SUPPLEMENTAL DATA (Ventresca Miller et al.)

Adaptability of millets and landscapes: Ancient cultivation in North-Central Asia

Modeling 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 to clarify the consumption of C_4 plants including maize and millet (Wilkin et al. 2020; Ventresca Miller and Makarewicz 2019; Ambrose, Buikstra, and Krueger 2003; Ventresca Miller et al. 2021). Isotopic values of pastoral populations have been found to track those of domesticated livestock (Ventresca Miller and Makarewiz 2019), 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(A. Ventresca Miller and Makarewicz 2019) and later with high-output cultivation that was supported by imperial institutions (Wilkin et al. 2020). Here we analyze new human and faunal collagen samples (n=156) from sites across Mongolia and southern Russia. Carbon and nitrogen stable isotope analyses provide direct evidence for human dietary intake relative to faunal isotopic reference sets. In addition, we compile previously published isotopic values (n=3208) from archaeological sites across Kazakhstan, Siberia, and Mongolia. This data is made available online as the North Central Asia isotopic database (NCAID; https://www.doi.org/10.48493/0g6y-6712). The new isotopic data can also be found below (Table S1).

Smoothed isoscapes of human bone collagen values for different temporal slices were produced using the model TimeR developed within the Pandora & IsoMemo initiatives (Wilkin et al. 2020; Cubas et al. 2020). TimeR is a generalized Bayesian additive mixed model which 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 done in R via a Shiny interface (Team 2021; Chang et al. 2017). 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) as part of the Pandora & IsoMemo app where 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 (Groß 2016).

Precipitation data is derived from the ‘Full Data Monthly Product of Monthly Global Land-surface Precipitation’ from the Global Precipitation Climatology Center (GPCC) data set, operated by the Deutscher Wetterdienst (DWD, National Meteorological Service of Germany) under the auspices of the World Meteorological Organization (WMO) (Schneider et al. 2020). The data was modeled using ArcGIS 10.8.2 to produce a measure of average yearly rainfall, representing an average year of precipitation, per the parameters of the dataset (Figure S1). To create Figure S2, we extracted the average yearly precipitation value for each site with stable carbon isotope values.

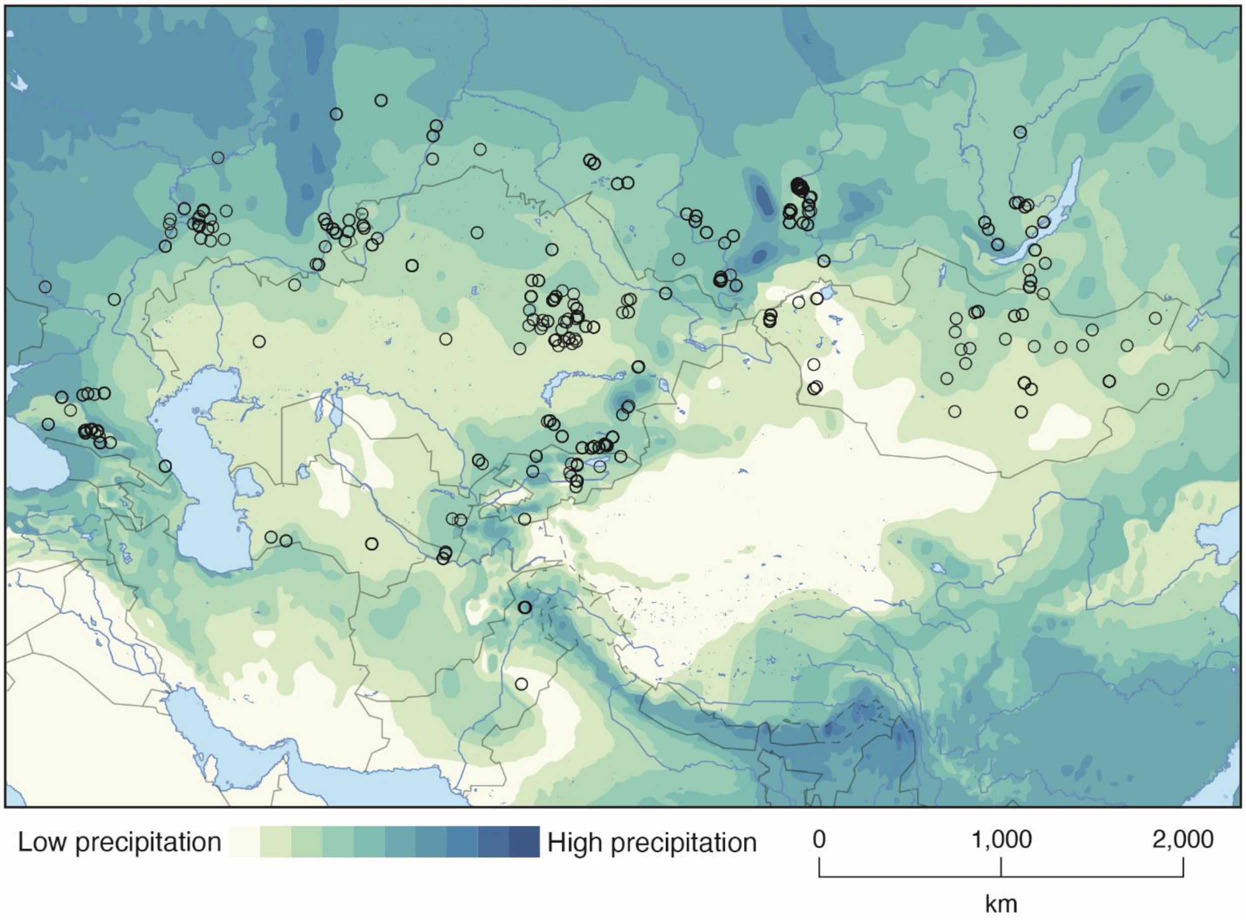

Figure S1 Average yearly precipitation (1891 through 2019) across north-central Asia (with sites plotted)

Further Analyses of Isotope Data

As this is a large dataset, we felt it was worthwhile to compare the stable carbon isotope values ($\delta^{13}C$) with average annual precipitation and temperature. A weak negative correlation was evident when $\delta^{13}C$ values were compared to average annual precipitation, with $\delta^{13}C$ values decreasing slightly as precipitation increased (Figure S2). There was a weak positive correlation between human $\delta^{13}C$ values and average annual temperature, with $\delta^{13}C$ values increasing slightly as temperatures increased (Figure S3). Thus, neither temperature nor precipitation alone are the primary driving factor of a shift in human carbon isotope values. Instead, the presence of croplands and grasslands tend to be indicators of locations where human $\delta^{13}C$ values have the greatest amplitude of change. In addition, it is in these locations where carbon isotope values begin to increase at early dates indicating new dietary inputs (Figure S4). In croplands, $\delta^{13}C$ values range from -24.8 to -10.5‰, with a shift to values greater than -16‰ as early as 3500 BCE. Similarly, in grasslands the range of carbon isotope values is quite wide (-24.5 to -11.3‰) with values greater than -16‰ after 1650 BCE. In forested zones, human $\delta^{13}C$ values range from -21.6 to -10.7‰, with a jump in values after 1550 BCE. In desert locales, the range of values is much narrower, from -20.1 to -12.2‰, with evidence for sustained higher carbon values after 700 BCE. These values are similar to shrublands, with values ranging from -20.9 to -14.1‰ and no tangible evidence of a drastic change in diet over time.

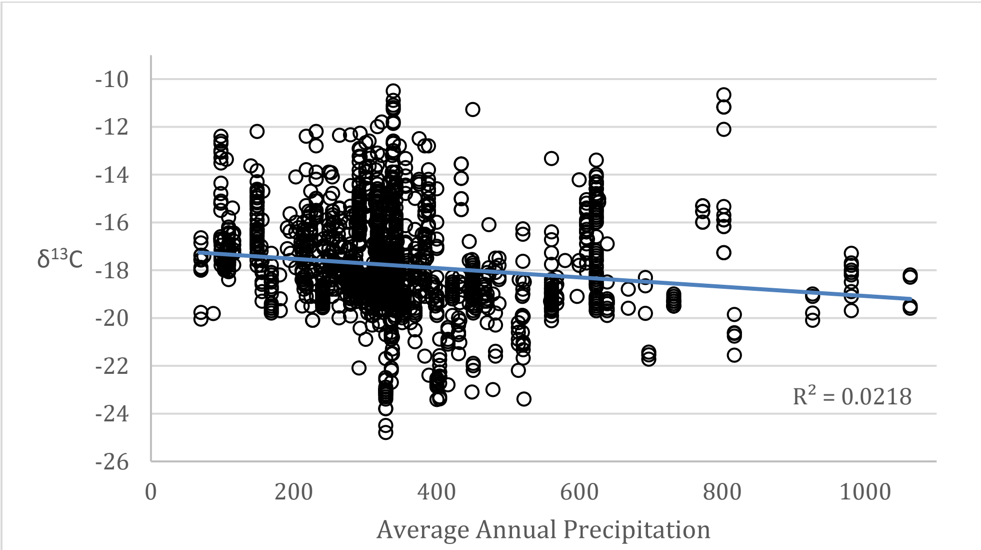

Figure S2 Carbon stable isotope values compared to average annual precipitation

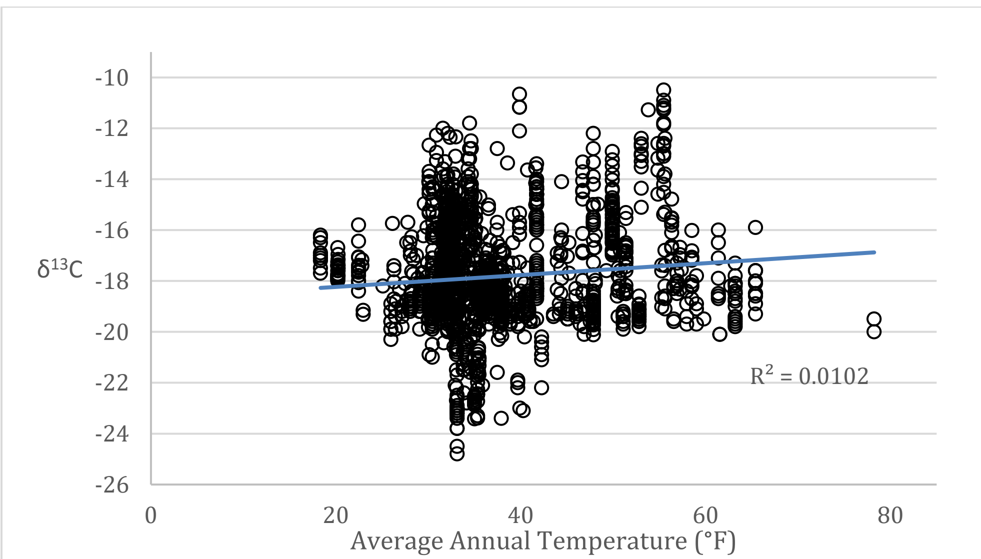

Figure S3 Carbon stable isotope values compared to average annual temperature

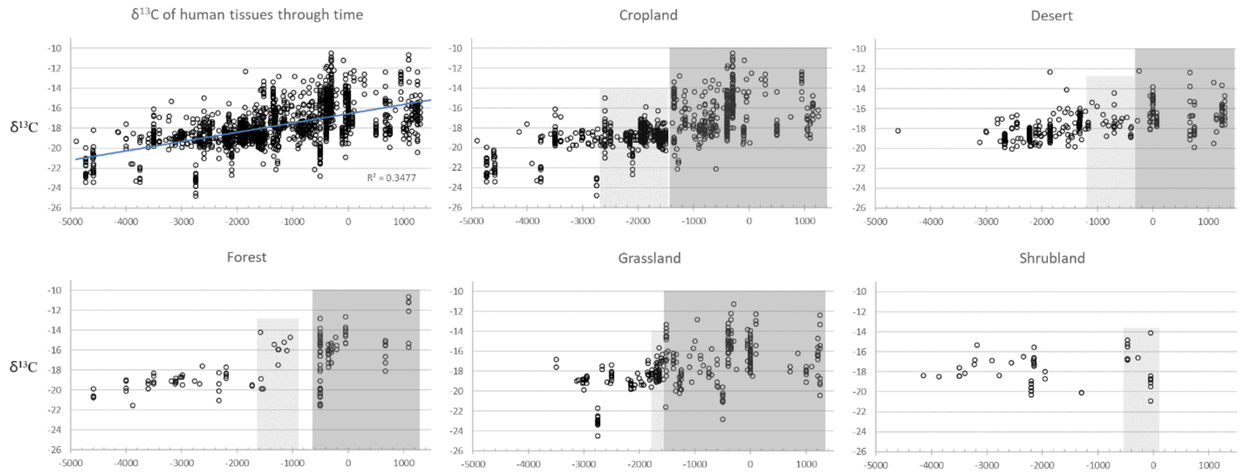

Figure S4 Human $\delta^{13}C$ values plotted through time relative to USGS landforms (Light grey indicates values higher than -16‰; Dark grey indicates values higher than -14‰).

We also examined possible shifts in the carbon isotope values of herbivores over time. We plotted herbivore values from all sites in north-central Asia to visualize any changes to underlying vegetation or impacts from human behavior. Generally, these values change very little, if anything with a slight increase over time, indicating a possible shift to more arid environments or foddering of livestock with millet (Figure S5). We also modeled changes in herbivore values in several locations to determine if there was variation at the local scale. While some of the plots provide evidence for small changes in herbivore diets, it remains unclear whether in later periods these are relative to precipitation or foddering (Figure S6). For example, in northern Mongolia carbon isotope values of herbivores increase over time suggesting that foddering was taking place, but this is dependent on only a few values. In contrast, in southeastern Kazakhstan carbon isotope values of herbivores decrease slightly over time, potentially due to foddering of livestock with millet chaff.

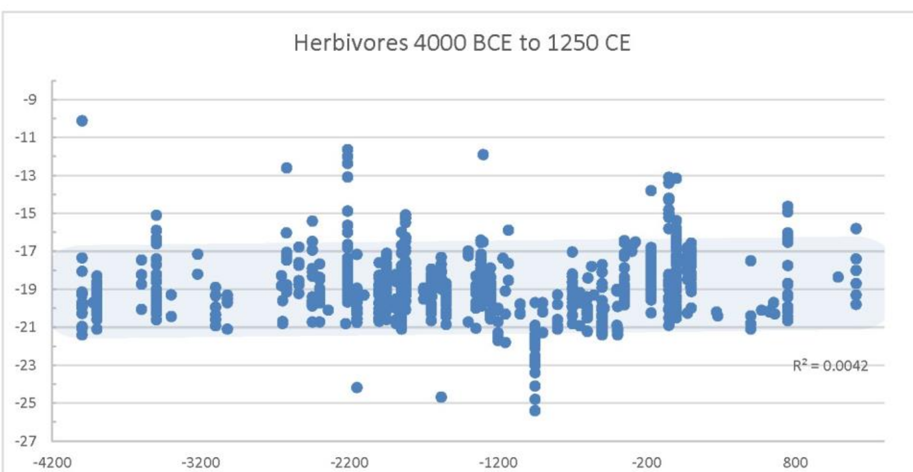

Figure S5 Stable carbon isotope values of herbivores plotted over time for all regions from 4000 BCE through 1250 CE

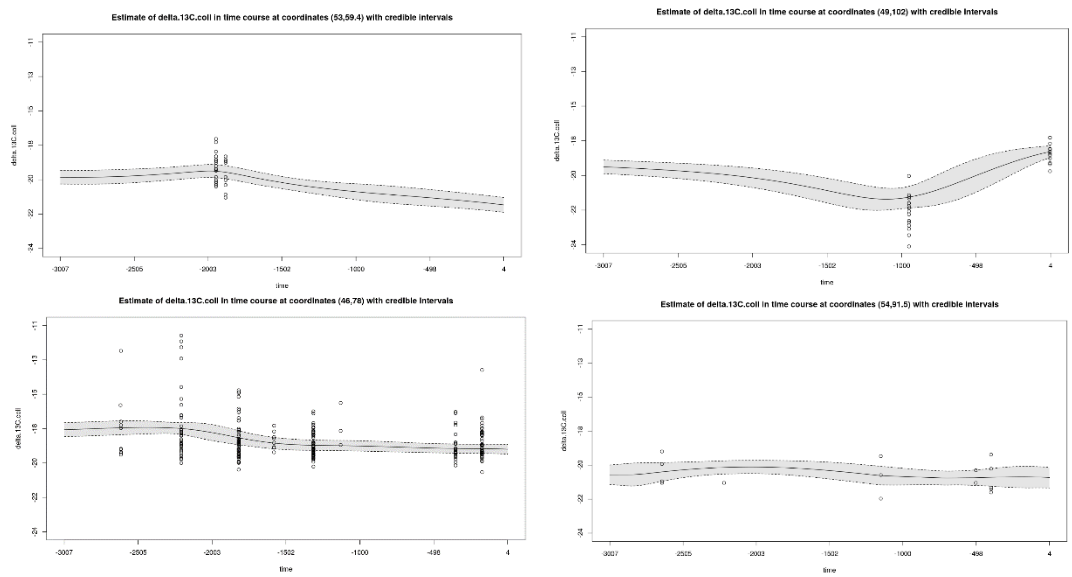

Figure S6 Modeling of stable carbon isotope values of herbivores from 3000 BCE through 100 CE for the Southern Urals (upper left), northern Mongolia (upper right), southeastern Kazakhstan (lower left), and the Minusinsk Basin (lower right).

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 Margulan 1979: 166 (fig. 190)

Figures

Figure S1 Average yearly precipitation across north-central Asia (with sites plotted)

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