Title: Synthesis of stable isotopic data for human bone collagen: a study of the broad dietary patterns across ancient China

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Abstract:

Ancient China is one of the most important regions for the development of agriculture in human history, contributing the two key crops millet and rice. Meanwhile, it was closely connected to the wider Eurasian network, receiving wheat and barley from the West. Because of the large isotopic differences between C_3 and C_4 crops, we are able to track their changing importance in different regions of China and underlying connections to their cultural and environmental contexts. We take a 'big data' approach, assembling the stable isotopic measurements on over two thousand ancient human bones. This is the first comprehensive meta-analysis of ancient Chinese human stable carbon and nitrogen isotope results and creates a more efficient tool for scholars to establish a fuller picture of dietary practices in ancient China. By charting their spatial-temporal variation, we can show that the primary crop facilitating the rise of the early Chinese state in the Central Plains was millet, particularly during the Bronze Age. The dominance of millet (C_4), from an isotopic viewpoint, offers an opportunity to investigate the major changes in dietary practice through the proxy of $\delta^{13}C$, as a result of shifts between millet and other major C_3 crops (rice, wheat and barley). More importantly, millet is probably one of the earliest examples for the existing local system in the Central Plains within which other imported elements (e.g. wheat) have to fit. This pattern, which has also been repetitively discovered with bronze and iron technology in later periods, starts to characterize some intrinsic features of Chinese prehistory.

Key words: Stable isotope analysis; Big data; Ancient China; Dietary change; Eurasian agriculture; East-West communication

1. Introduction

As one of the independent centres of agricultural development, China has not only contributed the domestication of millets (both broomcorn *Setaria italica* and foxtail *Panicum miliaceum*) and rice (*Oryza sativa*), but also received various other foods originating in Southwest Asia, such as wheat and barley (Dong et al., 2017; Fuller and Lucas, 2017; Jones et al., 2011; Liu et al., 2019b; Qin, 2012; Zhao, 2015). Over the last half century, a range of archaeological theories and scientific approaches have been employed to study the spatiotemporal development of agriculture in China, and its interaction with other aspects of human society. Major contributions have been made by palaeobotanical analyse (Zhao, 2011), stable isotopes (Hu, 2018), phytolith and palynological analyses (Weisskopf, 2017), starch residue studies (Yang et al., 2012), radiocarbon dating (Deng et al., 2020), and genetics (Lu et al., 2019).

Yet, important gaps in this research remain. Whilst a large amount of research effort has been channelled to studies on specific archaeological sites, little attention has been paid to searching for broader-scale patterns commensurate with a large-scale phenomenon such as the transfer and adoption of new crops in the context of an emerging state-level civilisation. This kind of broad-picture study, nevertheless, allows scholars to not only identify potential research gaps or outliers in the agricultural development in human history, but also be more engaged with subjects such as the spread of metallurgy (Pollard et al., 2017, 2018) and animal domestication (Vigne, 2011), human migrations (Ning et al., 2020), climate change (Chen et al., 2020) and many others, in order to create a multi-dimensional approach to socio-ecological and material interactions in the prehistoric period.

Although a variety of research methods are applied to the reconstruction of ancient dietary, because of their fundamentally different rationale, they provide different aspects of the answer to the same question. For instance, archaeobotanical results are able to tell us what specific foods were available to a community, whereas stable isotopic measurements on human bone illustrate a long-term average outcome of what had been actually consumed over a decade or more (Makarewicz and Sealy, 2015). Here, we have assembled a large number of stable carbon and nitrogen isotopic analyses on ancient Chinese human remains from publications, and have attempted to chart changes in these data over time and space (Figure 1, Atahan et al., 2014; Wang et al., 2017). Our prime objective is to make these isotopic data available for scholars to carry out more detailed studies in the future (online supplementary material I). In this paper, we aim to: a) provide a large-scale visualisation of the considerable changes in dietary practices from the early Neolithic (*ca.* 10,000 - 7000 BCE) to the Tang dynasty (681 - 907 CE); b) correlate these with other sources of evidence for changes in land use, agriculture practices, social choices and broad east-west communication; and c) use millet in the Late Neolithic and Bronze

Age Central Plains as a case study to show how this database can contribute to more detailed investigations. It is especially important to note that the key question here is the shifts as well as continuities in the long-term dietary practices as reflected by stable isotope values. The archaeological significance of these data should be explored alongside other lines of information (e.g. archaeobotanical finds, faunal data, material culture and environmental conditions). While it is impossible to assert that our database has included every single isotopic analysis that has been published for the study region, we are confident that it adequately captures the current state of the literature. In the context of a stable isotopic study of archaeological human remains, over 2000 data points represent relatively 'big data', allowing scholars to quickly establish a more comprehensive understanding of broad trends in certain aspects of dietary behaviour over the *longue durée* and to identify regional patterns or indeed gaps/outliers: for instance, there is a significant lack of data for sites in Southern China, and this should be a research priority. A key wider-scale question is when and how new imported crops (e.g. wheat) were accommodated within well-established subsistence systems focussed on other long-standing crops, most notably the dominant role played by millet in the Central Plains throughout prehistory. This also offers a vital clue to interpret the stable isotopic values of human bone collagen as the major shifts in $\delta^{13}C$.

2. The current state of the archaeology: millet, rice, wheat and barley

Caption: Figure 1. Sites mentioned in the text (1 Xianrendong, 2 Diaotonghuan, 3 Yuchanyan, 4 Shangshan, 5 Nanzhuangtou, 6 Jiahu, 7 Yuezhuang, 8 Hemudu, 9 Tianluoshan, 10 Liangzhu, 11 Donghulin, 12 Cishan, 13 Xinglongwa, 14 Zhaojiazhuang, 15 Xiaojingshan, 16 Banpo, 17 Baishicun, 18 Gouwan, 19 Jiazhuang, 20 Haojiatai, 21 Anyang, 22 Liuzhuang, 23 Peiligang, 24 Houli, 25 Dadiwan, 26 Qianzhangda, 27 Erlitou, 28 Sanxingcun, 29 Tashan, 30 Songze, 31 Yichuannanzhuang, 32 Beiqian, 33 Xinzhai, 34 Xiazhai, 35 Pingliangtai, 36 Erligang, 37 Liangchengzhen)

It is widely accepted that both millet and rice were independently domesticated in China but in different regions (Fuller and Lucas, 2017; Liu et al., 2018). The earliest records of domesticated millet known to us arguably date to the ninth millennium BCE, from sites such as Donghulin, Nanzhuangtou and Cishan in Northern China (Barton et al., 2009a; Bettinger et al., 2010; Yang et al., 2012). At the site of Cishan, the most striking feature is the 88 storage pits which contained 0.3–2.0 m thick layers of millet grains, adding up to 50 tons. The radiocarbon results are, however, highly controversial. Lu et al. (2009) suggest that the earliest dates could be pushed back to 8619-8287 BCE but this has been criticized on both sample and archaeological grounds (Zhao, 2011). In addition to Cishan, a number of other early Neolithic cultures, such as Peiligang and Houli in the Central Plains, Xinglongwa in the Northeast and Dadiwan in the Northwest, have also yielded grains of millet. So far, the earliest direct radiocarbon date from the millet grains comes from Xinglongwa, at 5670-5610 BCE (Zhao, 2011).

As attested by both palaeobotanical remains and isotopic analyses (see below), the use of millet flourished in the Yangshao period (*ca.* 5000 - 3000 BCE). An increasing number of regions, in addition to the Central Plains, appeared to have relied on millet-based agriculture, including the Hexi corridor and Central Asia which connects China to the West (d'Alpoim Guedes et al., 2014), and the Tibetan plateau (Chen et al., 2015; Dong et al., 2017) which connects China to the south (e.g. SE Asia).

In terms of rice domestication, Southern China, particularly the middle and lower Yangtze River valley, has attracted a great deal of attention. The trajectory between wild rice and systematic cultivation may have taken thousands of years and still remains an on-going research challenge (Weisskopf et al., 2015). An increasing amount of research tends to support a multicentric model of rice domestication, involving not only the Yangtze River valley, but also the Huai River and the Shandong peninsula. Fragmented remains of domesticated rice were first discovered in the sites of Xianrendong, Diaotonghuan and Yuchanyan in the middle Yangtze, all of which date to *ca*. 8000 BCE (Zhao, 2011). More evidence of rice has been found in the Shangshan culture of the lower Yangtze, the earliest date of which is now pushed back to 7400-7000 BCE (Zuo et al., 2017). In the Huai River valley, Jiahu is one of the best-known sites which have yielded evidence of early rice (*ca.* 7000-5600 BCE). Around four hundred grains of rice, together with stone tools for agricultural practices, a clear settlement pattern and domestic pigs, provide invaluable evidence for the status of rice-based agriculture in this region. Compared with Jiahu, the number of rice grains in the Shandong Yuezhuang site appears much less significant (only a few rice grains have been discovered so far dated to *ca.* 6000-5850 BCE, Crawford et al., 2006), and in later periods no sign of rice has yet been uncovered in Shandong (Jin et al., 2014). Further development of rice cultivation happened at the sites of Hemudu (5118-3762 BCE), Tianluoshan (*ca.* 5000-3000 BCE), and Liangzhu (3079-2521 BCE) in the lower Yangtze where it seems to have become the dominant staple crop (Fuller et al., 2009; Qin et al., 2009; Jin et al., 2019).

The first and foremost characteristic of wheat in Chinese prehistoric research is that it was a crop imported from the West in the late third millennium BCE and superimposed on the well-established millet-based agricultural practice, which offers excellent first-hand archaeological materials to compare and contrast different behavioural patterns ('invention' *vs.* adoption) towards the same crop in different regions (e.g. Near East, Iran, Central Asia *vs.* China). Continuity in local material cultures illustrates a gradual adoption of wheat into the existing local system (Barton and An, 2014). Based on decades of flotation work and direct radiocarbon dates, two possible routes have been proposed for the transmission of wheat into China: the Eurasian steppe route and the oasis route (Zhao, 2015). The Eurasian steppe route suggests that wheat arrived into the eastern part of the Eurasian steppe from the West, and then southwards into the middle and lower Yellow River valley via Northern China. In the oasis route, wheat travelled from Middle Asia into the Tarim basin through the Pamir highlands and then further eastwards along the oasis passages around the south and north edge of the Taklamakan desert into Xinjiang and Gansu. The two-route theory implies that the wheat dated to 2600-2000 BCE in different regions of China may be the result of different modes and episodes of communication with the outside. Based on similar materials, Dodson et al. (2013) suggest a hypothetical route similar to Zhao's Eurasian steppe route, but differs in the sense that wheat first became concentrated in the Gansu corridor and then moved in separate directions: westwards into Xinjiang and east into the Central Plains and Shandong. This has provoked sharp criticism by An and Barton (2013), concerning the provenance of the samples, the timing and routes of wheat, as well as wheat-millet interaction in Gansu. Among them, the wheat discovered in the Shandong Longshan culture appears most difficult to understand. Newly published radiocarbon dating confirms the earlier result on the wheat of the Zhaojiazhuang site at Shandong (2500-2200 BCE, Barton and An, 2014; Jin et al., 2011; Long et al., 2018) and again has posed a great puzzle for east-west interaction in the late third millennium BCE in Chinese archaeology (Dong, 2018). It is even more striking to see that wheat, which outperforms millet in terms of potential annual yields under most circumstances, was not widely cultivated in the Central Plains until the Han dynasty (206 BCE – 220 CE).

Like wheat, barley was another important crop travelling from the West into China around the end of the third millennium BCE. It was initially domesticated in Southwest Asia's Fertile Crescent around 8000 BCE and then found in the following regions in later periods: Turkmenistan (6500-3000 BCE), Pakistan (6000−3000 BCE), India (3000-2000 BCE) and the Inner Asian Mountain Corridor (2000-1000 BCE). The earliest direct radiocarbon dates on barley in China is 2136-1959 BC at Qinghai (Liu et al., 2017). As noted by Liu et al. (2017), there seems to be a thousand year gap between the occurrence of barley on the southern and northern edges of the Tibetan Plateau, which, following the three routes of wheat as discussed above, suggests a potential fourth route via the southern Tibetan Plateau for the translocation of crops between west and east (Liu et al., 2017). Thanks to strong resistance to drought and low temperatures, barley shows a remarkable adaptability to altitudinal and latitudinal extremes and was thus brought by millet cultivators to the Tibetan plateau, where it greatly facilitated human adaptation to this day (Chen et al., 2015). Another time lag is that barley did not appear in the Central Plains until the Western Han dynasty (202 BCE - 8 AD). It remains uncertain as to what prevented barley from moving eastwards to the Central Plains.

It is now widely accepted that millet and rice were staple food sources in prehistoric China, and almost all of the archaeological sites dating prior to the Qin dynasty in Central and Southern China have yielded millet and rice, respectively. However, it remains unclear why millet and rice became so persistent in China following their domestication. Was it due to their high yields and adaptability to local environment or were there other social or cultural reasons involved? What is equally unclear is when and how these crops arrived in different parts of China, and the degree to which different human populations relied on them and how this influenced their later response to wheat and barley. There are obvious climatic factors with rice and millet, with the former thriving in wetter, more tropical areas and the latter in cooler, more arid areas (Dong et al., 2017). Nevertheless, this does not account for the proposed, slow and limited initial uptake of wheat and barley by the people living in the Central Plains around 2000 BCE. As above mentioned, neither wheat nor barley became widely cultivated until the Han dynasty (206 BCE – 220 CE), which is nearly two thousand years after being introduced to the Central Plains.

3. The method: constructing and analyzing the database of Chinese human bone stable isotopes

The well-known saying ‘you are what you eat’ has been taken almost literally in archaeology for the last 50 years and human dietary reconstruction has been extensively carried out using stable isotope studies on bone collagen. As mentioned above, while macrofossils generated by flotation are often used to estimate the importance of various crops, the actual volume, weight as well as calories can be radically different. For instance, whilst many publications use the number of grains and the proportions between different crops to estimate their importance, the same number of grains (ubiquity) of foxtail millet provides approximately only 19% of the calories provided by rice. In this light, the merit of stable isotopic analyses of human bones becomes more obvious in that the data directly reflects what has been eaten over the long term rather than what was available to eat.

In China, applying isotopic analysis to the study of human palaeodiet began in the 1980s and has achieved substantial progress within Chinese archaeology (Cai and Qiu, 1984; Hu, 2018). For this paper, we have assembled a database of over two thousand paired measurements of $\delta^{13}C$ and $\delta^{15}N$ in human bone collagen from 95 publications (online supplementary material I). To our knowledge, all the stable isotopic data associated with ancient Chinese human bones are published either in English or Chinese. Whilst most scholars interested in this subject can read both languages and so access the publications, there is still tremendous amount of work of linking the isotopic data with other archaeological attributes, or in other words, to provide the contextual meta-data, including chronology, location, archaeological culture, age, gender, ethnicity and others (e.g. burial objects, social status, animal sacrifices, or more detailed chronological phase, in the note of the online supplementary material I). In some cases, we have identified data reproduced in other papers (or a translation of the original paper); therefore we only record the reference rather than duplicating the data. A common concern for such a large database is data quality, and whether there exist systematic errors that could potentially bias interpretations. The majority of the papers have reported the precision of their measurements as greater than 0.2‰ but without associated detailed information on internationally certified/in house standards (online supplementary material I). The other common means of assessing the validity of measurements (also preservation of the sample) is through C/N ratios (DeNiro 1985). Over 96% of samples fall into the good range (2.9-3.6, online supplementary materials II), with those not meeting this criterion excluded from the analysis. Based on the large datasets, for a broadly defined region, one can always find several smaller sets of data (often for different sites within this region) for cross-checking (online supplementary material I). This provides some checks on the broad trends presented in the following discussion, imparting a degree of robustness. This is also useful in identifying outliers. In addition, we have highlighted those published in both English and Chinese literature and manually removed duplicates for the analysis below. Other parameters such as %C, %N, and collagen yield have also been recorded in the online supplementary material I to monitor data quality. Kernel density plots are used to indicate the probability density of the data distribution and to aid visualization.

It goes without saying that stable isotopic data on faunal remains are central to many aspects of the interpretation of human data, providing baselines and elucidating the pathways by which C_3 and C_4 crops are incorporated into subsistence practices. Yet, for our purposes here, much can be said even without faunal data (e.g. Schulting, 2018). Rather than reconstructing or modelling specific diets, we are primarily interested in tracking the relative importance of these crops, whether or not mediated through domestic animals. Specifically, we focus on changing $\delta^{13}C$ values, which are largely caused by the rise and fall of millet (C_4) in relation to wheat, barley and rice across time and space. In addition, the management of animals in China varies significantly in different regions (e.g. Jing, 2008; Flad et al. 2007) and the collation of that data would require an independent project beyond the scope of this paper.

We divide the dataset according to geographical divisions that reflect the study region's underlying physical, climatic and cultural zones. Figure 2 shows the increase in the number of publications which contain stable isotope data on human bone collagen from China since 1984, divided up into five regions: North, Central Plains, Northwest, Southern Yangtze and 'others' (Figure 2b).

Approximately 50% of all the assembled data originates from the Central Plains, with the next largest contribution being 33% from Northwest China. It is not surprising that the Central Plains have attracted the most attention, as they represent the origins of the Chinese state. The next most significant area comes from Northwest China, mainly present-day Gansu, Qinghai and Xinjiang provinces, resulting from the importance of the Silk Road as one possible vector for the transfer of Western Asian influences, including wheat, pastoralism and metals. Given its importance for the origins of rice agriculture, the middle and lower Yangtze River valley has unfortunately received considerably less isotopic attention, thus leaving a significant gap in the current database. One possible reason for this is that the humid climate and generally more acidic soil conditions in the south limit bone preservation. Meanwhile, fewer sites dated to Neolithic and Bronze Age along the Yangtze River valley may also help to explain this lack of data (Hosner et al., 2016). Likewise, compared with the Central Plains and Northwest China, the amount of data for Northern China and other regions (including southwest and further south of the Yangtze River) is currently far from ideal.

These imbalances in the database can also be seen chronologically. The majority of the data are focused on the Late Neolithic period and Bronze Age. This clearly reflects research interest on the arrival of new crop species. For Early and Middle Neolithic sites, skeletons may be badly preserved, so that extracting well-preserved collagen becomes increasingly challenging. Conversely, in spite of good organic preservation, only 260 isotopic measurements have so far been published from excavations of the Qin, Han and later Dynasties (e.g. Zhang et al., 2010, 2013; Hou et al., 2012), demonstrating a significant lack of interest. As with the early stages of isotopic analyses in Europe and the Americas, this relates in large part to the initial focus on the appearance and spread of agriculture, and to the (often mistaken) notion that the subsistence economy of later periods is already well understood through other sources.

Caption: Figure 2. Summary of the current database of stable isotopic analyses of human bones in China (a. the distribution of stable isotopic data; b. geographical division in this paper).

4. Spatiotemporal distribution of stable isotopes: a comparative perspective

While the above-mentioned unevenness and gaps in the database may limit research on a site-specific level, a number of major dietary changes can be well illustrated, particularly for the Neolithic and Bronze Age periods. The biggest challenge in interpreting such data is the correlation of each stable isotopic data point with a precise chronology, since few skeletons are directly dated by radiocarbon. This can be resolved at a broad scale by associating the isotopic data with the time period assigned to the excavation context (or the archaeological culture), and undertaking diachronic analysis using a series of wide chronological windows. Under these circumstances, any changes that can still be seen must be considered archaeologically meaningful.

The contrast between the consumption of different foods is clear in the isotopic analyses of Chinese human skeletons. Figure 3 summarizes the distribution of $\delta^{13}C$ values in the entire database and shows a comparison with $\delta^{13}C$ values for C_4 and C_3 plants. We can assume that the dominant peak in the human bone data at around -8.5 ‰ represents individuals living on a predominantly C_4-based diet (again, whether this refers to the direct consumption of cereals, or to animals eating those cereals, or to both, e.g. Barton et al. 2009b). The difference between this value and the peak in the C_4 plant relates primarily to the well-known diet to bone collagen fractionation of ca. 5‰, plus the Suess effect in modern plant values (a reduction of ~1.5‰ in $\delta^{13}C$ due to the release of fossil fuels since the industrial revolution; Keeling, 1979).

Caption: Figure 3. The overall distribution of $\delta^{13}C$ results for ancient Chinese human remains (a) compared to data from plants with different photosynthetic pathways (b, Cerling et al., 1997).

4.1 Chronological variation in human $\delta^{13}C$ and $\delta^{15}N$ values within the defined regions

Caption: Figure 4. Plots of human $\delta^{13}C$ and $\delta^{15}N$ values, divided into time periods (the contours are produced by a kernel density function to estimate the probability distributions of $\delta^{13}C$ and $\delta^{15}N$, for technical details see Bronk Ramsey et al. (2015); simple x-y scatterplots can be found in online supplementary material II).

We next illustrate the temporal and spatial distribution of the stable isotopic data, with the objective of understanding dietary changes at another scale. Figure 4 shows examples of plots of $\delta^{13}C$ against $\delta^{15}N$ for the data within four regions (the Central Plains, Northwest China, Northern China and Southern China), divided into time slices. To facilitate the description of the data, a consistent six-fold division has been applied to each part of Figure 4. Values of $\delta^{13}C$ below -17.5 ‰ indicate a strong input of C_3 food, whereas those above -10 ‰ are taken to reflect predominantly C_4 consumption. Points between these values suggest a mixed contribution of both C_3 and C_4 crops. The nitrogen isotope data are divided into two parts, with the boundary set at $\delta^{15}N$ = 12 ‰. The upper range suggests greater input from aquatic (marine and/or freshwater) protein or other high-trophic-level foods, whereas the lower range suggests relatively lower trophic level consumption. This division is admittedly crude, and subsumes a range of quite different diets and is subject to differences in baseline isotopic ecologies, but at the broad scale of our analysis it is nevertheless useful (Schulting, 2018).

Before 2000 BCE in the Central Plains, the data lie in a horizontal band (Figure 4a). This suggests a range of diets, from almost pure C_4 to almost pure C_3 but the kernel density (where the contours are clustered) implies that the C_4 influence clearly outweighs C_3. Given the fact that C_4 plants are much less ubiquitous in nature than C_3, as well as the long history of millet cultivation before 2000 BCE in Northern and Central China (see references in Section 2), it is reasonable infer that this is the outcome of millet consumption. On the other hand, in addition to rice or possibly wheat, a variety of wild foods (e.g. nuts, beans, wild vegetation or fruits) could result in the similar C_3 signal in human bones. A number of well-known sites such as Jiahu (n=22), Xiaojingshan (n=7), Banpo (n=1), Bashicun (n=2), Gouwan (n=3), Jiazhuang (n=1), show compelling evidence for C_3 food in the Central Plains before 2000 BCE, though some of which have an admittedly small number of data. During the subsequent period 2000 - 1000 BCE, however, very few individuals exhibit $\delta^{13}C$ values below ca. -12 ‰, indicating a dramatic shift to millet.

Northwest China is radically different from the Central Plains (Figure 4b) and the isotopic patterns across the different time series between these two regions are almost mirror-like (Liu et al., 2014). Unlike the Central Plains before 2000 BCE, most of the data from Northwest China lie above -12 ‰, indicating a predominantly C_4 diet. At 2000 - 1000 BCE, whilst the Central Plains shows a shift to a remarkable dependence on C_4 ($\delta^{13}C$ < -11‰), Northwest China exhibits an extremely wide isotopic range in both $\delta^{13}C$ (-19‰ to -6‰) and $\delta^{15}N$ (7.5‰ to 17.5‰), suggesting a shift towards C_3, which we argue reflects the replacement of millet with wheat and barley. It is unlikely that, given the associated $\delta^{13}C$ values, the higher values of $\delta^{15}N$ reflect significant marine or freshwater input. Instead, these values are better understood in the context of increasing local aridification and pastoralism (An et al., 2004, 2005; Yang et al., 2019). Comparing Figure 4a and 4b shows that both the Central Plains and Northwest China experienced fundamental dietary changes but in completely different directions (the Central Plains: from a combination of C_3 and C_4 to dominated C_4; Northwest China: from dominated C_4 to a wide range between C_3 and C_4). Also apparent is that the period around 2000 BCE is a critical watershed.

Given the rich archaeological findings in Northern and Southern China and particularly their importance in the history of agricultural development, the current number of stable isotopic data for human bones for these two regions is rather too limited to enable scholars carry out in-depth or broad comparative studies with other regions (Figure 4c and d). For specific time periods for which the dataset is adequate, one can see that Northern China (post-1000 BCE) appears strongly dependent on C_4 (millet) with some mixing with C_3 whilst Southern China is more dominated by C_3 around 3000 - 2000 BCE.

A few clear outliers warrant comment. It is unusual to see collagen $\delta^{13}C$ values as low as ca. -25‰, as here seen at the sites of Jiahu and Tashan (online supplementary material I) ; an exception involves a significant contribution of freshwater resources in some contexts (Schulting, 2018). The $\delta^{15}N$ value exceeding 20‰ at Erlitou can also be highlighted (IA CASS, 2014). The interpretation of these individual outliers requires further analysis and contextualisation, firstly to confirm that they are 'real' (e.g. not misprints or instrument error), and secondly to understand what they mean (e.g. non-locals from regions with very different diets). With the large amount of data, it also becomes possible to readily identify distinct clusters of values that differ from others in the same region/period. For example, while the majority of $\delta^{13}C$ values from the Central Plains between 2000 - 1000 BCE show a predominantly C_4-based diet, a group of values stand out in the lower left part of Figure 4a, suggesting that some people in the Central Plains were still more dependent on C_3-based diets. These individuals come from a variety of sites (e.g. Cai and Qiu, 1984; IA CASS, 2014; others to be found in online supplementary material I), suggesting that predominantly C_3 diets still existed under the strong dominance of C_4 millet during 2000 - 1000 BC in the Central Plains, which raises further questions for more specific research (e.g. Cheung et al., 2017). Of course, their potential misattribution to this period would need to be excluded.

4.2 Spatiotemporal variation in stable carbon isotopic values

The dietary shifts and social significance reflected by the stable isotopic data become much clearer in their geographical context. Figure 5a (Before 3000 BCE) illustrates a "C_3 belt", stretching from the southern Yangtze Delta (Hemudu, Sanxingcui, Tashan, Songze) to the Huai River valley (Gouwan and Jiahu) and the Shangdong peninsular (Xiaojingshan) further north. This isotopic pattern is consistent with the cultivation of rice, with the possible addition of various wild C_3 foods – the inability of stable isotopes on their own to make this distinction is just one of the many areas in which palaeobotanical research makes an important complementary contribution. By contrast, surrounding this C_3-belt a C_4 signal clearly dominates. These elevated $\delta^{13}C$ signatures might be introduced by varying subsistence strategies. Both the Xinglongwa culture in the Northeast and the Dadiwan culture in the Northwest belong to the earliest communities with millet cultivation, whereas the Beiqian site along the eastern coast of Shandong has access to marine foods. All of these subsistence strategies can contribute to the elevation in $\delta^{13}C$. The identification of a C_3-belt emerges from the database. If this phenomenon proves to be real, this suggests that from the perspective of stable isotopes a similar dietary pattern extended from the Yellow River to the Yangtze and challenges the long-assumed "southern rice versus norther millet" division from the historical texts (Zhang et al., 2014). The C_3 belt virtually disappears in 3000 - 2000 BCE.

Caption: Figure 5. Spatiotemporal distribution of human $\delta^{13}C$ values.

The consumption of C_3 crops becomes increasingly marked 2000 - 1000 BCE (Figure 5c), particularly in Northwest China, including several sites along the Hexi corridor and in Xinjiang. The archaeobotanical evidence corroborates that this shift can be attributed to an increasing reliance on wheat (Liu et al., 2014). However, while wheat appears to have been widely accepted in Northwest China, and also to a lesser extent further east, it may have been available to a very restricted group of people in the Central Plains (Cheung et al., 2017). In other words, the Central Plains as a whole show far less interest in incorporating this new crop within the existing system that remained strongly focussed on millet (Boivin et al., 2012; Deng et al., 2020).

It is the subsequent period of 1000 BCE to the Qin Empire (221 - 206 BCE) that finally sees a decline in millet use in the Central Plains (Figure 5d; Li et al., 2020). The Shang Dynasty (ca. 1500 - 1046 BCE) acquired resources from various directions, including copper and tin from Southern China (Liu, 2016; Liu et al., 2019a) and animals such as horses from Northern China (Cao, 2014). This ultimately led to an increase in the movement of people and appears to have been accompanied by an increase in dietary diversity. This pattern may have continued until the Han dynasty but, unfortunately, the current database becomes extremely then so that little further information can be provided for the periods following the Qin Empire (Figure 5e).

The spatiotemporal pattern of the $\delta^{13}C$ data (Figure 5a-e) can be further linked to the broad narrative reflected by Figure 3-4. Millet was the main staple in the Central Plains from the Neolithic to historic times. This is even true for many periods in the Hexi corridor and further west. The two main C_3 crops, rice and wheat, show strong regional importance in Southern and Western China, respectively. Together with other C_3 foods, their movement into the Central Plains result in an increasingly mixed subsistence economy. The most critical period for such transmissions is from 1000 BCE to the Qin Empire, especially the Zhou dynasties (ca. 1045-221 BCE).

4.3 Spatiotemporal variation in $\delta^{15}N$ values

Caption: Figure 6. Plot of human $\delta^{15}N$ values, classified by region as defined in Figure 1 (a. histogram, b. box-and-whisker plot).

The Central Plains show a pronounced peak at 8‰, whereas the distributions from Northern and Northwest China, as well as Southern China, are slightly enriched to 9‰. The Northwest data depicts a visible increase in the frequency of even higher values (between 11 and 16‰) compared with other regions (also see Figure 6b).

Interpretation of $\delta^{15}N$ values is in many ways more complicated than that of $\delta^{13}C$, since it is heavily affected by climatic and environmental factors which can cause changes at the base of the food chain, as well as behavioural factors such as amount of meat and milk consumed or the manuring of crops (Makarewicz and Sealy, 2015). Nevertheless, the likely reason for the relatively high $\delta^{15}N$ values in Northwest China is growing aridity since 6000 BCE (An et al., 2004) and in particular, ~2000 BCE experienced a rapid climatic transition from wet to dry (An et al., 2005). The climatic records of Northwest China and human bone $\delta^{15}N$ values appear to correlate well with one another (Figure 7, see also Chen et al., 2020: Figure 3). There is a clear increase in $\delta^{15}N$ values after 2000 BCE in Northwest China, corresponding to a rapid drying event around that time. Equally important is a stronger pastoral element to the economy in Northwest China compared to the other regions (Yang et al., 2019), which may involve the potential use of dung for manuring (Bogaard et al., 2007). So far, comparable $\delta^{15}N$ values are only seen in Central Asia, which shows similar climatic conditions (Hermes et al. 2018).

Caption: Figure 7. Spatiotemporal distribution of human $\delta^{15}N$ values

5. West meets East: wheat and millet in the prehistory of the Central Plains

Caption: Figure 8. Summary of human stable isotopic data from the Late Neolithic to Early Bronze Age Central Plains (a. site-based distributions of $\delta^{13}C$; b. chronological control of sites listed in a).

The interaction between wheat and millet in the Central Plains is of great interest. It is not just a crucial example of the east-west communication along the prehistoric Silk Road, but an excellent study of how external elements fit into the well-established Chinese system. We hope to further illustrate here how wheat was excluded by millet, or by the underlying ritual system that underpinned Chinese society (Raswon, 2017), even though local environmental conditions are favourable for growing wheat and the political regimes changed from Late Neolithic, Erlitou, Erligang, Anyang and Western Zhou.

The decline of powerful regional centres around the Yangtze and Yellow Rivers in the late Neolithic created a critical window for the rise of the Chinese Bronze Age, represented firstly by Erlitou and then Erligang (Liu and Chen, 2012; Zhang et al., 2019). Around roughly the same time, wheat, bronze and domesticated animals started to appear in the Central Plains. Together with the locally domestically crops such as millet and rice, they made crucial contributions to the rise of an increasingly complex social structure. However, no significant dietary changes have been identified during the transition from the Late Neolithic to the Early Bronze Age in the Central Plains (ca. 2300 - 1000 BCE). The impact of wheat appears less important during this key transition (Deng et al., 2020). Rather, there seems to be a remarkable continuity of the predominance of millet, as clearly illustrated by the persistence of high $\delta^{13}C$ values (Figure 8). Again, whether this was through the direct consumption of millet, and/or through animals fed millet, does not matter for our argument.

Undoubtedly, given the fact that millet was already widely consumed in many Late Neolithic communities of the Central Plains, its dominance appears less likely to be a result of socio-political choice (e.g. the rise of Bronze Age material culture and related changes in technologies and political regimes). In fact, one of the reasons that Erlitou, the first major site of the Chinese Bronze Age, became so successful, is that it combined metallurgy from the steppe with local pottery traditions, as illustrated by a variety of bronze ritual vessels of which the shapes undoubtedly stemmed from Neolithic pottery (Zhang et al., 2019). Presumably, it was the food containers inherited from Neolithic periods that underpinned cooking practices, feasting rituals and basic agriculture, facilitating their retention as part of a tightly interlinked sociocultural, political religious and economic complex in the Bronze Age. In this case, all of the technological, social and political transformations shared the same agricultural basis, which was millet.

6. Conclusions

The most striking feature of subsistence practices in the Central Plains in prehistory is the persistent reliance on millet, which remained virtually unchanged for thousands of years despite changes in political regimes, technology and cultures. This draws a sharp contrast with the widespread uptake of wheat and barley in the west (Liu et al., 2019b). Wheat, though introduced to China at a relative early stage, was only a companion to millet. Such comparative studies can be very effective in understanding the intrinsic characteristics that support the entire system of China. In addition to wheat encountering millet during the Neolithic period, in the later Bronze and Iron Ages, we also see metallurgy as a foreign technology more successfully merged into the Chinese system only after a series of localisation processes led to a remarkable number of distinctive bronze ritual vessels and cast irons (Pollard et al., 2018; Rawson, 2017). Like the stable isotopic data on skeletal remains, the increasing quantities of archaeological data from recent years permit more in-depth studies on interactions between imported elements and local practices and traditions, enabling a better understanding of the cultural DNA of ancient China.

Acknowledgements

This work has been partially supported by FLAME (Horizon 2020 European Research Council Advanced Project 670010 FLAME: Flow of Metal Across Eurasia).

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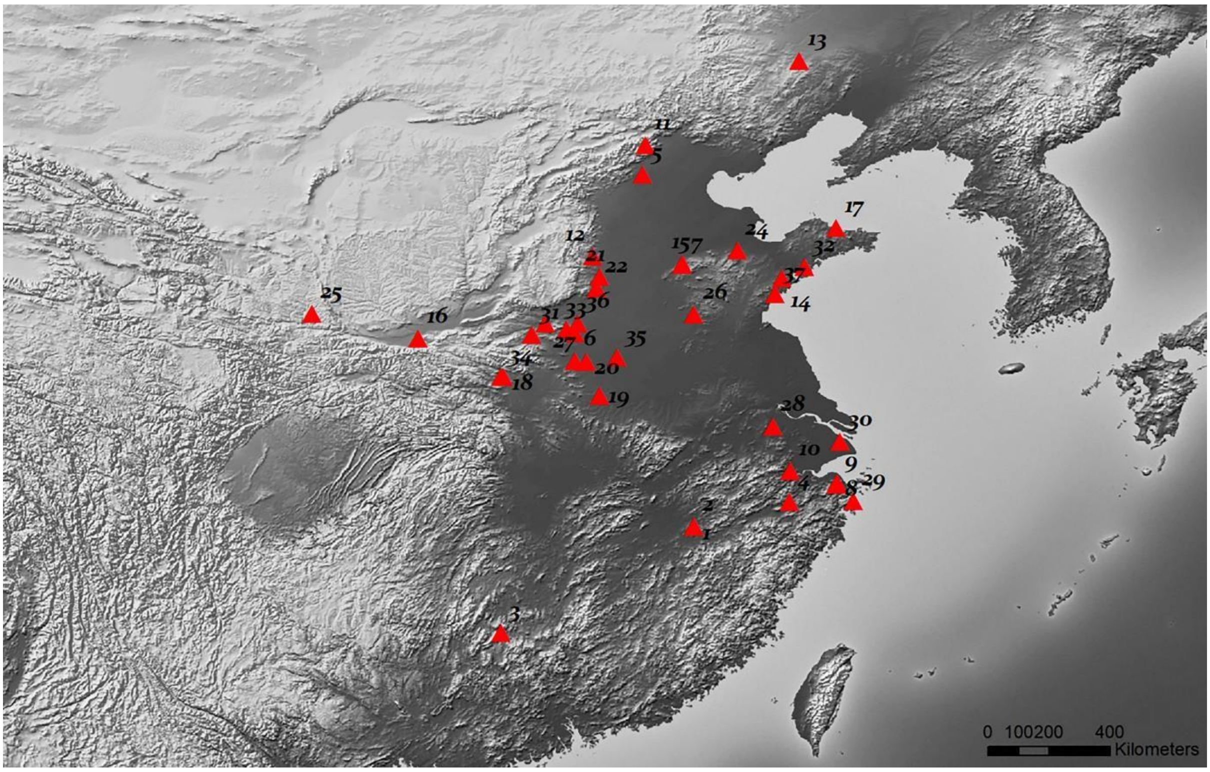

13
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157
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0 100200 400
Kilometers

Figure 1

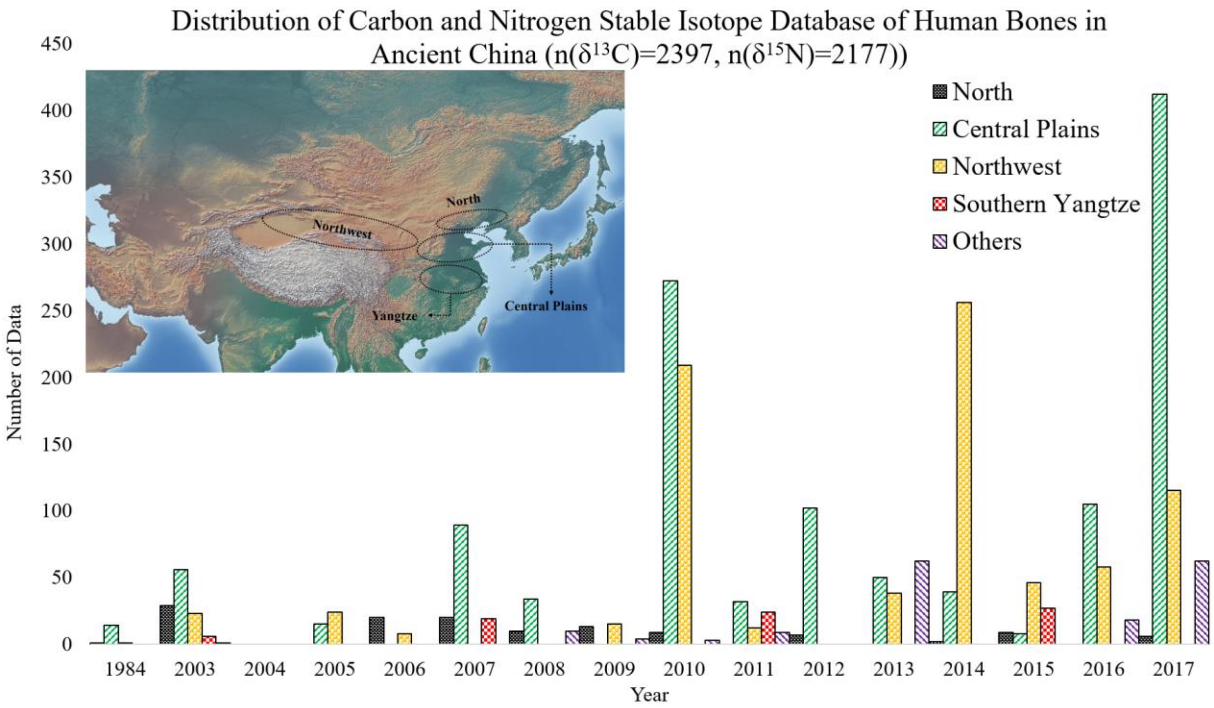

Distribution of Carbon and Nitrogen Stable Isotope Database of Human Bones in Ancient China (n(δ13C)=2397, n(δ15N)=2177))
North
Central Plains
Northwest
Southern Yangtze
Others
Northwest
North
Yangtze
Central Plains
Number of Data
Year
0
50
100
150
200
250
300
350
400
450
1984
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017

Figure 2.

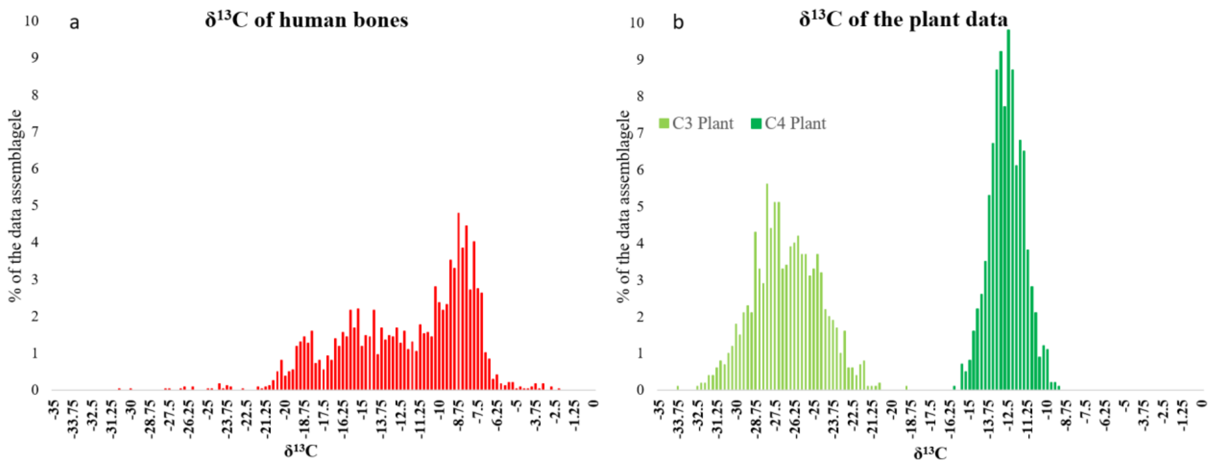

a
δ13C of human bones
% of the data assemblagele
δ13C
b
δ13C of the plant data
C3 Plant
C4 Plant
% of the data assemblagele
δ13C

Figure 3.

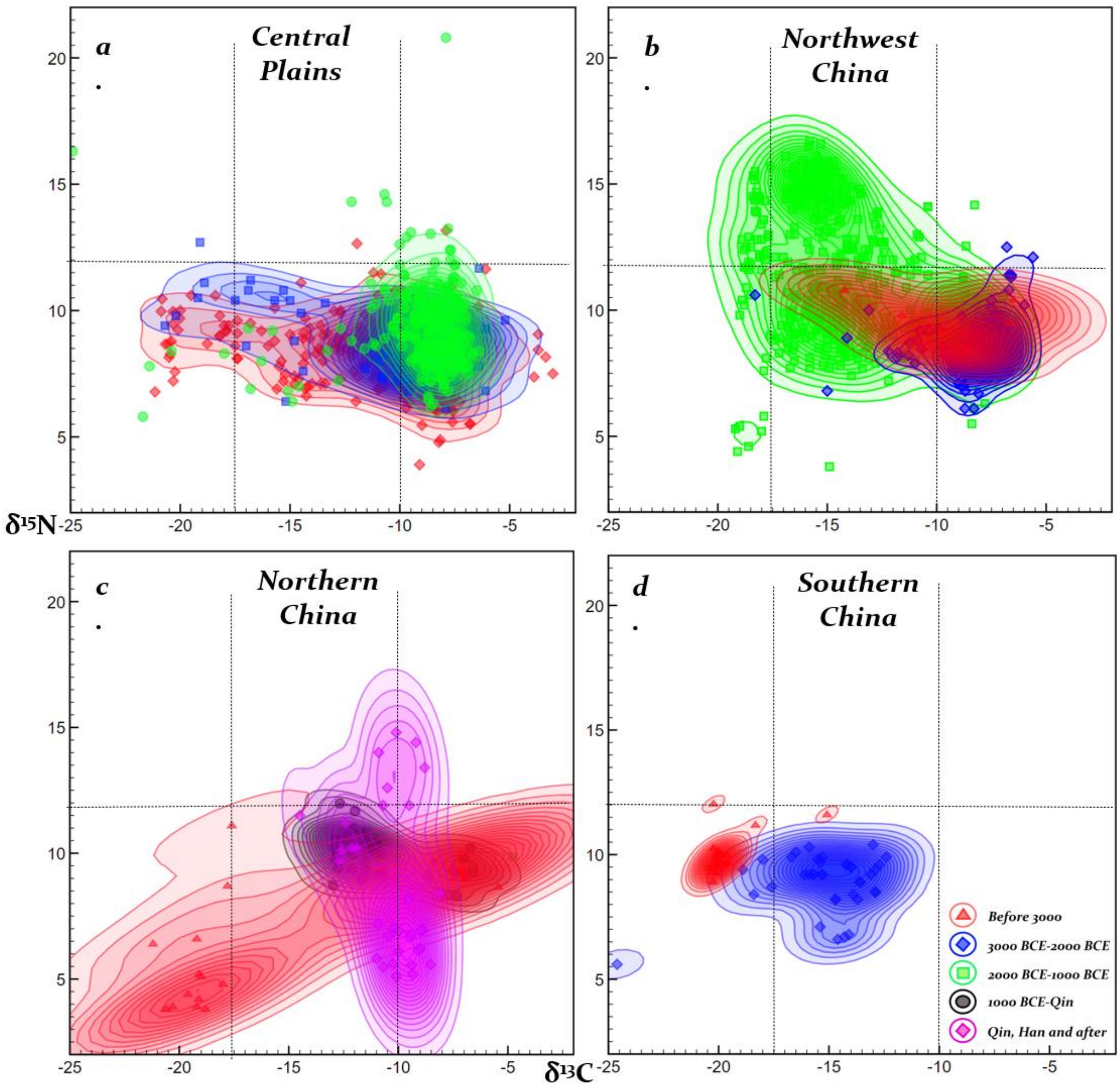

a
Central Plains
b
Northwest China
c
Northern China
d
Southern China
δ15N
δ13C
Before 3000
3000 BCE-2000 BCE
2000 BCE-1000 BCE
1000 BCE-Qin
Qin, Han and after

Figure 4

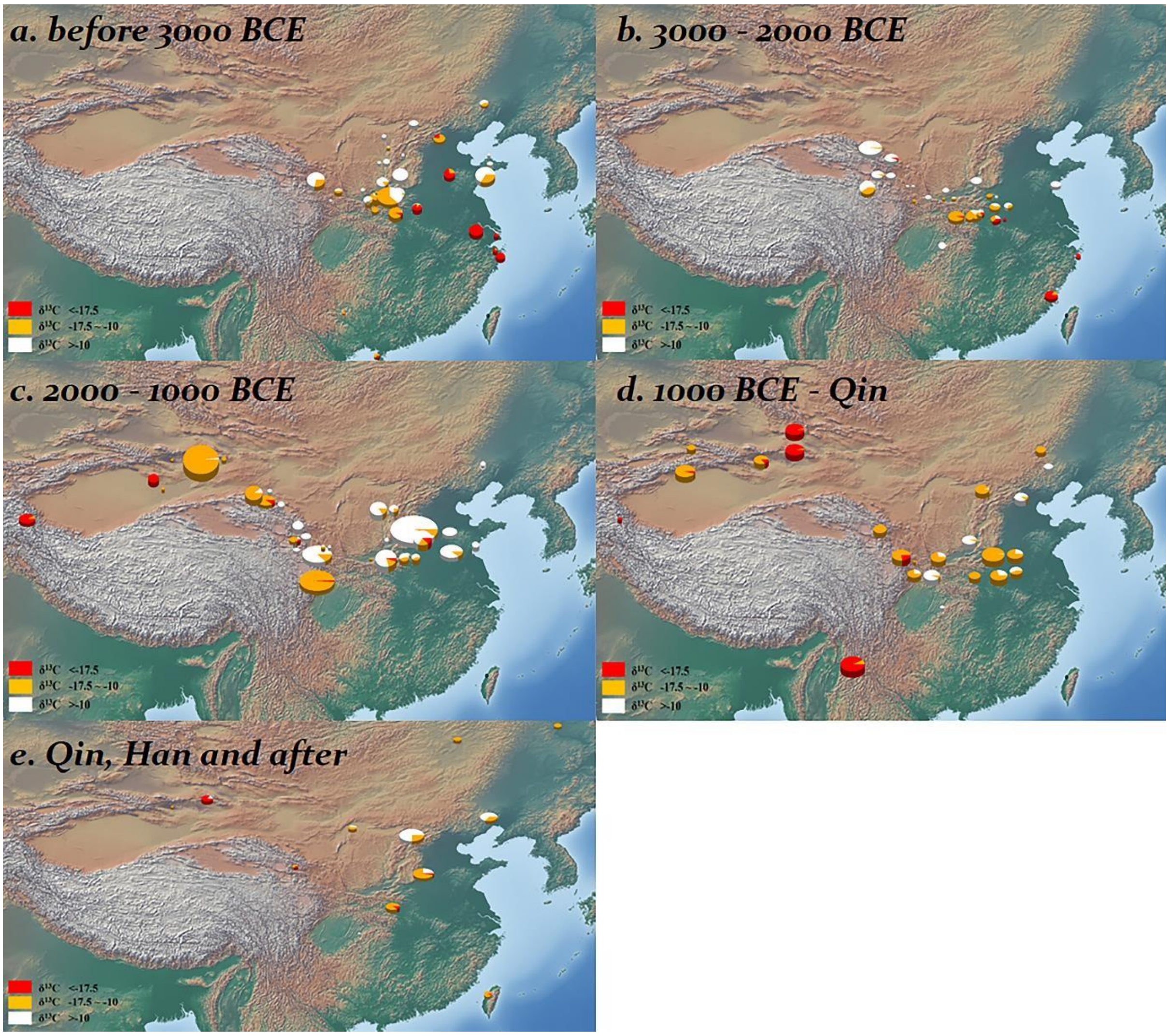

a. before 3000 BCE
δ13C <-17.5
δ13C -17.5 ~ -10
δ13C >-10
b. 3000 - 2000 BCE
δ13C <-17.5
δ13C -17.5 ~ -10
δ13C >-10
c. 2000 - 1000 BCE
δ13C <-17.5
δ13C -17.5 ~ -10
δ13C >-10
d. 1000 BCE - Qin
δ13C <-17.5
δ13C -17.5 ~ -10
δ13C >-10
e. Qin, Han and after
δ13C <-17.5
δ13C -17.5 ~ -10
δ13C >-10

Figure 5

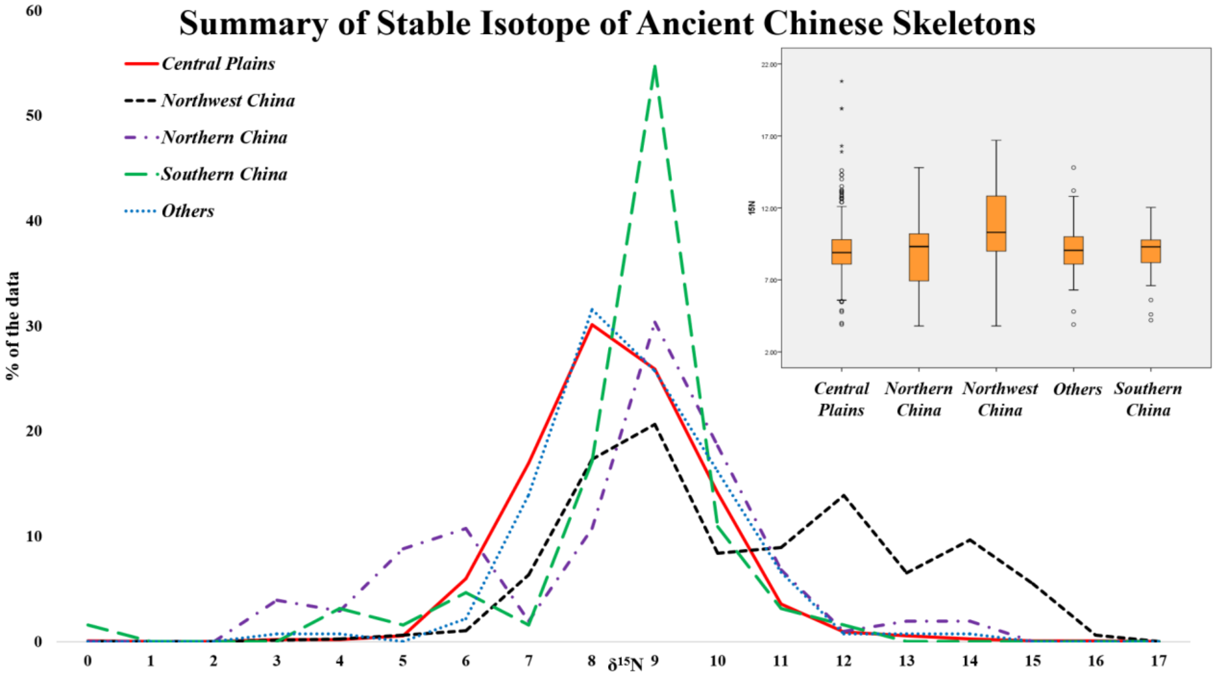

Summary of Stable Isotope of Ancient Chinese Skeletons
Central Plains
Northwest China
Northern China
Southern China
Others
% of the data
δ15N
Central Plains
Northern China
Northwest China
Others
Southern China

Figure 6

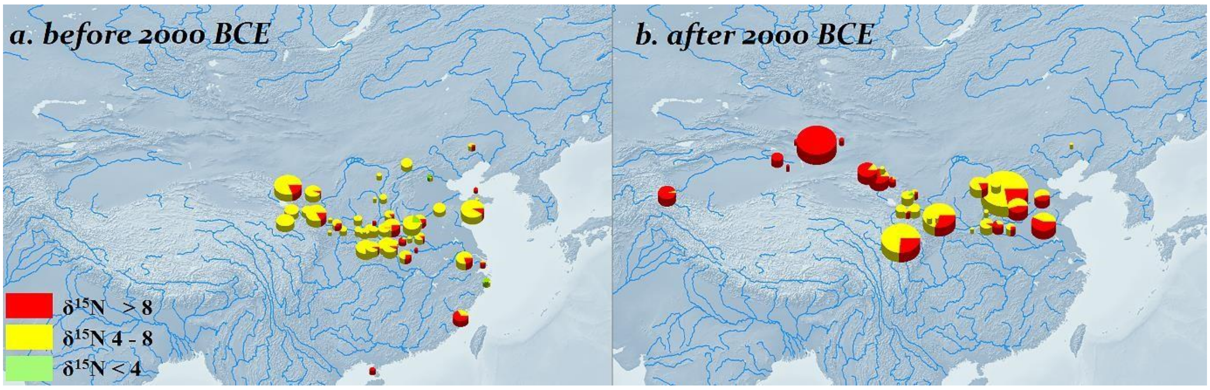
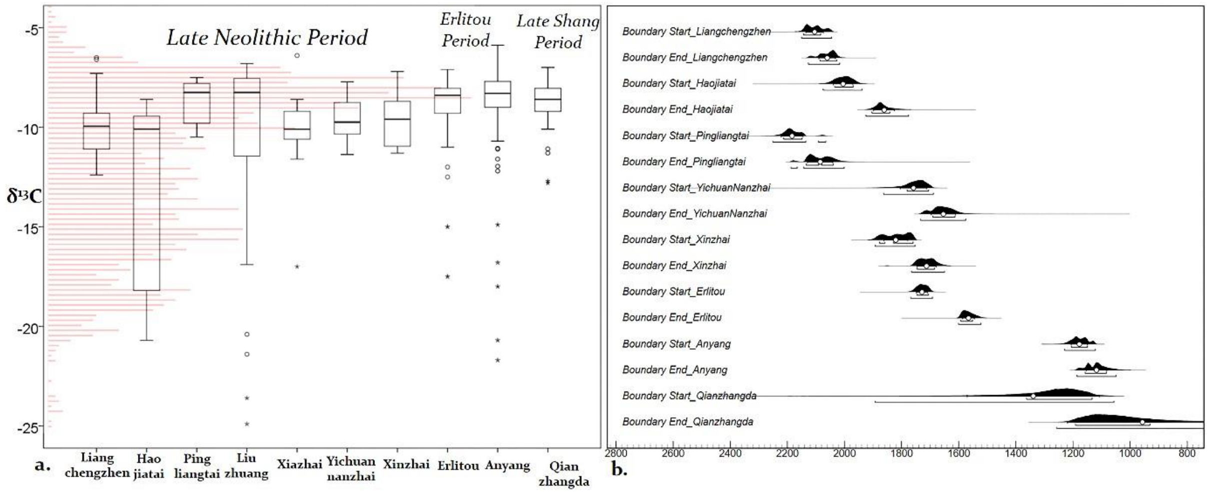

a. before 2000 BCE
b. after 2000 BCE
$\delta^{15}N$ > 8
$\delta^{15}N$ 4 - 8
$\delta^{15}N$ < 4

Figure 7



Late Neolithic Period
Erlitou Period
Late Shang Period
δ13C
-5
-10
-15
-20
-25
a.
Liang chengzhen
Hao jiatai
Ping liangtai
Liu zhuang
Xiazhai
Yichuan nanzhai
Xinzhai
Erlitou
Anyang
Qian zhangda
b.
Boundary Start_Liangchengzhen
Boundary End_Liangchengzhen
Boundary Start_Haojiatai
Boundary End_Haojiatai
Boundary Start_Pingliangtai
Boundary End_Pingliangtai
Boundary Start_YichuanNanzhai
Boundary End_YichuanNanzhai
Boundary Start_Xinzhai
Boundary End_Xinzhai
Boundary Start_Erlitou
Boundary End_Erlitou
Boundary Start_Anyang
Boundary End_Anyang
Boundary Start_Qianzhangda
Boundary End_Qianzhangda
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800

Figure 8