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Adaptability of Millets and Landscapes: Ancient Cultivation in North-Central Asia

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Abstract: Millet is a highly adaptable plant whose cultivation dramatically altered ancient economies in northern Asia. The adoption of millet is associated with increased subsistence reliability in semi-arid settings and perceived as a cultigen compatible with pastoralism. Here, we examine the pace of millet's transmission and locales of adoption by compiling stable carbon isotope data from humans and fauna, then comparing them to environmental variables. The Bayesian modelling of isotope data allows for the assessment of changes in dietary intake over time and space. Our results suggest variability in the pace of adoption and intensification of millet production across northern Asia.

Keywords: millet; isotope; water availability; carbon; pastoralism; bronze age; iron age; cultivation; Bayesian modelling; archaeology; Asia

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1. Introduction

Millets are small-seeded grasses that are grown globally as cereal crops for human consumption and animal fodder. Over the past several decades, there has been a global increase in the use of millet to mitigate the influence of climate change among vulnerable populations [1]. Millets have also been recognised as a critical crop in discussions of agricultural origins and dispersals, including the so-called 'Bantu expansion' in Africa [2] and the emergence of agriculture in southern [3] and northwestern India [4]. Patterns of millet use also illustrate how past economies dealt with climate change and uncertainty, for example in rural areas of Europe during the Medieval period [5]. In Asia, broomcorn millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) are the most common cultivated species. Millet is of special importance, as it is a drought-tolerant crop with a short growing season of only 60 days after planting [6,7]. The root structure of millet tends to be shallow, meaning ploughing or overturning soils may not be necessary for the crop to thrive [8]. Millet also has nodal roots that grow longer in dry soils, which is associated with increased shoot biomass and greater water-use efficiency [8]. Preferring to be grown in full-sun, millet performs well on high-elevation plateaus and in various soil types [6]. In addition, millet has a low seed-sowing-to-harvest value, meaning that fewer seeds need to be saved each year to maintain the crop for the following year.

The adaptability of millet to drier locales with a short growing season is argued to have played an important part in the transmission and adoption of the crop across northern Asia [9]. Traditionally considered a pastoralist realm, the steppes and forest-steppes are often perceived as marginal environments, areas that are less productive or more challenging for agricultural production. Despite perceptions of northern Asia as a continuous and homogeneous grassland, the region is actually a mosaic of ecological diversity, made up of deserts, alpine meadows, coniferous forest patches, areas of Artemisia-dominant vegetation, saline lakes, and mixed forests [10–12]. In some locales, significant altitudinal variation influences vegetation communities, ranging from low elevation arid steppes, to conifer and juniper forests, and eventually alpine meadows [10,12]. The main factors that constrained the successful adoption of millet cultivation appear to have been elevation and rainfall [13–15] in areas where crops or pastures are successful. In north-central Asia, millets are rarely grown above 2000 masl in northern locales and rarely above 3000 masl in southern areas. Similarly, arid zones with rainfall below 300 mm per year are challenging for millet cultivation, requiring sufficient irrigation for summer cultivation.

The adoption of domesticated plants by pastoral groups is an effective method of economic diversification that reduces dietary risk [16–18]. Millets integrate well with other crops within diversified farming systems and can be produced intensively as an irrigated summer crop [9]. Broad portions of northern Mongolia, Kazakhstan, and southern Siberia, contain areas where farming and cultivation have taken place (Figure 1). The spatial location of croplands from the modern era suggests that arable land varied across the steppes. Here, ethnographic and historical data have confirmed that millet-based cultivation has been repeatedly incorporated into pastoral economies (see discussion [19]). While many scholars have suggested that early millet was transmitted by pastoralists along pathways of connectivity such as mountain corridors [20] or along ancient Silk Roads [21], our findings indicate that the presence of arable land (Figure 1) and precipitation (Figure S1) were more important factors (see below). While rainfed cultivation does occur in the foothills of mountains, a greater proportion of arable land is found in the open steppes of northern Kazakhstan and southern Siberia.

In northern Asian archaeology, one of the main concerns from an economic perspective has been the perceived lack of an effective source of carbohydrates for pre- and proto-historic populations living in the region. Preconceptions regarding a shortage of arable land and economic dependence on herding has led some scholars to erroneously suggest that the survival of early polities depended on trade to access grains from nearby agricultural societies [22]. Other scholars have noted that the rapid growth and relative ease of tending millet make it compatible with the lifeways of many pastoralist groups. Challenging misconceptions about the agricultural component of pre-modern economies has involved tracking the arrival and spread of millet across northern Asia [23]. For example, in Mongolia, the intensification of millet consumption has been linked to economic diversity and the expansion of state power among the Xiongnu and Mongol Empires [23,24].

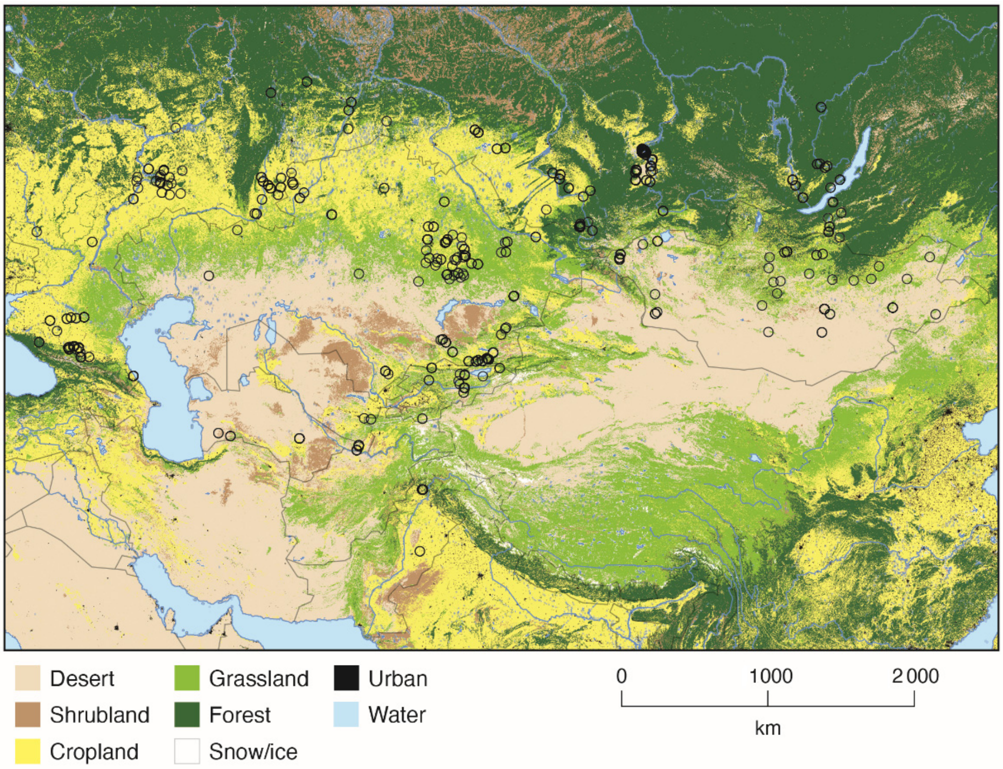


Figure 1. Map of ecological zones across north-central Asia (with sites plotted).

Here, we combine new isotopic results with the largest isotopic database thus far assembled for the stable carbon and nitrogen analyses of bone collagen (Table S1). This includes human and faunal (bone collagen) isotope results compiled from well-dated sites across Kazakhstan, Russia, and Mongolia spanning from the Neolithic through Medieval era. The role of ecological variation in shaping past economies in northern Asia is explored by mapping modern ecosystems across the region (Figures 1 and S1) to determine suitable locales for millet cultivation. We have identified areas where irrigation, or more intensive management techniques, transformed unlikely locales into suitable loci for millet-based farming by mapping published precipitation and cropland data across Kazakhstan, Mongolia, and Siberia [10,12]. Recent work has shown that between 4000 BCE and 100 CE most of north-central Asia was within the thermal niche, between 100% and 70%, for millet [25]. This lines up well with faunal data that we modelled, which estimated that collagen values of herbivores were generally stable over time, indicating that vegetation availability was similar with a trend toward slightly more arid conditions or the foddering of livestock with millet (Figures S5 and S6). Combined, these indicate that the use of modern precipitation and landform data is relevant for understanding north-central Asia in the past. Over the past decade, the modelling of Big Data has led to new insights into shifting patterns of dietary intake, demography, and land use [23,24,26–28]. Here, we integrated Big Data mapping with novel Bayesian modelling (of human and faunal isotope data) to determine the most promising regions for millet cultivation.

Existing Evidence for the Spread of Millet

Initial millet domestication occurred in northeastern China, where securely dated broomcorn millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) grains have been recovered. Cache deposits of millet were identified at the sites of Dadiwan (ca. 5900 cal.

BCE) [29], Yuezhuang (6000–5700 cal. BCE) in Shandong [30], and the site of Xinglonggou (5670–5610 cal. BCE) located in Inner Mongolia [31]. It is clear that both domesticated plants were cultivated by 6000 BCE, and that cultivation intensified by 3900 BCE [9]. The cultivation of millet reached the eastern edge of the Himalayan Plateau by 3200 BCE [32] and far eastern Russia by ~3800 BCE [33,34]. Between the early periods of initial domestication and the intensification of production, there was a long delay before millet was translocated across Asia (Figure 2).

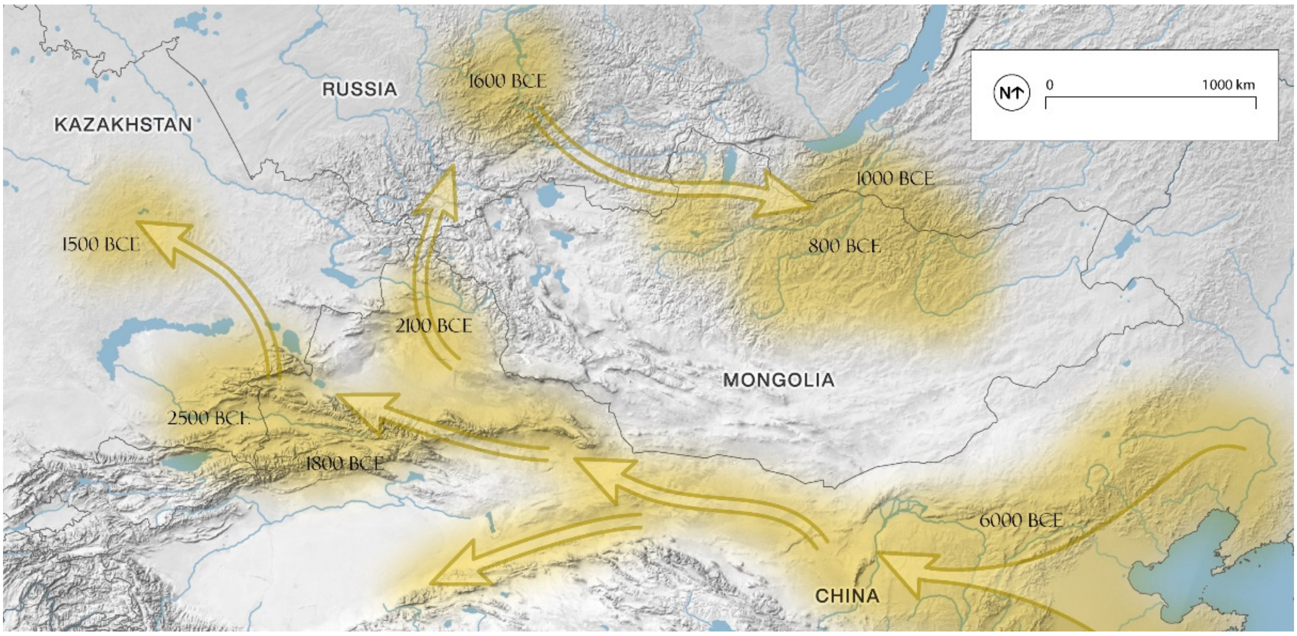


Figure 2. The spread of millet from northern China into areas of north-central Asia.

Evidence of millet grains in southeastern Kazakhstan indicate it was cultivated there by 2300 BCE [35,36], while isotopic research suggests that livestock in the Dzhungar mountains were foddered with millet as early as 2700 BCE [37]. Recent data from the Tian Shan Mountains demonstrate that millet was a significant dietary component among some groups by 2300 BC [38]. In the Altai Mountains of Xinjiang, millet grains have been dated to 2100 BCE [39] and in the Tarim basin slightly later at ~1800 BCE [21,40–42]. For portions of northern Asia, the pathways and timing of the spread of millet and intensification of production remain largely unresolved. Palaeobotanical research has advanced this knowledge, yet there are limitations to the temporal and spatial breadth of these data, especially in Mongolia, due to deflated occupation layers and limited implementation of modern archaeobotanical methods, such as flotation.

Although archaeobotany is the method of choice for studying and identifying human crop use in the past, issues of preservation and spatial coverage can make it difficult to effectively track the dispersal of crops and their overall importance to human diets. Fortunately, differences in the isotopic values of C_3 (most wild temperate grasses, shrubs, and trees and the domesticates wheat, barley, and rice) and C_4 crops (most wild tropical grasses and the domesticates of millet and maize) [43] enable us to identify a reliance on millet in human and animal diets. Isotope analysis can also assess the proportion of millet reliance in past economies, especially in periods when it became a staple food. In North America, stable isotope analysis has been used in this way to demonstrate the transition to domesticated maize [43]. Similar techniques have been used in Asia to track millet consumption [23,24]. Researchers are turning to stable isotope analysis to fill in gaps in our understanding of the transmission of domesticated crops, linking these findings to environmental variables across northern Asia.

2. Materials and Methods

Modelling of Isotope Data

Dietary intake has previously been investigated through paired $\delta^{13}C$ and $\delta^{15}N$ values of human bone collagen in various locales across the globe, including to clarify the consumption of C_4 plants including maize and millet [23,24,43,44]. Isotopic values of pastoral populations have been found to track those of domesticated livestock [23], suggesting a heavy reliance on milk and meat products. The intensification of millet consumption, as demonstrated through isotopic analyses, has been associated with increased connectivity [23] and later with high-output cultivation that was supported by imperial institutions [24]. One of the benefits of modelling isotopic data is that it gives us the potential to tease apart the consumption of millet by humans relative to livestock ingesting millet or other C_4 plants. It also provides a clear visual representation of the data over time with the benefit of a Bayesian model of the dataset. Here we analyse new human and faunal collagen samples (n = 156) from sites across Mongolia and southern Russia (Table S1). Stable carbon and nitrogen isotope analyses provide evidence for human dietary intake relative to faunal isotopic reference sets. In addition, we compile a large dataset of previously published isotopic values (n = 3208) from archaeological sites across Kazakhstan, Siberia, and Mongolia. These data are made available online as the North Central Asia isotopic database within the Pandora data platform (NCAID; https://www.doi.org/10.48493/0g6y-6712, accessed on 11 September 2023). All citations of original data can be found in the isotopic database. NCAID is a member of the IsoMemo network of independent isotopic databases (https://isomemo.com/, accessed on 11 September 2023).

Smoothed isoscapes of human bone collagen values for different temporal slices were produced using the model TimeR developed within the Pandora & IsoMemo initiatives [24,45]. TimeR is a generalised Bayesian additive mixed model that estimates the smoothness of a surface from data and includes a trades-off bias against variance to make optimal predictions of unseen data. Model inputs included human bone collagen values (filtered for C:N atomic ratios between 2.9 and 3.6), latitude and longitude, and the temporal range associated to each sample (input expressed as uniform distribution but modelled as a normal distribution with a standard deviation corresponding to one quarter of the width of the date range). Modelling was performed in R via a Shiny interface [46]. This interface is available online and as a local installation via GitHub (installation name MpiIsoApp found here: https://pandoraapp.earth/app/iso-memo-app; https://github.com/Pandora-IsoMemo/drat, accessed on 11 September 2023). It is a part of the Pandora & IsoMemo platform (https://isomemoapp.com/, accessed on 11 September 2023) in which different types of spatiotemporal modelling are included. The full code for the latter is also made available via GitHub. Model likelihood and parameter priors are as given here [47].

The precipitation data we use for comparison are derived from the 'Full Data Monthly Product of Monthly Global Land-surface Precipitation' from the Global Precipitation Climatology Centre (GPCC) data set, operated by the Deutscher Wetterdienst (DWD, National Meteorological Service of Germany) under the auspices of the World Meteorological Organization (WMO) [48]. The data were modelled using ArcGIS 10.8.2 to produce a measure of average yearly rainfall, representing an average year of precipitation from 1971 to 1980, per the parameters of the dataset.

3. Results

3.1. Stable Carbon and Nitrogen Results

Measurements of stable carbon and nitrogen isotopes were conducted on human and faunal bone from 15 archaeological sites across Mongolia (n = 10) and southern Russia (n = 5). These new data represent periods that predate the introduction of domesticates through the Iron Age (Table S1). In Mongolia, the sites include Airagiin Gozgor, Avn Khukh Uul, Altan Tolgoi-2, Bayan Ondor, Kharuul Uzuur-4, Khev-2, Shombuuzyn-Belchir, Takhiltyn-Khotgor, Talkigat Uzuur-5, and Tsagaan Asga. Sites in southern Russia, specifically in Buryatia, include Fofonovo, Il'movaya Pad', Ivolga, Pesterevo 82, and Podzvonkaya.

3.1.1. Sites in Mongolia

At the Bronze Age site of Avyn Khukh Uul-5, there were five human and nine faunal samples available for analysis. Human $\delta^{13}C$ values ranged from −20.1‰ to −16.9‰, while faunal values ranged from −16.8‰ to −21.0‰. Human $\delta^{15}N$ values ranged from 6.2 to 14.5‰ compared to faunal values from 4.8‰ to 8.5‰. From Altan Tolgoi-2, another Bronze Age site, there were only two human samples available for isotopic study. These had carbon isotope values of −17.5‰ and −17.1‰, with nitrogen isotope values of 14.1‰ and 14.6‰. The site of Bayan Ondor dates to the Bronze Age and had a total of seven human samples for analysis. Their $\delta^{13}C$ values ranged from −19.8‰ to −16.7‰, and their $\delta^{15}N$ values ranged from 7.0‰ to 15.1‰. From the Bronze Age site of Kharuul Uzuur-4, there was one human and one horse sample available for analysis. The human and horse $\delta^{13}C$ values were −20.7‰ and −18.4‰, while their $\delta^{15}N$ values were 11.6‰ and 4.8‰, respectively. The site of Khev-2 had one human and two horse samples available. The human $\delta^{13}C$ value was −19.8‰ and their $\delta^{15}N$ value was 6.4‰. Horses had a range of $\delta^{13}C$ values from −17.2‰ to −17.0‰ and a range of $\delta^{15}N$ values from 12.7‰ to 13.6‰. At Khokh Uzuur-1, there was a single human sample with a $\delta^{13}C$ value of −17.4‰ and a $\delta^{15}N$ value of 13.6‰. From the site of Takhilgat Uzuur-5, there were four animal and nine human samples that were analysed. $\delta^{13}C$ values of humans ranged from −18.1‰ to −15.8‰, with $\delta^{15}N$ values from 13.0‰ to 17.3‰. Faunal remains at the site had carbon isotope values from −18.4‰ to −17.4‰ and nitrogen isotope values from 7.2 to 12.3‰. Finally, at the site of Tsagaan Asga, there were 15 human samples that were measured. Their range of $\delta^{13}C$ and $\delta^{15}N$ values were from −18.0‰ to −16.7‰ and 13.3‰ to 15.1‰, respectively.

Several Iron Age sites had osteological remains available for analysis. At Airagiin Gozgor, a total of five humans and 28 faunal values were measured, with human $\delta^{13}C$ values ranging from −16.3‰ to −12.3‰, while those of the fauna ranged from −20.0‰ to −16.4‰. Human $\delta^{15}N$ values ranged from 10.7‰ to 12.9‰ compared to faunal values from 5.0‰ to 14.0‰. At the Xiongnu site of Shombuuzyn Belchir, there were eight humans and 22 fauna samples available. Human values had a range of $\delta^{13}C$ values from −17.8‰ to −17.0‰ and a range of $\delta^{15}N$ values from 13.1‰ to 15.3‰. Fauna from the site had $\delta^{13}C$ values ranged from −20.3‰ to −16.9‰ and $\delta^{15}N$ values ranging from 4.8‰ to 9.5‰. A second Xiongnu-era site of Takhiltyn Khotgor had six human and two faunal samples available for analysis. The range of human $\delta^{13}C$ values was from −17.8‰ to −16.5‰, while the range of $\delta^{15}N$ values was 12.4‰ to 13.8‰. Only two faunal values were measured, with $\delta^{13}C$ values of −17.8‰ and −16.8‰, and with $\delta^{15}N$ values of 17.0‰ and 17.8‰.

3.1.2. Sites in Russia (Republic of Buryatia)

The site of Fofonovo dates to the Neolithic period, with a total of twelve individuals that were analysed. Humans had a range of $\delta^{13}C$ values from −20.0‰ to −18.7‰ and a range of $\delta^{15}N$ values from 15.1‰ to 17.3‰. At the later site of Pesterevo 82, which dates to the Bronze Age, human $\delta^{13}C$ values were −18.1‰ and −17.7‰, while $\delta^{15}N$ values were 10.8‰ and 11.4‰, respectively. At the Early Iron Age site of Podzvonkaya, a single individual had a $\delta^{13}C$ value of −15.0‰ and a $\delta^{15}N$ value of 11.3‰. At later Iron Age sites, there are values for nine human individuals from Il'movaya Pad' and four values for ancient fish from Ivolga. The range of $\delta^{13}C$ values for humans from Il'movaya Pad' were from −15.3‰ to −12.7‰, while the range of $\delta^{15}N$ values was 11.8‰ to 13.1‰. Only three values of fish from Ivolga were measured with $\delta^{13}C$ values from −22.4‰ to −12.0‰ and $\delta^{15}N$ values from 10.3‰ to 11.4‰.

3.2. Patterns of Millet Dispersal

Our current analysis suggests that the early introduction of domesticated millet into northern Asia first occurred in ecological hot spots for cultivation, specifically in present day locales identified as cropland and where rain-fed agriculture was possible (Figures 1 and S1). Important ecological hotspots include rich grasslands, foothills on the windward side of mountains where precipitation collects, as well as near rain-gathering rocky outcrops, alluvial fans, and river basins (Figures 1, 2 and S1). In north-central Asia, the earliest evidence for millet crops and foddering of livestock occurs in southeastern Kazakhstan before 2500 BCE [37], which aligns well with our model. Early cultivation occurred in the alluvial fan, where sediment and water collected after flowing down from higher altitude locales. From there, ecological hotspots of arable land, with high rainfall and deep sediment, such as the Minusinsk Basin, appear as locales where millet cultivation began relatively early.

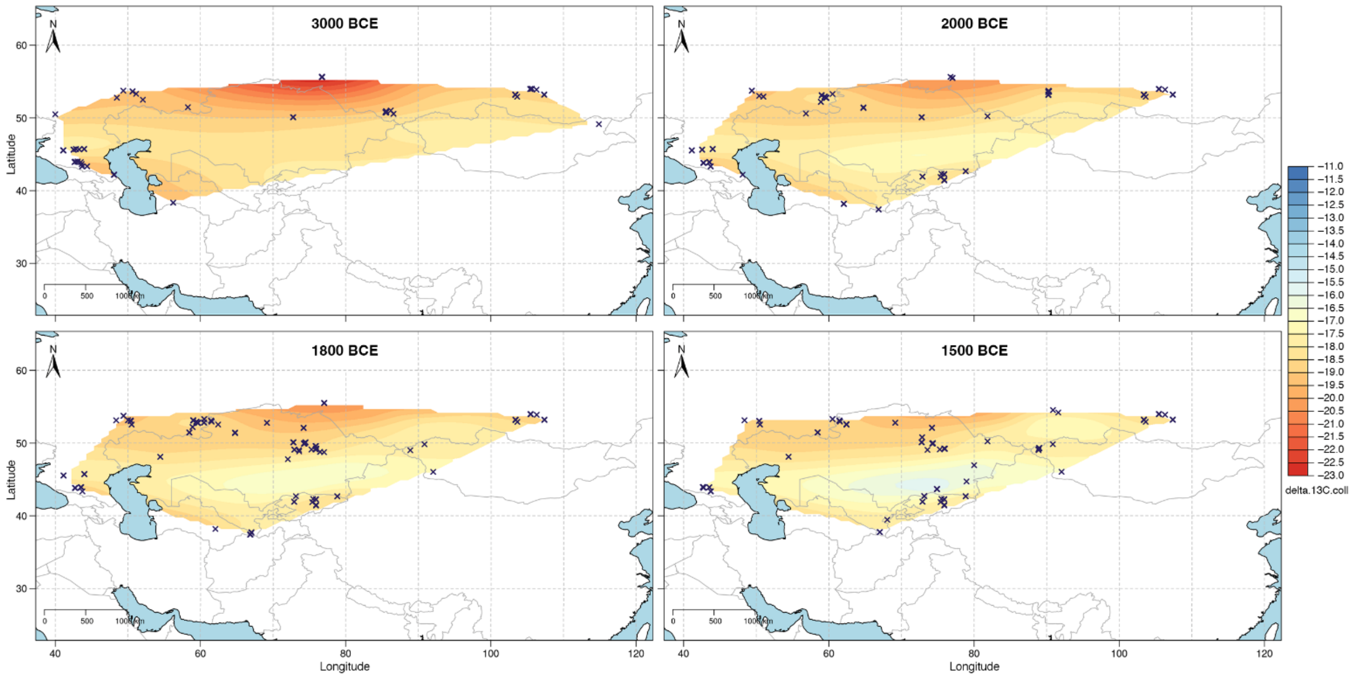
Some researchers have suggested that the initial introduction of millet into the Minusinsk Basin began as early as 2000 BCE based on shifting isotopic values [23], while other scholars have suggested this began later, by 1400 BCE [49]. Our Bayesian isoscape indicates that millet was consumed by as early as 1600 BCE (Figure 3a). By 1500 BCE there is unambiguous evidence for millet consumption among populations in the Minusinsk Basin and in central Kazakhstan; the latter has evidence that rain-fed agriculture was possible at the base of granite outcrops in the Kent Mountains [49–52]. Both locales are designated as cropland (Figure 1). In portions of the eastern steppe with mixed forests and cropland, millet consumption has been identified southeast of Lake Baikal by 1000 BCE (Table S1; Figures 2 and 3b; new results in this paper) and by 800 BCE in far northern Mongolia [24]. The later adoption of millet in the eastern steppe may be the result of variation in networks of connection, more arid conditions, or due to resilience in pastoral lifeways. Further, the lack of favourable cropland combined with less yearly precipitation in Mongolia, compared to other areas of the steppe may have further contributed to a delayed introduction of millet.

In drier areas, which did not have high potential for agriculture (Figure 1), the early introduction of crops was facilitated by low-investment infrastructural changes to the landscape, including the alteration of waterways. In central Kazakhstan, there is evidence for the construction of stone-lined channels, perhaps for irrigation purposes, during the Late Bronze Age (1500–1000 BCE) (Figure S7) [53,54]. Water and snowmelt flowing from granite outcrops and small river valleys was secured behind these channels, along with soils, thus improving soil productivity. Stone-lined channels were advantageous in the steppe, but were relatively low-investment, making the recognition of these features challenging. The open steppe in central Kazakhstan is similar to landscapes in central Mongolia and southern Buryatia (near Lake Baikal), where flat plains meet low mountains and outcrops. Rain-fed agriculture or pasture improvement is possible at the base of hills, thus similar features might be identified in these locations to facilitate the cultivation of millet (Figure S1).

3.3. Intensification of Production

North-central Asia is often depicted as a zone of pastoral dominance due to the persistent narrative that agriculture is challenging in the steppe and forest-steppe. However, the mapping of arable land across the region indicates that there are numerous locales that are productive for farming. Archaeological evidence for the intensification of millet production is often overlooked. Our model indicates that millet cultivation intensified over time in north-central Asia, as reflected in shifting coloration (from red to yellow to blue) of the map, indicating increasing carbon isotope values. During the Iron Age (~800 BCE to 500 CE), millet farming became one of the primary subsistence bases in vast portions of the western steppe, with millet consumption intensifying in the eastern steppe by ~200 BCE. Notable exceptions include the Trans-Urals region where C_3 plants, likely wheat or barley, predominated during this period. The intensification of agricultural production is associated with areas that invested in infrastructure for cultivation. The advent of small- and large-scale irrigation projects, including the alteration of waterways and construction of irrigation canals [53,54], dramatically altered the agricultural potential of northern landscapes. The adaptability of millet also made it a robust choice for drier locales, promoting its continued use and popularity over long time scales.

In eastern Kazakhstan, the model indicates there is an early shift towards intensification of agricultural production seen primarily at sites on the alluvial fans north of the Tian Shan, where water flowing from the mountains was redirected to agricultural fields and diverted into ditches and channels [55]. After 400 BCE, floodwater farming reached its peak [56,57], which coincided with an increase in the number of settlements [58]. Our model indicates that this intensification occurred earlier, from at least 700 BCE (Figure 3a,b). Full-scale irrigation canals were constructed at the site of Tuzusai (SE Kazakhstan), where rainfall was in short supply during the summer months [59]. The economy was based on millet, wheat, barley, and livestock [60]. Domesticated cultigens and livestock were also effectively managed, with evidence for crop scheduling and the fertilisation of fields with livestock manure, alongside livestock foddering and transhumance [59]. Scholars have also speculated that millet began to be integrated into a system of seasonal crop rotations, whereas in early urban centres across southern Central Asia millet was adopted as an irrigated summer crop [9].



(**a**)

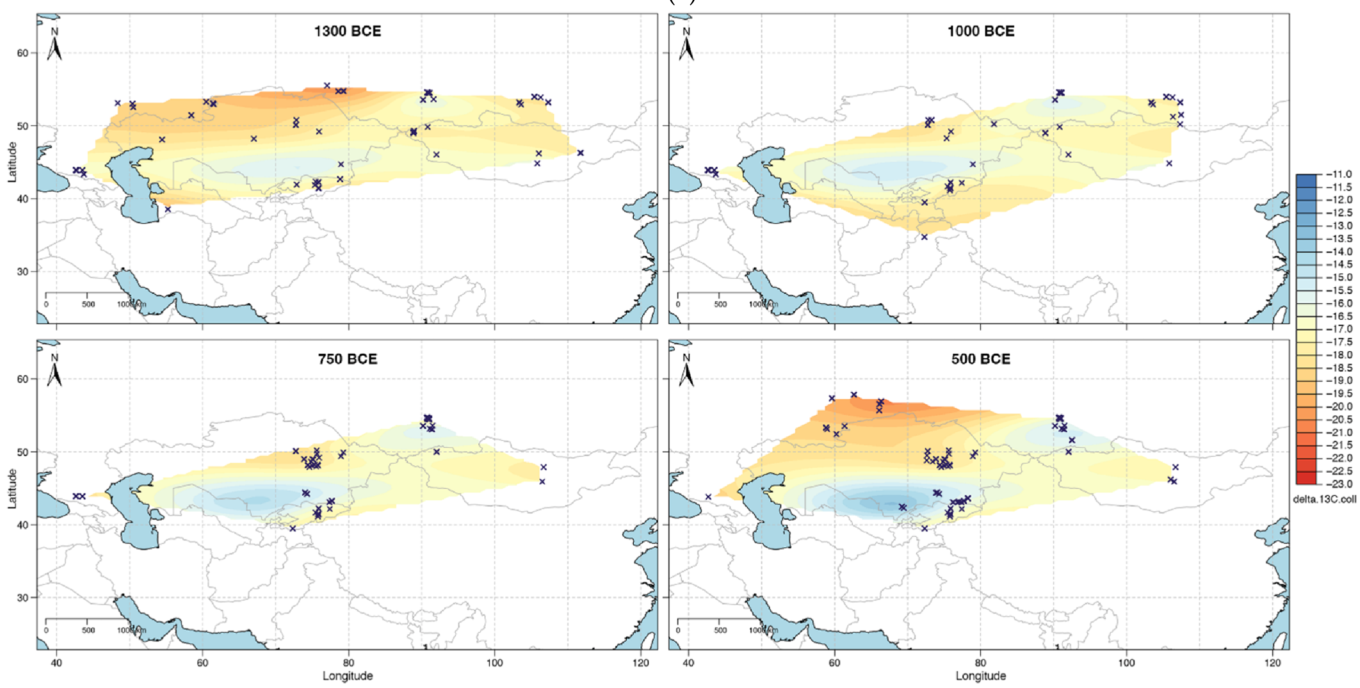


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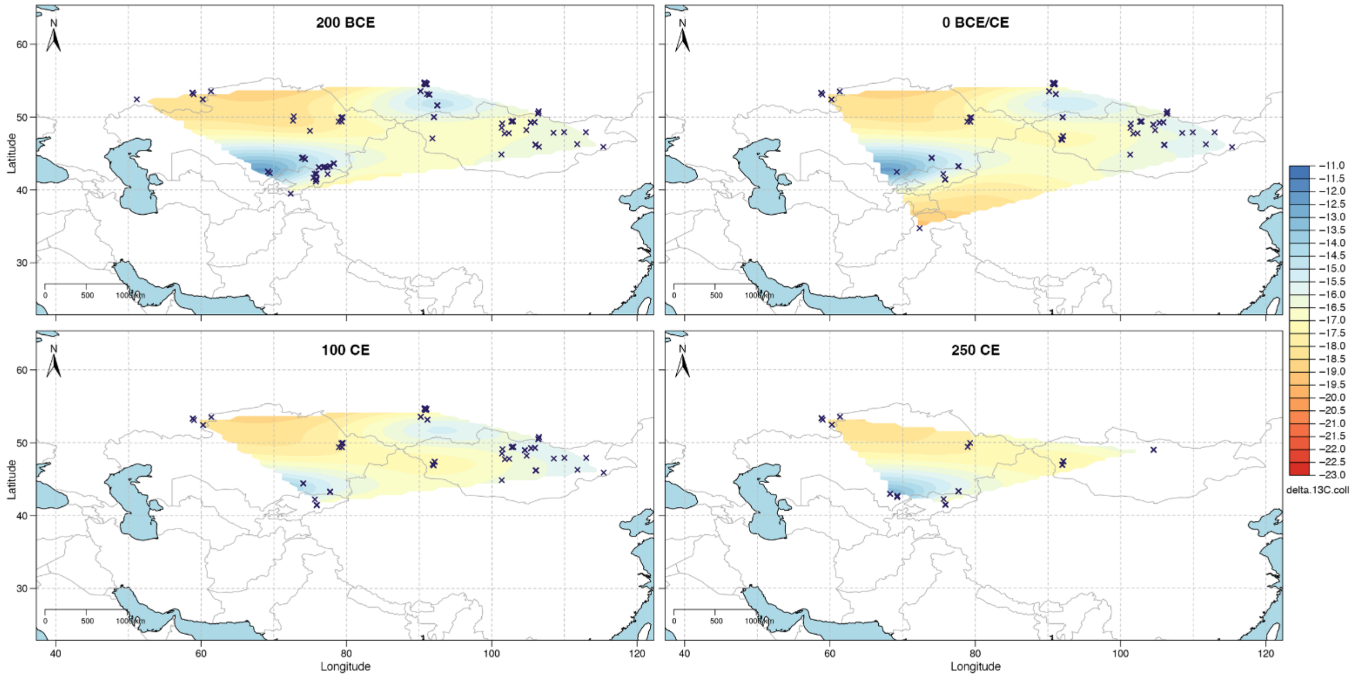
Figure 3. *Cont.*



(**c**)

Figure 3. Bayesian isoscapes of stable carbon isotope values for human collagen at different time slices with archaeological sites marked with an 'X'. (**a**) Bayesian isoscape at3000 BCE, 2000 BCE, 1800 BCE, and 1500 BCE. (**b**) Bayesian isoscape at 1300 BCE, 1000 BCE, 750 BCE, and 500 BCE. (**c**) Bayesian at 200 BCE, 0 BCE/CE, 100 CE, and 250 CE.

During the Xiongnu empire era on the eastern steppe (~200 BCE to 200 CE), the consumption of millet intensified (Figure 3c). Located along major river courses such as the Selenge, Orkhon, and Kherlen, sites of the Xiongnu empire were situated in locales where farming was advantageous. There is convincing evidence that farming occurred locally with the identification of grains that were unprocessed and coupled with their chaff [61,62]. An increased investment in farming practice at village sites, located southeast of Lake Baikal, is evidenced by the presence of ploughshares, hoes, and grinding stones [63,64]. At the Xiongnu-period town of Ivolga and the nearby cemetery site of Il'movaya Pad, isotopic evidence indicates that diets were primarily millet-based (Figure 3c). As the Ivolga settlement is located along the Selenge River, it may be that water was diverted from the river to irrigate agricultural fields. The recovery of long-season crops that require more water and labour to cultivate, such as wheat and barley, further supports a greater investment in cultivation. Finally, textual sources from the era document how farming production was administered by the Xiongnu Empire, namely through the reallocation of grains by the 'Lord of Millet Establishment and Distribution' [65,66].

4. Discussion

Early evidence of millet consumption occurred in areas where cultivation was straightforward, with the appropriate soils and rainfall for supporting crop growth. This included locales with arable land and higher amounts of precipitation, for example in alluvial fans and the foothills on the windward sides of mountains where sediment and water accumulate. In other locales, such as the semi-arid steppe, there is a patchwork of arable land where rain-fed agriculture is possible, for example at the base of hills or rocky outcrops. As millet production and consumption increased, it became evident in the form of elevated carbon isotope values in human tissues. Importantly, we demonstrate that millet was translocated in a patchy manner, tracking cropland in rain-fed locales across northwestern China and into southern Central Asia. Eventually, millets were cultivated in northern locales such as the Minusinsk Basin, while initially bypassing most of Mongolia. Only later did millet cultivation begin in parts of Inner Asia, including Mongolia and areas surrounding Lake Baikal, where pastoral groups and well-established hunter–gatherer communities had resilient and long-lasting economies. We demonstrate that the intensification of millet production occurred in areas of arable land, first in alluvial fans and river basins and only later along river courses.

The adoption of millet occurred in fits and starts across the region, with early evidence found in the alluvial fans to the north of the Tian Shan mountains (SE Kazakhstan) and in the Minusinsk Basin along the Yenisei River. It is also in these locations that millet intensification is evident during the Early Iron Age (Figure 3b). In drier locales and high elevation settings, the first cultivation of millet began slightly later (Figure 3c). A delay in the intensification of millet production in these northern zones, for example, along major rivers such as the Selenge, did not occur until the Late Iron Age (Figure 3c). Similar trends are seen for the adoption of maize in Mesoamerica, where the plant was first adopted in areas where it was highly productive and only later in high elevation and drier zones [67].

Efforts to increase agricultural production are advantageous in places where rain-fed farming is possible or riverine flow is uninterrupted. Investments in landscapes and infrastructure, including the redirection of water and construction of irrigation canals radically altered agricultural outputs in later periods. Other improvements, such as the manuring of fields, may have served a dual purpose as livestock ingested chaff after the harvest while depositing nitrogen-rich droppings. The shallow root structure of millet, its adaptability to various soil types, and efficient water use made it the ideal crop for building resilient economies in northern Asia. On a global scale, the incorporation of millet as part of local diets built economic resilience through a diversification of food production strategies [2,5,24,50].

Our results highlight that millet was adopted in locales that have previously been disregarded as marginal, with early evidence in well-watered areas with arable soils and later evidence coinciding with infrastructural improvements to enable cultivation in more challenging conditions. Contrary to previous models, in which the transmission of livestock and grains is argued to have occurred only along a single continuous mountain corridor or along routes of exchange associated with the proto-Silk Roads, our results indicate that the transmission of millet was also linked to arable land in steppe landscapes where rain-fed agriculture was possible. The spread of millet cross-cut mountain corridors into open landscapes in the western steppe and central Siberia following waterways and cropland. After the initial expansion of millet cultivation, the range of settings where the crop could be grown diversified, a pattern seen also with other crops (e.g., pearl millet in Africa [68]).

While the cultivation of domesticated grains is often linked to population growth, an initial demographic shift towards greater populations in the steppe appears to take place in earlier periods, just centuries after the adoption of ruminant livestock [69]. However, the eventual emergence of hierarchical societies does appear to coincide with the intensification of crop cultivation and economic diversification. The first kingdoms [66], or polities, in north-central Asia are evident in the Early Iron Age in southeastern Kazakhstan and the northern Altai Mountains in periods with millet cultivation. Similarly, the rise of the Xiongnu Empire in Mongolia occurs in concert with the intensification of millet production.

5. Conclusions

In this paper, we presented new stable isotopic values of humans and fauna from Mongolia and Russia which were compared with previously published data and modelled across north-central Asia. These new data provide greater insight into the transmission of millet in the northern realms, for example, the dates for the consumption of millet in northern Mongolia and Buryatia have been pushed back to ~900 BCE (Figure 2). These are areas that in the modern area have agricultural fields that are minimally tilled and rain-fed. We also examined herbivore values over time to determine if there were drastic changes to vegetation in north-central Asai during these periods. At broad scales herbivore values did not change very much over time, with a slight increase suggesting either more arid environments or the foddering of domestic ruminants with millet in later periods (Figures S5 and S6). Our Bayesian model of isotope data provided us with a clear representation of human dietary intake spatially and temporally. Millet was adopted first in locales that were well-watered with arable soils and later in areas where infrastructural improvements enabled cultivation. Millets are highly adaptable plants that offered new pathways towards resilient economies in the past, especially in semi-arid settings. Nevertheless, key factors in millet cultivation were productive soils and water availability, whether through precipitation, the alteration of waterways, or irrigation. The intensity of water management practiced appears to be intricately linked to the degree to which crops formed a primary or secondary component of agro-pastoral lifeways. Models that focus purely on environmental assumptions for a crop such as millet are unlikely to demonstrate the complexity of crop adaptability and the interventions of humans in transforming landscapes to increase productivity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13112848/s1, Supplemental Text [70]; Figure S1: Average yearly precipitation across northern Asia (with sites plotted); Figure S2: Carbon stable isotope values compared to average annual precipitation; Figure S3: Carbon stable isotope values compared to average annual temperature; Figure S4: Human δ13C values plotted through time relative to USGS landforms (Light grey indicates values higher than −17‰; dark grey indicates values higher than −14‰); North Central Asia isotopic database: https://www.doi.org/10.48493/0g6y-6712 (available online after publication); Figure S5: Stable carbon isotope values of herbivores plotted over time for all regions from 4000 BCE through 1250 CE; Figure S6: Stable carbon isotope values of herbivores plotted over time for all regions from 4000 BCE through 1250 CE; Figure S7: Drawing of a Final Bronze Age dam or irrigation canal from the site of Korgantas (Bayanayl Region of Central Kazakhstan); Reconfigured based on ([53], fig. 190).

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