or Black Seas and later married and moved to the steppe. As newcomers they lived in a new steppe environment for a short period before death. At least the isotope data point to this outcome as the isotope values of the two females differ from the isotope values of other local people, whose diet system was typical for Model 2.

Several individuals of the Early Catacomb cultures (for example, *senilis* female from Khar-Zukha) have a very high $\delta^{13}C$ value, i.e. –15.42‰, and a very high $\delta^{15}N$ value, i.e. +18.10‰. The woman in the example consumed marine food. She may have moved to the open steppe from the coastline region. She died surrounded by people whose diet system was different from her own.

It is possible that East Manych Catacomb individuals buried at Temrta III, Kurgan 1, Grave 6 (20–30 years old); Mandjikiny-1, Kurgan 10, Grave 2 (female of 45–50) and Mandjikiny-1, Kurgan 14, Grave 1 (male of 30–35) were members of family groups that migrated during the winter seasons to the coastline areas of the Azov and the East Black seas. These three individuals have the highest values of nitrogen and carbon. These values indicate marine food consumption.

The humans analyzed (n=96) lived in diverse areas and at different times. We assume that almost all individuals concerned (except one male from the Nalchik cemetery) were mobile pastoralists, though it is evident that development of a new mode of pastoral life does not authomatically change diet. It is possible that severe conditions of the steppe environment and constant dependence on pasture productivity and water availability let the mobile steppe population to use all food resources they could find in the exploited areas.

Variations among isotope data obtained for each culture, as well as among individuals buried in different burial grounds, can be explained by the migration of small family groups along numerous routes across diverse geographical zones. Apparently, these groups used different food resources. There were summer and winter pastures in open steppe areas and near river valleys, as well as in the North Caucasus foothills and along the coastline of the Caspian and Black Seas. Mobility patterns also varied. Yamnaya groups migrated along rivers in the winter, moving short distances in the summer. They moved within a small area not more that 10–20 km distant from the river to watershed plateaus. Catacomb herders, by contrast, travelled over greater distances, sometimes hundreds of kilometres (Shishlina, 2008).

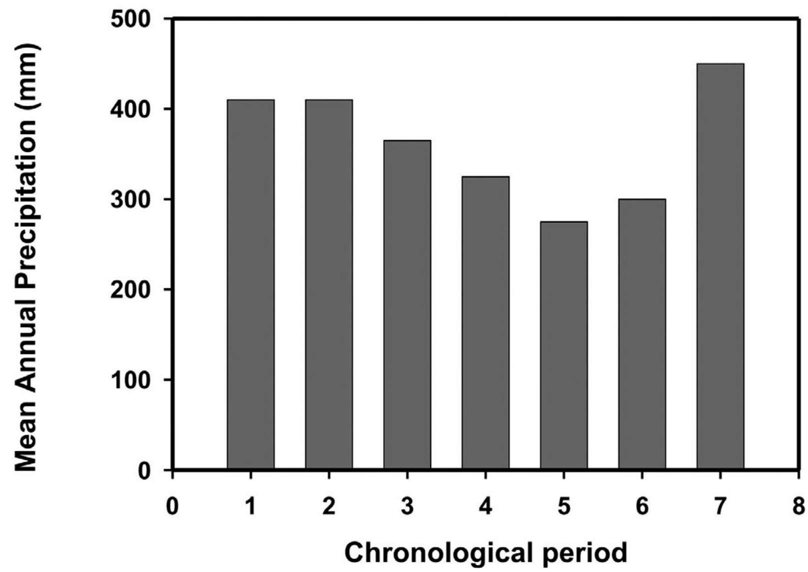

Fig. 5 | Mean annual precipitation during archaeological cultures (Demkin et al., 2002). 1 Eneolithic, 2 Majkop, 3 Yamnaya, 4 Early Catacomb, 5 East Manych Catacomb, 6 Lola and Krivaya Luka

The dependence of $\delta^{15}N$ values in human and animal collagen on annual precipitation has been discussed for several arid zones, where this ecological factor causes $\delta^{15}N$ enrichments in plants and soil. Reduced precipitation causes low $\delta^{15}N$ values in herbivores as well (Iacumin et al., 1998; Schwarcz et al., 1999).

Therefore, aridization on the Caspian Steppes and in the Don River area that occurred in the second half of 3000 BC caused changes in pasture and sources of water. The lack of water and deficiency of pastures led to more frequent movements and this, perhaps, caused stress in animals and the enrichment of nitrogen in the animal bone collagen as well as in plants. We assume that the most likely key drivers of the overall trend are temperature changes and the amount of precipitation (Fig.5).

Hence, our hypothesis states that the values of the isotope ratios in humans and animals as well as in plants may be due to climate, i.e. temperature, precipitation, day length, glaciation; the ecosystem and stress, i.e. volcanic eruptions, floods and even the struggle to survive. Changes in precipitation are reflected in changes in isotope values (Table 6).

Average values for $\delta^{13}C$ and $\delta^{15}N$ obtained for human and domesticated animal collagen from the cultures analyzed demonstrate a linear correlation with climate characteristics as well as the geographical area exploited and possible types of economic models. Such changes occurred during 4000–3000 calBC.

This is illustrated by the example with animals (Fig. 6). Over time, the $\delta^{13}C$ value shifts from –22.5 to –16‰; $\delta^{15}N$ values changes from +5 to +9–10‰. The similar trend is illustrated by the example with humans (Fig. 7). Over time the $\delta^{13}C$ value shifts from –22.5 to –16‰; $\delta^{15}N$ values change from +5 to +14–15‰.

Table 6 | Correlation of average isotope data obtained for humans, animals and plants when are available from cultures in question and annual precipitation

Culture/human/animal	$\delta^{13}C$, ‰	$\delta^{15}N$, ‰	Annual precipitation (Demkin et al. 2002)
Eneolithic (4300–3800 calBC)			
Human	–21.0	+13.3	400–420 mm
domesticated animal	–20.0	+7.3	
plants	n/a	n/a	
Steppe Majkop (3500–3000 calBC)			
Human	–18.1	+14.1	400–420 mm
domesticated animal	–22.5	+5.5	
plants	n/a	n/a	
Yamnaya (3000–2500 calBC)			
Human	–17.2	+15.2	350–380 mm
domesticated animal	–19.4	+6.5	
plants	–24.3 (n=1)	+6.4 (n=1)	
Early Catacomb (2700–2400 calBC)			
human	–17.8	+15.0	350–300 mm
domesticated animal	–18.7	+8.4	
plants	–25.9 (n=8)	+8.1 (n=8)	
East Manych Catacomb (2500–2200 calBC)			
human	–17.2	+15.3	250–300 mm
domesticated animal	–17.6	+9.0	
plants	–25.5 (n=6)	+14.1 (n=6)	
Lola and Krivaya Luka (2200–2000 calBC)			
human	–18.1	+14.7	300 mm
domesticated animal	–18.0	+8.4	
plants	–22.6 (n=1)	+10.72 (n=1)	

Conclusions

Isotope data demonstrate a very broad range in $\delta^{13}C$ and $\delta^{15}N$ values for the Bronze Age cultures of the area under discussion. The more ancient a sample in age, the lower the $\delta^{13}C$ and $\delta^{15}N$ values found. Stable isotope values in plants, animal and humans are very sensitive to climate changes. Annual precipitation and temperature were key factors in driving the overall isotope trend.

The data obtained has helped us propose two fodder models for domesticated animals and three diet models for humans. $\delta^{13}C$ and $\delta^{15}N$ values in animal bones indicate that different pastures were used by local mobile groups. Apparently such pastures were located in different ecological environments. Indirectly this points to population movements across the exploited area. Some archaeological plant samples dating to the period of aridization are characterized by very high $\delta^{15}N$ values. Such plants were probably included in the animal fodder and this was reflected in the isotope ratio in domestic animals.

Humans had a mixed diet, which is why regular patterns of changes in the isotope ratios of carbon and nitrogen are more subtle. There is a small group of humans from the North Caucasus who con-

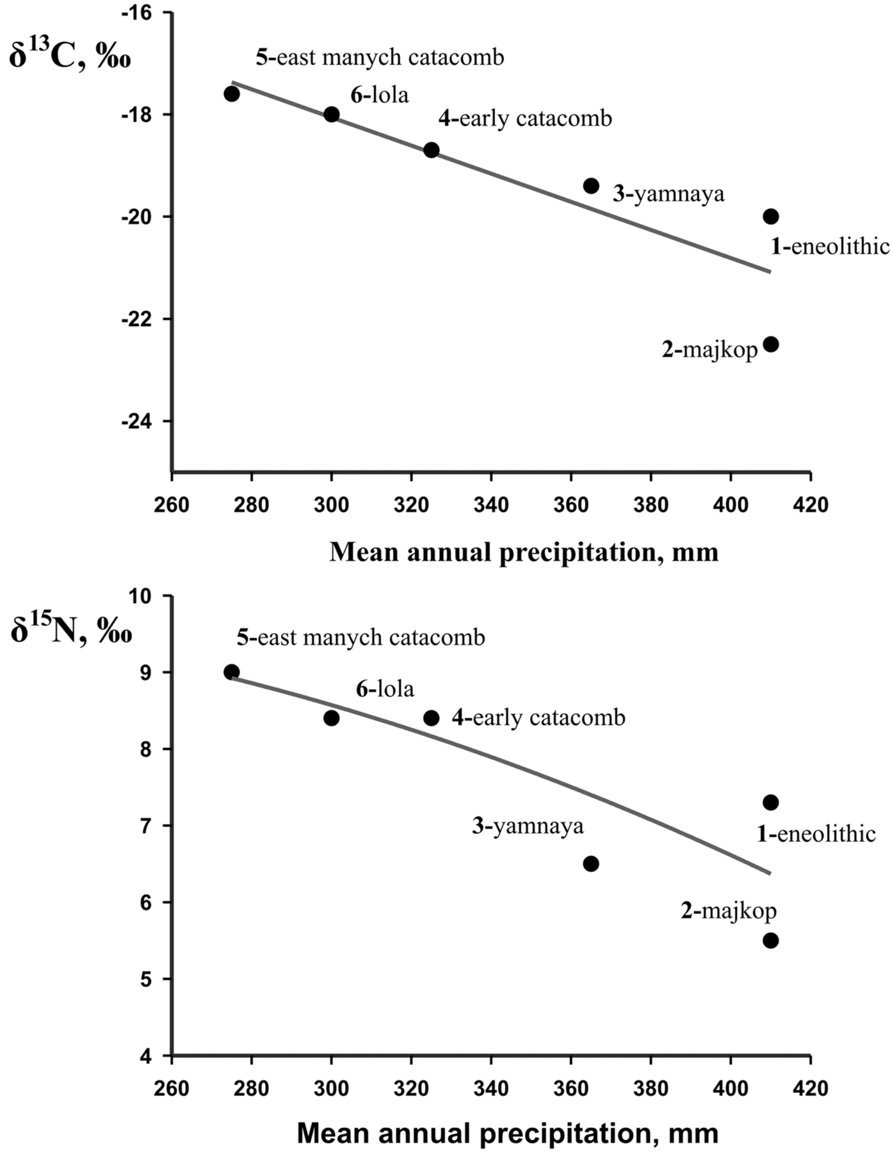

Fig. 6 | Graph plotting average values of $\delta^{13}C$ and $\delta^{15}N$ for domesticated animals against annual precipitation

sumed mostly vegetable food (C_3 plants) and the flesh/milk of domesticated animals. The diet system characteristic for the humans whose main area of occupation was the steppe included the flesh/milk of herbivores, river and lake aquatic products, and wild C_3 plants. These data are confirmed by ethnobotanical evidence (Shishlina et al., 2007). The third group of people consumed marine food. They may have moved to the open steppe from the North Caucasus coastline region and then died surrounded by people whose diet system was different from their own. We have not been able to identify the reasons for their move to the deep steppes from a maritime coastline (Black Sea? Azov Sea? Caspian Sea?), but it is clear that the last 10 years of their lives were not spent on the steppe but instead very close to the sea (Shishlina et al., 2009).

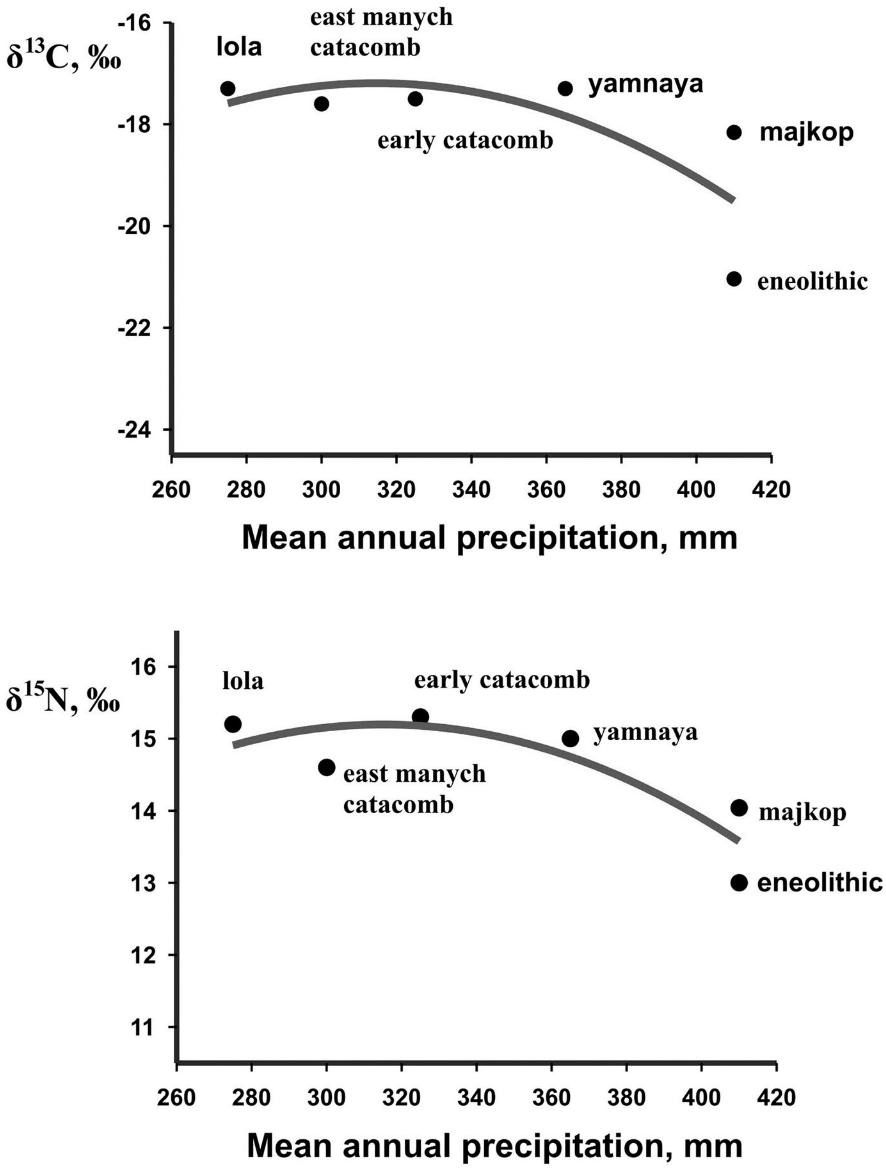

Fig. 7 | Graph plotting average values of $\delta^{13}C$ and $\delta^{15}N$ in humans against annual precipitation

The isotope data we have obtained demonstrate that the human diet system changed due to economy, nature of exploited local food resources and climate changes, and in particular, aridization of climate and change in the level of precipitation in the second half of the 3rd millennium BC.

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Table 3 | Faunal stable isotope data from the Caspian and Volga Steppes and the North Caucasus area

Site name	Sample	Species	δ13C, ‰	δ15N, ‰
Eneolithic period: 4300–3800 calBC				
Khvalynsk II	grave 10	cattle (*Bos*)	–20.0	+7.5
Khvalynsk I	grave 127	animal? bone	–20.7	+14.5
Khvalynsk I	grave 147	sheep (*Ovis aries*)	–17.8	+11.6
Myskhako I	B-39, level 15	dolphin	–13.5	+9.2
Myskhako I	E-24, level 16	cattle (*Bos*)	–19.6	+7.9
Myskhako I	E-24, level 16	cattle (*Bos*)	–20.0	+6.41
Steppe Majkop period: 3500–3000 calBC				
Novosvobodnaya/Klady	kurgan 2	deer teeth	–22.9	+6.9
Novosvobodnaya/Klad y	kurgan 2	deer teeth	–22.1	+4.0
Yamnaya culture period: 3000–2500 calBC				
Mu-Sharet-4	kurgan 1, grave 3	sheep (*Ovis aries*)	–18.8	+7.2
Zynda-Tolga-3	kurgan 1, grave 4	sheep (*Ovis aries*)	–23.5	+11.8
Sukhaya Termista	kurgan 1, grave 11	ungulate bone	–19.9	+5.7
Panitskoye	grave 6A	ungulate bone	–19.4	n/a
Early Catacomb culture period: 2700–2400 calBC				
Peschany-V	kurgan 1, ritual place 1	horse (*Equus caballus*)	–21.1	+4.6
Peschany-V	kurgan 5, grave 3	saiga (*Saiga tatarica*)	19.3	+8.5
Peschany-V	kurgan 5, grave 3	sheep (*Ovis aries*)	–18.5	+9.5
Peschany-V	kurgan 5, grave 3	sheep (*Ovis aries*)	–19.3	+8.5
Temrta III	kurgan 1, ritual place 7	sheep (*Ovis aries*)	–19.4	+9.5
Temrta III	kurgan 1, ritual place 1	horse (*Equus caballus*)	–19.9	+5.9
Temrta-I	kurgan 1, grave 3	sheep (*Ovis aries*)	–21.5	+12.4
Temrta-I	kurgan 1, grave 3	sheep (*Ovis aries*)	–18.2	+11.2
Baga-Burul	kurgan 5, grave 19	sheep (*Ovis aries*)	–18.5	+9.9
Mandjikiny-1	kurgan 54, ritual place	sheep (*Ovis aries*)	–18.6	+7.4
Zunda-Tolga-5	kurgan 1, grave 4	sheep (*Ovis aries*)	–17.9	+12.6
Zunda-Tolga-5	kurgan 1, grave 7	ungulate bone	–20.0	+5.3
Temrta V	kurgan 1, grave 2	ungulate animal bone	–18.2	+8.7
Temrta V	kurgan 1, grave 7	ungulate bone	–21.0	+5.3
VMLBII,66	kurgan 80, grave 3	sheep (*Ovis aries*)	–17.9	+9.0
VMLBII,66	kurgan 9, grave 2	sheep (*Ovis aries*)	–18.6	+6.8
Steppe North Caucasus culture period: 2700–2400 calBC				
Zunda-Tolga-1	kurgan 1, grave 11	sheep (*Ovis*)	–18.1	+8.2
Mu-Sharet-1	kurgan 1, grave 6	sheep (*Ovis*)	–16.5	+11.3
Mu-Sharet-1	kurgan 1, grave 6	sheep (*Ovis*)	–20.2	+13.0
Mu-Sharet-1	kurgan 1, grave 6	sheep (*Ovis*)	–16.5	+11.3
East Manych and West Manych Catacomb cultures period: 2500–2200 calBC				
Baga-Burul	kurgan 5, ritual place 4	horse (*Equus caballus*)	–20.6	+6.2
Baga-Burul	kurgan 5, ritual place 4	cattle (*Bos*)	–16.6	+9.9

Table 3 | continued

Site name	Sample	Species	δ13C, ‰	δ15N, ‰
Baga-Burul	kurgan 5, ritual place 15	sheep (*Ovis aries*)	–19.3	+8.2
Baga-Burul	kurgan 1, grave 3	cattle (*Bos*)	–19.1	+9.2
Baga-Burul	kurgan 1, grave 3	sheep (*Ovis aries*)	–19.3	+7.3
Baga-Burul	kurgan 5, grave 12	sheep (*Ovis aries*)	–16.6	+10.7
Baga-Burul	kurgan 5, grave 8	sheep (*Ovis aries*)	–17.4	+9.2
Ostrovnoy	kurgan 5, grave 38	sheep (*Ovis aries*)	–19.2	+6.6
Ostrovnoy	kurgan 5, grave 9	sheep (*Ovis aries*)	–17.7	+6.4
Ostrovnoy	kurgan 3, grave 9	sheep (*Ovis aries*)	–18.1	+7.6
Ostrovnoy	kurgan 6, grave 8	sheep (*Ovis aries*)	–19.5	+8.1
Ostrovnoy	kurgan 6, grave 8	sheep (*Ovis aries*)	–18.2	+7.5
VMLBI,65	kurgan 43, grave 1	sheep (*Ovis aries*)	–19.9	+9.7
Zunda-Tolga-1	kurgan 8, grave 1	sheep (*Ovis aries*)	–18.6	+8.7
Zunda-Tolga-1	kurgan 9, grave 1	sheep (*Ovis aries*)	–17.3	+9.7
Zunda-Tolga-1	kurgan 10, grave 3	sheep (*Ovis aries*)	–18.8	+5.1
Chilgir	kurgan 1, grave 4	sheep (*Ovis aries*)	–15.5	+12.0
Chilgir	kurgan 2, grave 5	sheep (*Ovis aries*)	–21.5	+9.2
Chilgir	kurgan 3, ritual place B	cattle (*Bos*)	–16.1	+11.9
Temrta V	kurgan 1, grave 4	sheep (*Ovis aries*)	–16.0	+10.1
Yergueni	kurgan 6, grave 3	sheep (*Ovis aries*)	–14.2	+12.7
Yergueni	kurgan 6, grave 2	sheep (*Ovis aries*)	–15.5	+12.0
Yergueni	kurgan 6, grave 5	sheep (*Ovis aries*)	–16.2	+13.1
Yergueni	kurgan 6, grave 10	sheep (*Ovis aries*)	–15.9	+10.3
Mandjikiny-I	kurgan 14, grave 1	sheep (*Ovis aries*)	–16.3	+10.3
Mandjikiny-I	kurgan 14, ritual place 21	sheep (*Ovis aries*)	–24.1	+10.3
Shakhaevskaya	kurgan 4, grave 32	fish pike	–16.5	+14.9
Kovalevka*	kurgan 3 grave 2	fish (Rutilus frisii (Nordm)	–23.8	+8.5
Rykan**	level 2	cattle (*Bos*)	–19.8	+5.2
Rykan**	level 2	cattle (*Bos*)	–19.8	+6.7
Lola culture period: 2200–2000 calBC				
Ostrovnoy	kurgan 3, grave 39	sheep (*Ovis aries*)	–16.3	+12.3
Ostrovnoy	kurgan 6, grave 9	sheep (*Ovis aries*)	–15.8	+4.6
Temrta-1	kurgan 2, grave 8	cattle (*Bos*)	–18.6	+9.7
Sukhaya Termista I	kurgan 1, grave 10	ungulate bone	–18.9	+7.0

* Excavation of V.A.Gorodsov, Donets River region, State Historical museum collection
** Rykan Catacomb culture site is located in the Voronezh area, Middle Don River region

Table 4 | Human stable isotope data from the Caspian and Volga Steppes and the North Caucasus area

Site name	Sample	Sex/age	δ13C, ‰	δ15N, ‰
Eneolithic period: 4300–3800 calBC				
Khvalynsk II	grave10	male	–20.3	+13.9
Khvalynsk II	grave18	human	–22.3	+13.5
Khvalynsk II	grave 24	human	–20.2	+13.7
Khvalynsk II	grave 34	human	–20.5	+10.2
Khvalynsk II	grave 35	human	–21.9	+13.7
Nalchik	grave 86	male adult	–20.7	+8.9
Steppe Majkop period: 3500–3000 calBC				
Mandjikiny-1	kurgan 14, grave 13	male	–18.8	+11.6
Sharakhalsun-6	kurgan 5, grave7	child	–16.7	+15.2
Sharakhalsun-6	kurgan 2, grave17	child	–18.3	+13.4
Aygursky-2	kurgan17, grave 6	human	–18.5	+15.9
Zolotarevka-1	kurgan 22, grave11	human	–18.5	+14.1
Yamnaya culture period: 3000–2500 calBC				
Mu-Sharet-4	kurgan 12, grave 1	male 17–20	–18.0	+14.3
Mandjikiny-2	kurgan 11, grave 2	male 35–45	–17.5	+15.2
Mandjikiny-2	kurgan 11, grave 3	women 45–50	–16.6	+18.0
Mandjikiny-1	kurgan 14, grave 12	male 17–25	–18.6	+14.1
Mandjikiny-1	kurgan 14, grave 10	male 20–25	–18.1	+14.0
Mu-Sharet-4	kurgan 11, grave 3	woman 14–17	–16.5	+15.3
Khar-Zukha	kurgan 2, grave 3	woman 20	–16.0	+13.7
Poludny	kurgan 2, grave 7	male 45	–17.4	+15.0
Chilgir	kurgan 2, grave 3	male *matures*	–15.4	+17.6
Peschany V	kurgan 1, grave 3	male 30–40	–18.8	+13.2
Sukhaya Termista	kurgan 1, grave 11	female	–15.7	+16.6
Grachevka	kurgan 5, grave 2	juveniles	–19.0	+10.5
Yashkul 1	kurgan 1, grave 18	adult	–15.3	+18.4
Early Catacomb culture period: 2700–2400 calBC				
Peschany V	kurgan 1, grave 1	female 25–35	–18.2	+14.1
Peschany V	kurgan 1, grave 5	human adult	–16.2	+16.5
Peschany V	kurgan 2, grave 3	male 40–45	–18.1	+15.7
Peschany V	kurgan 3, grave 1	male 45–50	–17.0	+17.1
Peschany V	kurgan 3, grave 2	male 40–45	–21.5	+15.2
Peschany V	kurgan 4, grave 1	male 50–60	–17.3	+16.1
Peschany V	kurgan 5, grave 6	child 4	–17.7	+16.1
Peschany V	kurgan 5, grave 5	adult	–17.5	+15.2
Temrta III	kurgan 1, grave 1	female 30–35	–18.3	+14.9
Temrta III	kurgan 1, grave 4	male 40–45	–18.1	+14.7
Temrta III	kurgan 2, grave 1	male? 45–50	–17.8	+14.1
Temrta-I	kurgan 1, grave 2	female 20–25	–17.5	+13.1
Temrta-I	kurgan 1, grave 3	child 10–11	–17.6	+15.5

Table 4 | continued

Site name	Sample	Sex/age	$\delta^{13}C$, ‰	$\delta^{15}N$, ‰
Temrta-I	kurgan 2, grave 3	child 10	–17.5	+16.2
Baga-Burul	kurgan 5, grave 6	male 30–35	–18.7	+12.6
Mandjikiny-2	kurgan 37, grave 3	male 15–16	–16.5	+16.5
Mandjikiny-2	kurgan 42, grave 1	female 40–45	–17.1	+17.2
Mandjikiny-2	kurgan 42, grave 4	child 3–4	–15.2	+18.1
Mandjikiny-2	kurgan 45, grave 2	male 17–20	–17.1	+17.5
Mandjikiny-2	kurgan 54, grave 6	female 25–35	–17.5	+15.0
Mandjikiny-1	kurgan 14, grave 6	male 55–65	–17.5	+15.4
Mu-Sharet	kurgan 8, grave 3	female 17–19	–17.4	+15.5
Ulan-Zukha	kurgan 3, grave 8	adult	–17.5	+14.4
Zunda-Tolga-2	kurgan 1, grave 1	male adultus	–17.4	+16.1
Zunda-Tolga-2	kurgan 2, grave 1	male >50	–17.2	+16.6
Zunda-Tolga-2	kurgan 2, grave 3	male around 35	–18.6	+13.9
Zunda-Tolga-5	kurgan 1, grave 5	male senilis	–18.6	+14.0
Zunda-Tolga-5	kurgan 1, grave 7	female 50–55	–17.7	+14.9
Temrta V	kurgan 1, grave 2	female 17–20	–17.9	+12.4
Temrta V	kurgan 1, grave 2	male 20–25	–20.6	n/a
Temrta V	kurgan 1, grave 3	female 40–50	–17.9	+10.7
Temrta V	kurgan 1, grave 3	female 40–50	–17.4	+15.4
Temrta V	kurgan 1, grave 3	male 40–50	–17.7	+12.7
Temrta V	kurgan 1, grave 3	male 40–50	–17.1	+15.6
Khar-Zukha –1	kurgan 5, grave 3B	female senilis	–15.4	+18.1
Khar-Zukha –1	kurgan 7, grave 4	male 30–35	–18.1	+14.1
Khar-Zukha –1	kurgan 1, grave 5	male 45–50	–17.6	+15.6
Sukhaya Termista I	kurgan 1, grave 2	adult	–18.9	+11.9
Sukhaya Termista I	kurgan 3, grave 20	male 40–45	–19.2	+13.6
Sukhaya Termista I	kurgan 1, grave 3	female 18–20	–17.5	+15.0
Sukhaya Termista II	kurgan 1, grave 11	female 25–30	–15.7	+16.4
Sukhaya Termista II	kurgan 1, grave 13	male >55	–16.8	+15.2
Steppe North Caucasus culture period: 2700–2400 calBC				
Zunda-Tolga-1	kurgan 1, grave 11	male 15–17	–18.4	+12.2
Mandjikiny-2	kurgan 7, grave 2	male 30–40	–17.7	+16.0
Yashkul 1	kurgan 1, grave 13	juvenile	–17.7	+12.1
East Manych and West Manych Catacomb cultures period: 2500–2200 calBC				
Baga-Burul	kurgan 5 grave 11	female 25–35	–16.9	+15.8
Baga-Burul	kurgan 5, grave 21	male < 45	–17.8	+14.2
Ostrovnoy	kurgan 3, grave 10	male 35	–17.6	+12.7
Zunda-Tolga-1	kurgan 9, grave 1	male 50	–16.9	+14.1
Zunda-Tolga-1	kurgan 10, grave 2	female 50–60	–16.5	+16.3
Zunda-Tolga-1	kurgan 10, grave 3	male 35	–19.3	+14.1
Zunda-Tolga-5	kurgan 1, grave 5	male 50–60	–18.6	+14.0
Chilgir	kurgan 1, grave 4	female < 45	–17.2	+15.7

Table 4 | continued

Site name	Sample	Sex/age	δ13C, ‰	δ15N, ‰
Temrta V	kurgan 1, grave 4	female 25–35	–17.7	+ 9.4
Temrta III	kurgan 1, grave 6	human 25–30	–15.4	+18.6
Peschany-V	kurgan 1, grave 4	male 30–35	–16.0	+16.1
Peschany-V	kurgan 5, grave 5	male 50–60	–17.5	+15.2
Mandjikiny-I	kurgan 10, Grave 2	female 45–40	–16.7	+17.2
Mandjikiny-I	kurgan 14, grave 1	male 30–35	–16.5	+17.6
Chogray IX	kurgan 14, grave 8	adult	–17.7	+14.5
Chogray IX	kurgan 8, grave 2	adult	–17.9	+15.4
Lola and Krivaya Luka cultures period: 2200–2000 calBC				
Ostrovnoy	kurgan 3, grave 39	female 20–30	–17.3	+16.0
Mandjikiny-1	kurgan 9, grave1	male 35–40	–17.1	+15.0
Yashkul 1	kurgan 1, grave 19	juvenile	–16.3	+18.3
Temrta-1	kurgan 2, grave 8	male 40–50	–18.4	+12.9
Temrta-1	kurgan 2, grave 5	male	–16.9	+11.1
Sukhaya Termista	kurgan 1, grave 2	adult	–18.9	+11.1
Sukhaya Termista	kurgan 1, grave 10	female 45–35	–17.3	–14.5
Sukhaya Termista	kurgan 1, grave 4	juvenile 16–18	–16.9	+14.9
Khar-Zukcha	kurgan 5, grave 2A	adult	–17.9	+14.5
Linevo	kurgan 6, grave 6	adult	–19.1	+8.9
Linevo	kurgan 8, grave 2	adult	–18.4	+9.6