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# Varying cultivation strategies in eastern Tianshan corresponded to growing pastoral lifeways between 1300 BCE and 300 CE

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This study combines plant stable isotope and archaeobotanical analyses to explore how ancient pastoral communities in varying landscapes of eastern Tianshan managed their barley fields. The question is less archaeologically investigated, as recent discussions have focused on pastoral and nomadic activities. Results show that diversified cultivation strategies were employed in barley cultivation at different locations in eastern Tianshan. We also observed a diachronic transition toward less labour-intensive crop management corresponding to a growing pastoral lifeway from the late Bronze Age (1300–800 BCE) to historical periods (400 BCE–300 CE). These results inform us about the mechanism by which southwest Asian originated domesticates were adapted to the Inner Asian environments in the context of the early food globalisation.

KEYWORDS
**isotope, barley, eastern Tianshan, irrigation, manuring, archaeobotany**

## Introduction

In this article, we explore the cultivation strategies employed by ancient communities in the eastern Tianshan foothills between 1,300 BCE and 300 CE. Did the herders carry out intensive barley (*Hordeum vulgare*) cultivation with irrigation and manuring in pastoral-optimal environments? One of the recent developments in Old World archaeology has been the realisation of the movements of cultigens (and livestock) East and West across the Eurasian landmass thousands of years before the historic Silk Route (e.g., Jones et al., 2011; Liu et al., 2019). Accumulating evidence suggests an eastern dispersal of the Fertile Crescent cereals, notably free threshing wheat (*Triticum aestivum*/*durum*) and barley, was paralleled by the western movement of broomcorn and foxtail millet (*Panicum miliaceum* and *Setaria italica*) across the continental interior during the second millennium BCE. Recent analyses ascertained the chronology of the cereal movement (e.g., Liu et al., 2017; Zhou et al., 2020) and established the importance of Inner Asian Mountain Corridors (Frachetti, 2012; Spengler, 2015). However, the mechanism by which novel crops were adapted to the existing agropastoral landscapes remains unclear and is subjected to cultural-specific investigations (e.g., Vaiglova et al., 2020; Li et al., in press).

There has been a considerable recent development in the eastern Tianshan mountains with intensive field investigation and specialist research, resulting in a better understanding of the settlement pattern and subsistence strategies of a series of agropastoral sites commonly referred to as the eastern Tianshan complexity (Ma, 2014; Ma et al., 2014a,b; Xi et al., 2020a,b). These communities were herders with sheep, goats, cattle, and horses who also carried out barley and millet cultivation (Ling et al., 2013, 2016; Li et al., 2020, 2021; Tian et al., 2021a,b). Central to our inquiry is the conceptual conflict between pastoral and cultivation activities and the labour arrangement to facilitate both. Pastoral economies employ extensive labour approaches, in which productivity is driven by the size of herds and the quality and expansiveness of the pastures. Cultivation in traditional farming society, on the other hand, is often limited by land availability, and within this context, productivity is driven by intensive labour input. Recent excavations at eastern Tianshan and burgeoning plant stable isotope analysis provide a unique opportunity to measure the historically less investigated cultivation strategies in pastoral landscapes.

Stable carbon and nitrogen isotope compositions measured in archaeobotanical remains are informative to the plants' growing conditions. Particularly, $\delta^{13}C$ values of $C_3$ plants can help infer crop water status (Farquhar et al., 1989; Araus et al., 1997; Flohr et al., 2011; Wallace et al., 2013). Plant $\delta^{15}N$ values enable the assessment of soil $^{15}N$ enrichment caused by aridity, soil denitrification, and anthropogenic activities such as manuring (Bogaard et al., 2007; Fraser et al., 2011). Macrofossil analysis focusing on weed taxonomy enables insights into field conditions and crop processing (e.g., Hillman, 1984; Stevens, 2003; Harvey and Fuller, 2005). These approaches allow direct assessment of past crop water status and growing conditions, which have shed light on early crop management in Europe, the Middle East, and East Asia (Bogaard et al., 2016, 2018; Styring et al., 2017; Alagich et al., 2018; Li et al., in press). Here we apply a similar approach to the study of agricultural practices in the eastern Tianshan Mountains.

## Eastern Tianshan complexity and the study area

Situated at the easternmost part of the Inner Asian mountain ranges, the eastern Tianshan has been a cultural crossroad since antiquity, connecting the Hexi Corridor and Gobi Desert to the eastern Eurasian Steppe and Inner Asian mountains. In the past decade, intensive field investigations led by a team of archaeologists from Northwest University, Xi'an, revealed abundant archaeological remains from numerous sites dating between 2000 BCE and 1000 CE and transformed our understanding of the region's early history (Ma, 2014). Most sites are found in three counties, Barkol, Hami, and Yiwu, located along the northern slopes of the Tianshan Mountains with altitudes ranging between 1,600 and 2,200 metres above sea level (m.a.s.l.). This region has highly diverse ecosystems, consisting of mountain steppes, coniferous forests, moraine hills, alluvial fans, and saline lakes. Nowadays, the climate is characterised by a relatively short-cool summer (17°C in July on average) and a long-frozen period (−17.5°C in January on average) and is generally considered a semi-arid environment (100–200 mm for annual precipitation) (Zhang, 1993; Liu, 1994). Modern residents practice spring-sown agriculture and seasonal transhumant pastoralism between foothill and mountainous environments.

Isotopic values measured on skeletal remains suggest a $C_3$ plant-based human diet at Shirenzigou during the first millennium BCE (Ling et al., 2013, 2016), although other research has documented millet consumption at other locations in the region (Liu and Reid, 2020). Lacustrine sediments from Lake Tuolekule (also known as Yanchi) and Barkol revealed a gradual contraction of lake areas during the late Holocene (An et al., 2011; Xue and Zhong, 2011). The lake area of Barkol, for example, decreased significantly around 4000 years ago with subsequent a shrinkage occurred around 2000 years ago (Wang et al., 2014).

The study sites in this research can be divided into two phases according to radiocarbon measurements (detailed below): The Bronze and Iron Age (Phase I) occupations date to c. 1300–800 BCE, and the later historical period (Phase II) dates to between c. 400 BCE and 300 CE. Most sites are dated to the earlier Phase I, including sites located on moraine hills (2,000–2,200 m.a.s.l.), such as Shirenzigou IV (Wang et al., 2009), Hongshankou (Ma et al., 2014a), and Kuola (Xi et al., 2020a), and lakeside sites such as Haiziyan at the shore of Lake Barkol (1,600 m.a.s.l.) (Ren et al., 2021) and Yanchigucheng near Lake Tuolekeule (1,950 m.a.s.l.) (Xi et al., 2020b). Those sites consist of stone-built dwellings with compartments enclosed by walls and roofed by wooden and mudbrick structures. Inside the dwellings, fireplaces, and associated ash dumps and trash pits were recovered, together with saddle-shaped grinding stones, stone pestles and hoes, and pottery jars, among other artefacts. Notably, storages with charred barley grains were recovered from Shirenzigou IV and Haiziyan, and archaeobotanical research established the importance of barley cultivation to subsistence (Ma et al., 2021; Ren et al., 2021; Tian et al., 2021b).

Only Shirenzigou III in Barkol is dated to Phase II. The site is fully excavated, including four dwellings (F1, F2, F3, and F4) located on hill slopes between 2,000 and 2,100 m.a.s.l. F1 is the largest stone-enclosed structure (85.5 m × 50 m) and could be the central building of the site (Ren, 2012; Tian et al., 2018). By contrast, other stone structures are smaller semi-subterranean buildings (<100 $m^2$), surrounded by lower and thinner stone walls. This resonates with the hypothesis of growing nomadism during phase II, marked by changing burial customs and horse-riding evidence and unambiguous cultural exchange with the Altai region that has been discussed extensively (Ma, 2014; Ning et al., 2019; Li et al., 2021).

## Materials and methods

### Sampling and archaeobotanical analysis

During the excavations of Shirenzigou IV, Hongshankou, Haiziyan, and Shirenzigou III in Barkol, flotation samples ($n$ = 350, 2,290 L) were collected from different features, including pits, ash dumps, brunt floors, and fireplaces within the dwellings (**Supplementary Tables 2, 3**). Additional soil samples from Yanchigucheng ($n$ = 3, 17 L) and Kuola ($n$ = 3, 23 L) were acquired during a field survey and collected from cultural layers on exposed profiles. All samples were floated using the bucket flotation method described in Pearsall (2016) and Zhao (2010). Light fractions were collected and suspended through a 0.2 mm mesh. Archaeobotanical analysis was subsequently conducted in the Paleoethnobotany Laboratory at Northwest University, Xi'an, China. Analysis followed the laboratory procedure described in Zhao (2010), using seed atlases and taxonomic keys for identification (Wei, 1993; Zhang, 2000; Qiang, 2002; Liu et al., 2008; Ullrich, 2011), as well as the Flora of China online database[1] for taxonomic nomenclature. Considering the varying quantities of samples and differences in contexts at each site, we use calculated density (the number of seed remains per litre of samples) as well as portions in our analysis (Marston, 2015).

### Plant stable isotope analysis

We selected 36 charred barley grains from Shirenzigou VI ($n$ = 10), Haiziyan ($n$ = 10), Yanchigucheng ($n$ = 4), Kuola ($n$ = 2), and Shirenzigou III ($n$ = 10) (each sample consistes of a single charred barley grain). We did not include millet in the isotope analysis as the very small number of millet remains (two broomcorn and one foxtail millet from Shirenzigou III only) precluded the possibility of sampling. After removing visible surface contaminants by gentle scrapings, plant samples were pre-treated with 0.5 M HCl acid for 30 min at 80°C as described by Vaiglova et al. (2014). After freeze-drying, samples were weighed and transferred into tin capsules. Subsequent stable carbon and nitrogen isotopic values were measured using an elemental analyser coupled to a Delta V Plus continuous flow isotope ratio mass spectrometer located at the Biogeochemistry Lab, Washington University in St. Louis. $\delta^{13}C$ and $\delta^{15}N$ values were calibrated relative to VPDB and AIR, respectively, using international standard of USGS 40 ($\delta^{13}C$ = −26.4‰, $\delta^{15}N$ = −4.5‰) and USGS 41a ($\delta^{13}C$ = +36.6‰, $\delta^{15}N$ = −4.5‰) and two in-house standards acetanilide ($\delta^{13}C$ = −29.5‰, $\delta^{15}N$ = +47.6‰) and BR millet (Bob's Red Mill millet flour; $\delta^{13}C$ = −13.2‰, $\delta^{15}N$ = +3.3‰). Following Szpak et al. (2017)'s procedure, the variability of the calibration standards ($S_{srm}$) was determined to be 0.09‰ for $\delta^{13}C$ and 0.17‰ for $\delta^{15}N$. According to the repeated measurements of international calibration standards, check standards, and sample replicates, the precision [u($R_w$)] was determined to be 0.18‰ for $\delta^{13}C$ and 0.43‰ for $\delta^{15}N$, respectively; accuracy [u(bias)] was determined to be 0.11‰ for $\delta^{13}C$ and 0.24‰ for $\delta^{15}N$ based on the difference between the observed and defaulted δ values of the check standards and standard deviations of them. Overall, the standard uncertainty for $\delta^{13}C$ is 0.20‰ and for $\delta^{15}N$ is 0.49‰.

Considering the fluctuation of atmospheric $\delta^{13}C$ values through times, we calculated $\Delta^{13}C_{plant-air}$ values to infer differences in the water status of crops from the study sites (Farquhar et al., 1989). The $\Delta^{13}C$ values were calculated from the determined $\delta^{13}C_{plant}$ values and a $\delta^{13}C_{air}$ value approximated by the AIRCO2_LOESS system (Ferrio et al., 2005), using the equation defined by Farquhar et al. (1989):

$$\Delta^{13}C(‰) = (\delta^{13}C_{air} - \delta^{13}C_{plant})/[1 + (\delta^{13}C_{plant}/1000)]$$

### Accelerator mass spectrometry radiocarbon measurements

We selected fourteen samples, including charred grains, animal bones, and wood charcoal, for radiocarbon ($^{14}C$) analyses at Beta-Analytic based in Miami, USA ($n$ = 11) and Radiocarbon Accelerator Laboratory, Peking University, China ($n$ = 3). The pretreatment methods were similar, with a standard acid-base-acid (ABA) chemical pretreatment method followed by combustion and graphitisation prior to accelerator mass spectrometry (AMS) analyses. All radiocarbon dates were calibrated in OxCal 4.4 (Ramsey, 2017) using the IntCal20 calibration curve (Reimer et al., 2020).

## Results and analytical frameworks

In this section, we shall announce the results of the three methodological strains: AMS radiocarbon measurement, archaeobotany, and stable isotope analysis. We shall also inform the readers about the analytical framework applied in evaluating the results.

## Radiocarbon results and chronology

Accelerator mass spectrometry radiocarbon results are listed in **Figure 1** and **Supplementary Table 1**. Most samples are dated (calibrated) from approximately 1300 BCE to the first centuries CE (**Supplementary Table 1**). Accordingly, study sites can be assigned into two phases, confirming observations based on uncovered archaeological remains. The early phase (Phase I) associated with the Bronze and Iron Ages are dated between ca. 1300 to 800 BCE, and the late phase (Phase II) is dated between ca. 400 BCE and 300 CE.

## Archaeobotanical assemblages

Results of archaeobotanical analyses show that barley (likely six row naked form, *Hordeum vulgare* subsp. *vulgare* L.) was the dominant crop (10,594 grains out of 17,064 total seeds remain count) of all sites in this study. Only two charred broomcorn and one foxtail millet grain are recovered from Shirenzigou III (Tian et al., 2018). Seeds of weedy taxa were also recovered in considerable quantities ($n$ = 4,798) (**Supplementary Tables 2, 3** and **Figures 2, 3**). Wood charcoal is abundant in the assemblages. Weed taxa can be grouped into two categories. First, arable weeds common for agricultural fields such as *Setaria viridis*, *Avena fatua*, *Chenopodium album*, *Medicago* sp., *Silene conoidea*, *Lepyrodiclis holosteoides*, *Vaccaria segetalis*, *Thlaspi arvense*, and *Convolvulus* sp. ($n$ = 2,779). The second group includes weed taxa that are adaptive to well-watered soils, notably, *Galium* sp., *Polygonum* sp., *Medicago* sp., and *Carex* sp. ($n$ = 2,019) may reflect well-watered soils for barley cultivation (Wei, 1993; Qiang, 2002; Ullrich, 2011; Motuzaite Matuzeviciute et al., 2020). Other plant taxa, for example, *Astragalus* sp., *Melilotus* sp., *Corispermum* sp., *Artemisia* sp., *Nitraria* sp., etc., have also been recovered in these assemblages.

## Plant isotope compositions

Carbon and nitrogen isotope compositions ($\delta^{13}C$ and $\delta^{15}N$ values) measured as well as converted $\Delta^{13}C_{plant-air}$ values are reported in **Supplementary Table 4**. We follow Wallace et al. (2013)'s interpretative framework of the barley isotope composition based on modern experiments in the semi-arid Eastern Mediterranean to infer the water status of past crops. The original thresholds between "poorly watered" and "moderately watered" (17‰ for barley), and between "moderately watered" and "well-watered" (18.5‰) are refer as "Optimal Watering Threshold" (OWT) and "Superfluous

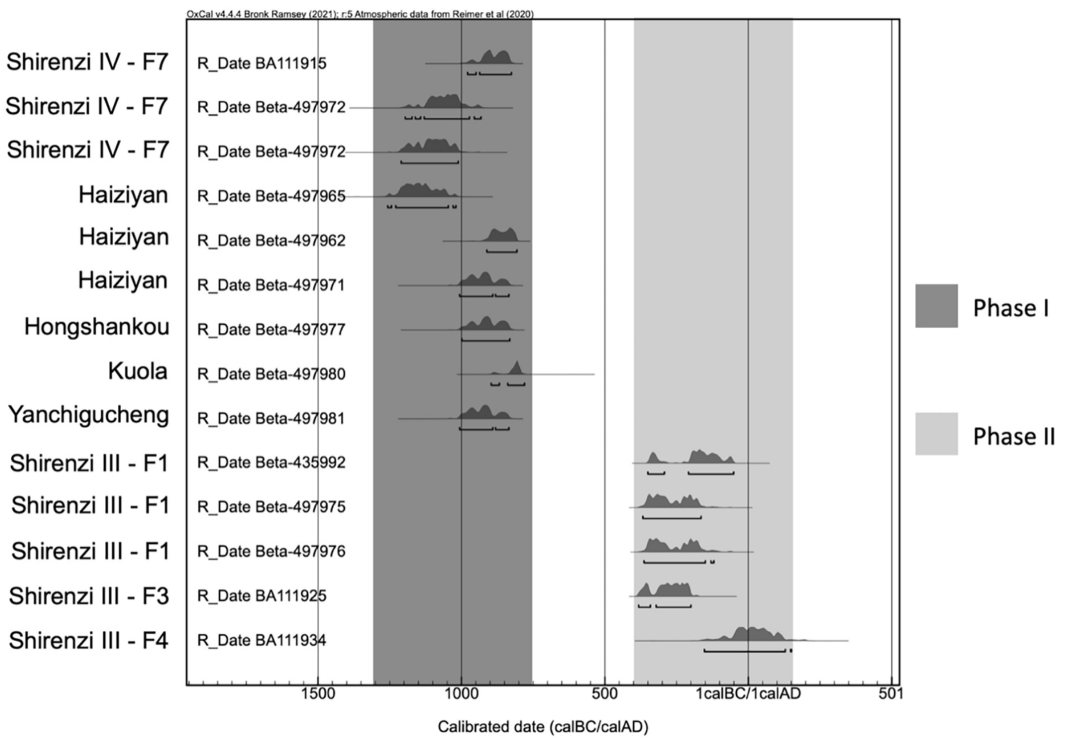


FIGURE 1
Accelerator mass spectrometry (AMS) radiocarbon results generated by this study together with previously published $^{14}C$ measurements as detailed in **Supplementary Table 1**. These results confirm the two occupational phases of the eastern Tianshan complexity (ETC) sites.

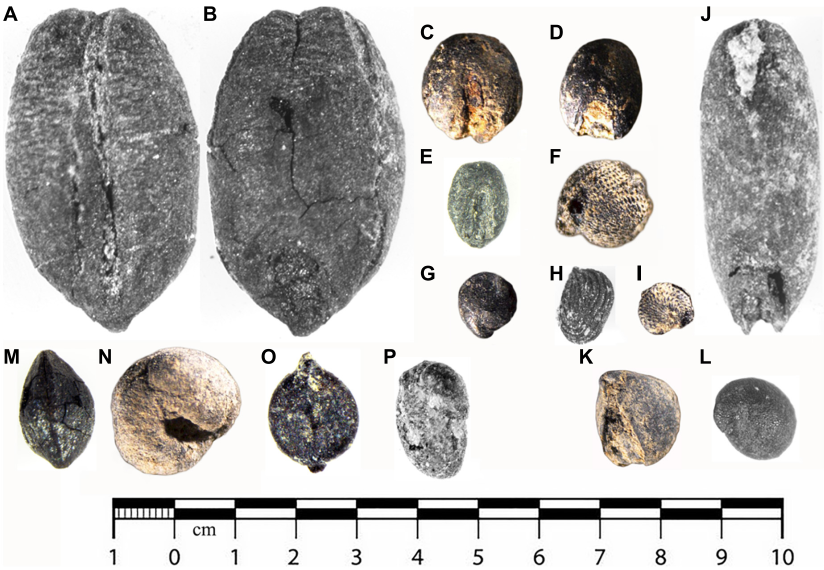


FIGURE 2
Charred grains recovered from excavated eastern Tianshan complexity (ETC) sites. **(A)** *Hordeum vulgare* (ventral side) and **(B)** *Hordeum vulgare* (dorsal side) from barley cache at Shirenzigou IV F7; **(C)** *Setaria italica* from Shirenzigou III F1; **(D)** *Panicum miliaceum* from Shirenzigou III F1; **(E)** *Setaria viridis* from Shirenzigou III F1; **(F)** *Lepyrodiclis holosteoides* from Shirenzigou III F1; **(G)** *Chenopodium album* from Shirenzigou III F1; **(H)** *Thlaspi arvense* from Shirenzigou III F4; **(I)** *Silene conoidea* from Shirenzigou III F1; **(J)** *Avena fatua* from Haiziyan; **(K)** *Convolvulus* sp. from Shirenzigou III F1; **(L)** *Vaccaria segetalis* from Haiziyan; **(M)** *Carex* sp. from Shirenzigou IV F7; **(N)** *Galium* sp. from Shirenzigou III F1; **(O)** *Polygonum* sp. from Haiziyan; **(P)** *Medicago* sp. from Shirenzigou III F1.

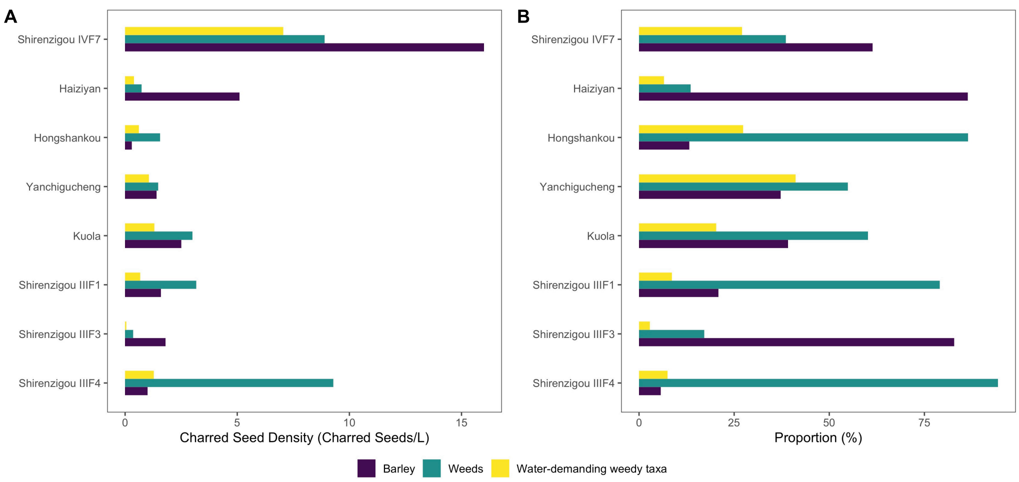


FIGURE 3
The density **(A)** and proportion **(B)** of charred barley (purple), weeds (including arable weeds and water-demanding weeds, green), and water-demanding weeds (yellow) recovered from eastern Tianshan complexity (ETC) study sites.

Watering Threshold" (SWT), respectively. In order to assess the manuring condition of archaeological barley, we established a local vegetation baseline of c. 2.8‰ by using average $\delta^{15}N$ values of archaeological herbivores' collagen and subtract 4.5‰, the average offset between contiguous trophic levels (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Ling et al., 2016).

Figure 4A displays the variances of $\Delta^{13}C$ values of different sites. A considerable number of barley samples ($n$ = 24) are below OWT—Shirenzigou III ($n$ = 6) and Haiziyan ($n$ = 8)—signifying water stress during plant growth. Shirenzigou IV and Kuola samples display a much better water condition as most samples are above the OWT threshold ($n$ = 8 for Shirenzigou IV and $n$ = 2 for Kuola). The altitude effect on

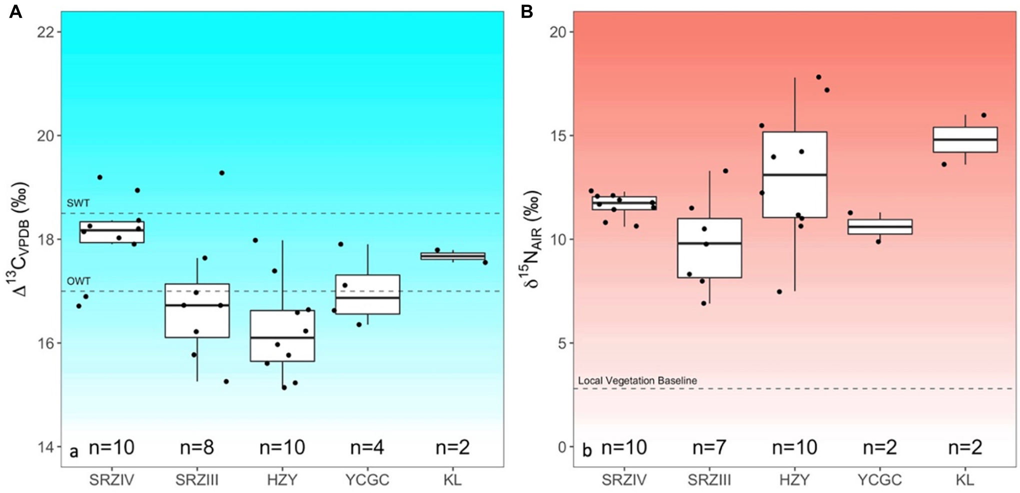


FIGURE 4
**(A)** $\Delta^{13}$C and **(B)** $\delta^{15}$N values measured in charred barley grains from eastern Tianshan complexity (ETC) sites. Dashed lines represent the threshold of "Optimal Water Status" (OWT) and "Superfluous Water Status" (SWT) for barley (Wallace et al., 2013; Vaiglova et al., 2020), and the estimated $\delta^{15}$N baseline of local vegetation using average $\delta^{15}$N values of archaeological herbivores (Ling et al., 2016).

the $C_3$ plants may apply due to changes in atmospheric pressure and high carboxylation efficiency at high altitudes leading to foliar $^{13}$C depletion (Körner and Diemer, 1987; Morecroft and Woodward, 1990). However, the pattern is largely driven by taxonomic combinations rather than foliar $\delta^{13}$C variations within single species (Szpak et al., 2013). Currently, there are no available data to evaluate the altitude effect of barley. Given the ETC sites are located around 2,000 m.a.s.l. We estimate the OWT and SWT thresholds would be slightly higher than what Wallace and colleagues established originally, making the observed "water stress" more pronounced. Since our interpretations are based on large relative differences between sites at similar evaluations, the altitude effect is not deemed meaningful.

Turning to $\delta^{15}$N values, **Figure 4B** demonstrates that all samples yield significantly higher $\delta^{15}$N values than the local vegetation baseline. The large variations of $\delta^{15}$N values, both between and within sites, suggests a variably but universally favorable nutrient supply of barley cultivation in this region.

# Discussion

We will next consider the temporal and spatial patterns of barley cultivation in eastern Tianshan. We will first focus on changes in cultivation strategies through time. This is most clear at Shirenzigou. With its long-term occupational history, different sites at Shirenzigou offer insights into changes in subsistence strategies between the prehistoric and historical periods (Phase I and II). Secondly, as study sites are situated in markedly different environments, we shall explore the potential distinctions at the hill sites (Shirenzigou, Hongshankou, and Kuola) compared to areas near the lakes (Haiziyan and Yanchigucheng).

## Changing cultivation strategies between 1300 BCE–300 CE

The isotopic results show a clear difference in water management and potentially soil preparation between the early and late occupational phases of Shirenzigou. The site has been central to archaeological investigations as one of the largest settlements in eastern Tianshan. Previous research revealed an increase in nomadic lifeways from the late Bronze Age to the historical period (Ma, 2014; Ma et al., 2014b). The two localities under investigation, Shirenzigou IV (SRZIV) and Shirenzigou III (SRZIII) were occupied during Phase I (1300–800 BCE) and Phase II (400 BCE–300 CE), respectively (**Figure 1**). This provides an opportunity to explore changes through time.

Most of the barley grains from the Bronze Age SRZIV display $\Delta^{13}$C values above the OWT (**Figure 5A**), indicating that their growth was not limited by water availability. Barley is adapted to arid environments since it is drought-resistant and is the pivot crop of rainfed agriculture in southwestern Asia (e.g., Riehl, 2012). In the eastern Tianshan, where the climate is dry, no evidence for enhanced precipitation is attested in palaeoclimatic records for the investigated period (Xue and Zhong, 2011; Wang et al., 2014). For this reason, the high-water status of barley crop observed isotopically at Shirenzigou could not be achieved without artificial water management. This doesn't necessarily mean channel irrigation (such evidence is absent archaeologically). Barley could be

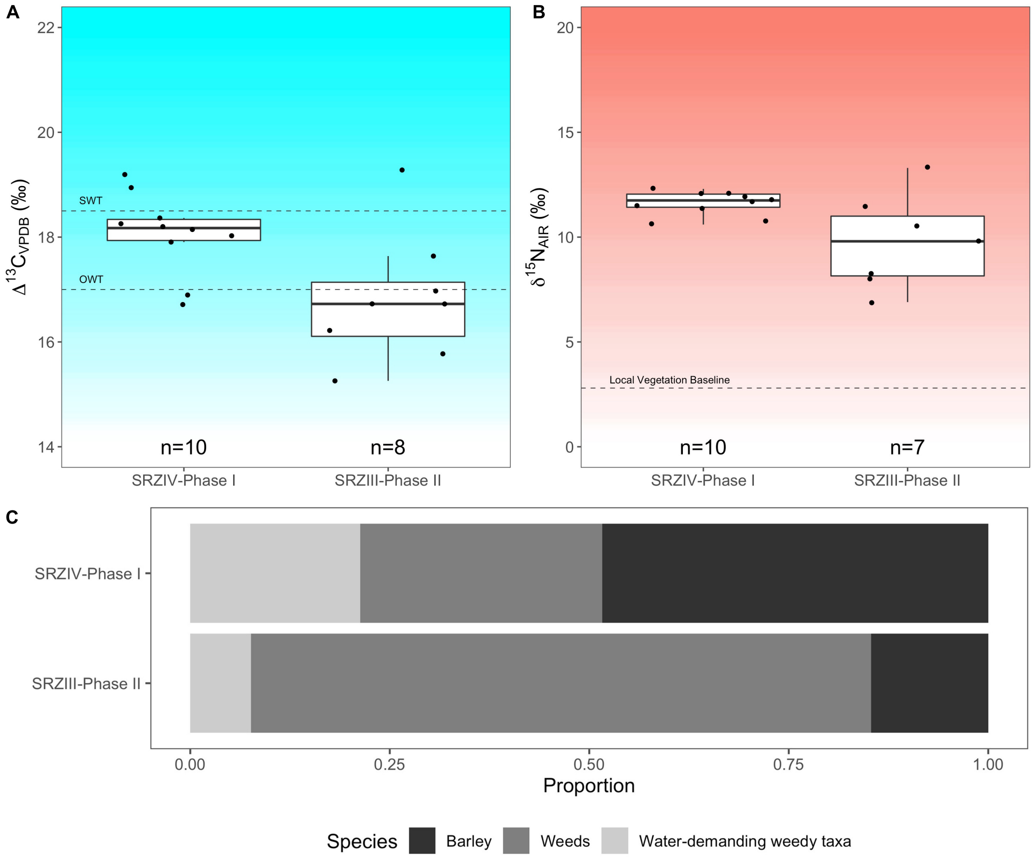


FIGURE 5
**(A)** $\Delta^{13}C$ and **(B)** $\delta^{15}N$ values of archaeological barley recovered from Shirenzigou IV of Phase I and Shirenzigou III of Phase II; **(C)** proportion of barley, arable weeds (excluding water-demanding weeds) and water-demanding weeds in the archaeobotanical assemblages of Shirenzigou IV (Phase I) and Shirenzigou III (Phase II).

strategically sown in areas with high water retention close to runoffs of snowmelts perhaps with small ditches to diffuse water or more sophisticated management of snowmelts at higher elevations with human or animal labour. In contrast, barley remains from the historical SRZIII show unambiguous water stress, with the plant development being limited by water availability (as $\Delta^{13}C$ values below the OWT). This suggests that barley crops in the later occupational phase were either less watered or sown at drier locations than in the Bronze Age.

A similar diachronic change, though less clear, is seen in barley $\delta^{15}N$ values at SRZIV and SRZIII (**Figure 5B**). Crop $\delta^{15}N$ values reflect nitrogen isotope compositions of the soil in which they are grown. The system is driven by nitrogen cycle openness and mycorrhizal associations that appear to be the dominant factors controlling nitrogen isotope variation in plants and soils (Szpak, 2014). In this context, soil $^{15}N$ enrichment can be caused by a host of both environmental factors (e.g., nutrient status, salinity, topography, water saturation, etc.) and anthropogenic factors (e.g., Vaiglova et al., 2020). The latter has received much archaeological attention concerning application of animal manure has been found to increase the $\delta^{15}N$ values of soil and crops significantly (e.g., Bogaard et al., 2013). Barley $\delta^{15}N$ values from SRIV and SRZIII display wide ranges. This observation suggests that crops were cultivated in variable soil conditions in both periods, which could result from several natural causes and the manuring effect combined (Groffman and Hanson, 1997; Finlay et al., 2008; Fraser et al., 2011; Styring et al., 2016). As barley grains from both sites display $\delta^{15}N$ values significantly higher than the local vegetation baseline, anthropogenic activities such as the application of animal manure or organic waste likely contributed to the soil $^{15}N$ enrichment. Otherwise, we expect the nitrogen isotope values to be closer to the baseline. Although natural causes (e.g., soil denitrification or aridity) cannot be excluded, the difference between SRZIV and SRZIII might indicate that barley fields were less manured during Phase II compared to Phase I. This resonates with the plant water status discussed above, suggesting less labour input/care in agricultural fields in a later phase.

The archaeobotanical results seem to support such a conclusion further. Tian et al. (2021a) observed a change

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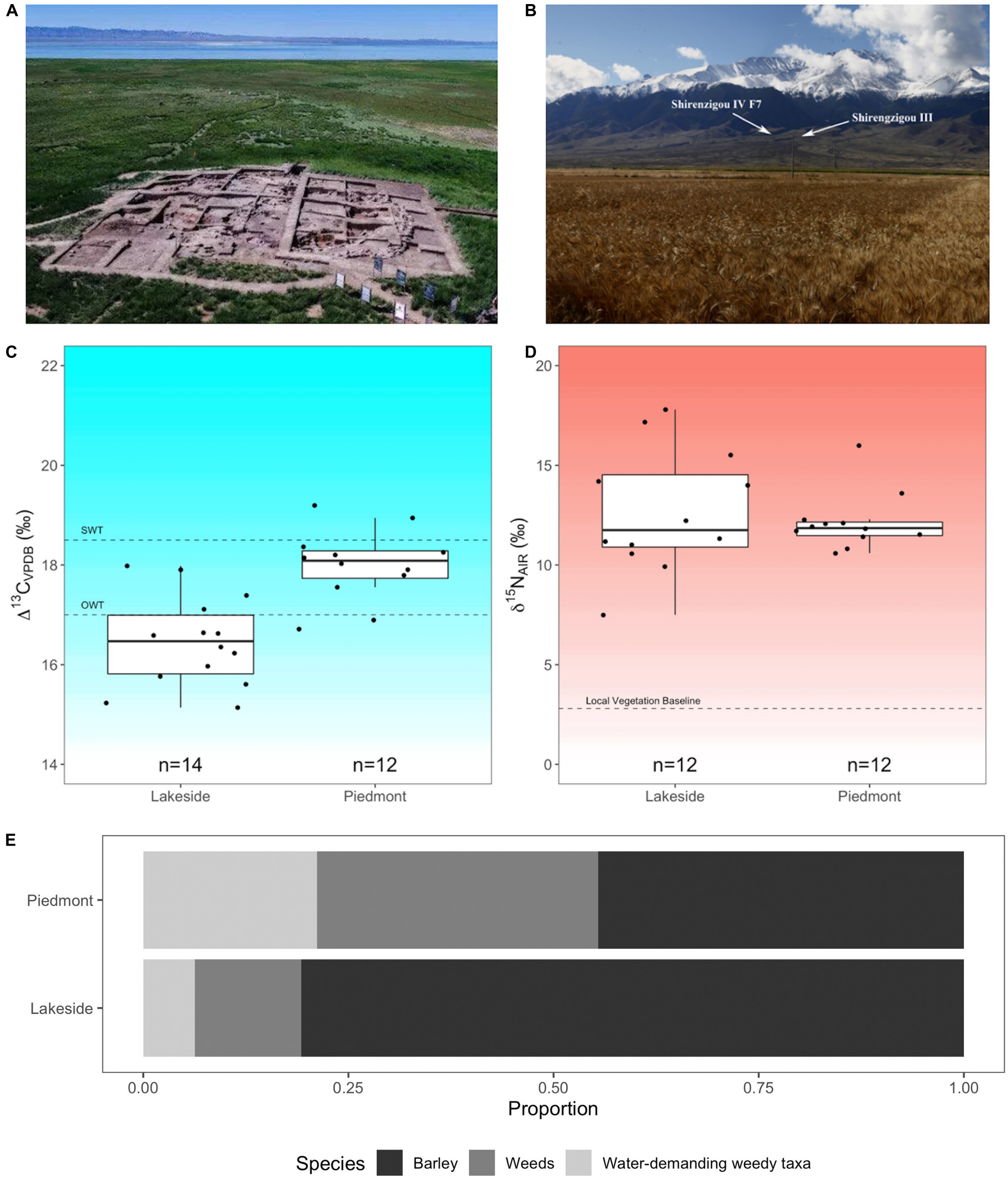


FIGURE 6
**(A)** The typical landscapes of Bronze Age lakeside sites (the excavation area of Haiziyan in 2017) and **(B)** piedmont sites (the piedmont landscape of Shirenzigou) in the eastern Tianshan region; **(C)** $\Delta^{13}C$ and **(D)** $\delta^{15}N$ values of archaeological barley from lakeside (Haiziyan, Yanchigucheng) and piedmont sites (Shirenzigou IV, Hongshankou, Kuola); **(E)** proportion of barley, arable weeds (excluding water-demanding weeds) and water-demanding weeds uncovered from lakeside and piedmont sites.

in weed abundance through time, with a lower weed/barley ratio in the Bronze Age and a higher weed/barley ratio in the historical period. While the density of weeds decreases over time (**Figure 3**), their proportional input increases from the early to the late period (**Figure 5C**). The proportional input of water-demanding weeds decreased over time echoing the observation of less irrigation as suggested by carbon isotope compositions. It should be noted that this observed pattern could be driven by crop processing with increases in post-harvest and pre-storage labour biasing toward higher weed/barley ratios and higher weed proportion as the grains were removed

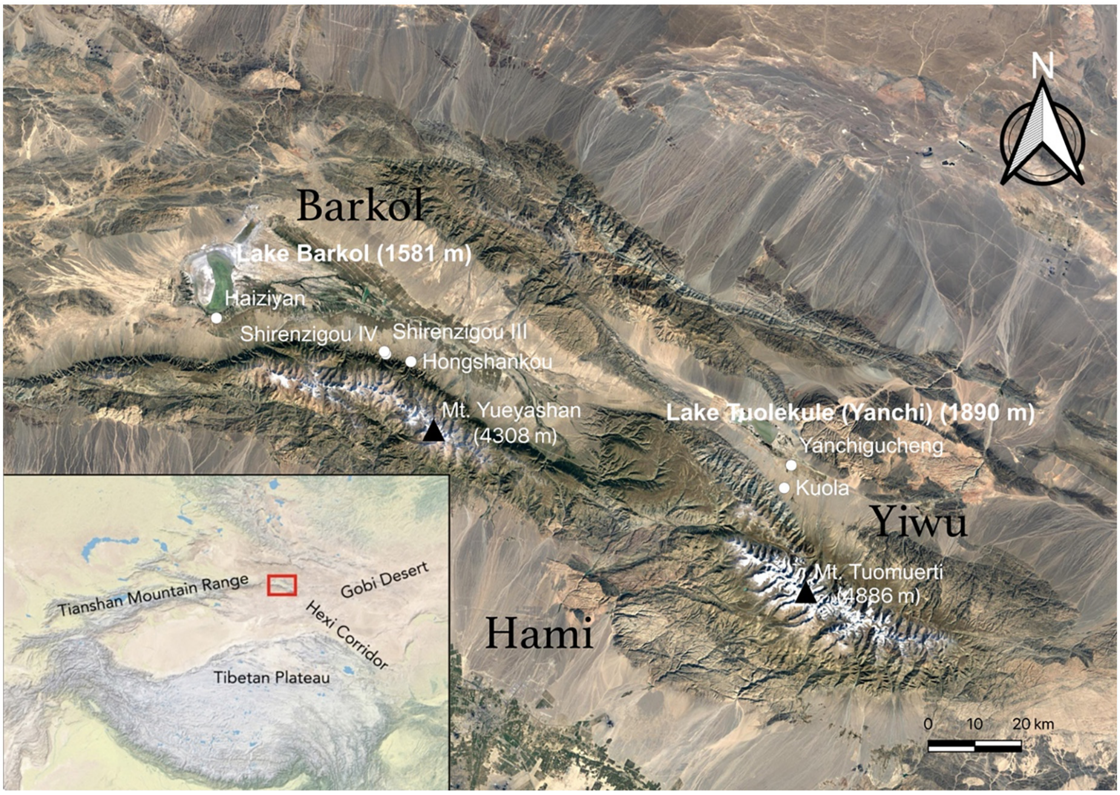


FIGURE 7
The locations of Shirenzigou IV (SRZ IV, 2,140 m.a.s.l.), Shirenzigou III (SRZ III, 2,200 m.a.s.l.), Haiziyan (HZY, 1,600 m.a.s.l.), Yanchigucheng (YCGC, 2,020 m.a.s.l.), Kuola (KL, 2,200 m.a.s.l.) and Hongshankou (HSK, 2,200 m.a.s.l.) in the eastern Tianshan region. The lowest and highest elevations of Barkol are at Lake Barkol (1,581 m.a.s.l.) and Yueyashan (4,308 m.a.s.l.), respectively. The lowest and highest elevations of Yiwu are at Lake Tuolekule (1,890 m.a.s.l.) and Tuomuerti (4,886 m.a.s.l.), respectively. Maps were generated using ArcMap v. 10.2 with data credit to National Park Service Natural Earth physical map (public domain).

for consumption (Stevens, 2003) or due to the scale of processing and/or producer/consumer status of the site (Jones, 1985; Van der Veen and Jones, 2006). Future research considering assemblage formation processes in contexts will guide our understanding. A definitive conclusion cannot be reached with the current available evidence. However, an alternative interpretation of the high weed proportion and weed/barley ratio at historical SRZIII is less pre-harvest labour, such that fewer weeding activities led to higher weed ubiquity in the assemblage. This possibility supports the isotopic results, suggesting less labour investment in field conditions before the harvest with regards to irrigation, manuring, and weeding. The decrease of water-demanding weed taxa (**Figure 5C**) over time could also be understood in the context of reduced irrigation.

In modern-day eastern Tianshan, spring-sown wheat is an important crop cultivated on the alluvial landscape with channel irrigation. This is an extensive system. According to local residences, each household (2–4 family members) is responsible for more than 10,000 square metres of arable land. As such, labour deficiency restrains intensive field activities such as weeding, and many weeds can be observed in the fields during the growing season.

## Field management system between lakeside and foothill site

As discussed, the study sites are situated in markedly different environments, including areas on the piedmont hills such as the Shirenzigou group, Hongshankou, and Kuola and sites near the lakeshores Haiziyan and Yanchigucheng (**Figures 6, 7**). Barley grains from lakeside sites display significantly lower $\Delta^{13}C$ values (below OWT) than barley from the hill sites (**Figure 6**). The lower $\Delta^{13}C$ values at the lakeside sites could be the results of high soil salinity near the saline Lake Barkol and Tuolekule. Controlled experiments show that increases in soil salinity correspond to reducing the leaf stomatal conductance, resulting in lower $\Delta^{13}C$ values and yield (Isla et al., 1998). In addition to the high soil salinity, lakeside sites are located on flat terrains at distances to the foothill runoffs or springs, making irrigation more difficult. Combined, agricultural fields near the lakes were likely more water-stressed.

In contrast, barley samples from piedmont hill sites yield $\Delta^{13}C$ values that are mostly above OWT (with two exceptions). Some samples are even above SWT (**Figure 6**). This suggests barley crops from those sites were well-watered. These results enable an observation of distinct cultivation strategies concerning water regimes (including both irrigation and strategic planting in soils with high water retention) at the piedmonts and lakeshores.

This observation resonates with the archaeobotanical results, suggesting a difference between the environmental conditions of barley fields by the lakeside and on the foothills. The densities of barley grains, weeds, and water-demanding taxa in the piedmont sites (Shirenzigou IV F7, Kuola, and Hongshankou) all outnumber their counterparts on the lakeside (Haiziyan and Yanchigucheng, **Figure 3**). The proportions show a different pattern with arable and water-demanding weeds are lower at the lakeside in comparison to the piedmont sites. The percentage data are subject to further scrutiny considering assemblage formation as grain/weed ratio typically reflect crop processing activities rather than field condition (e.g., Stevens, 2003; Van der Veen and Jones, 2006). That issue aside, some arable weeds are informative to crop growing conditions and can provide complementary information (e.g., Bogaard et al., 2016). It is noticeable that water-demanding taxa such as *Carex, Galium, Polygonum,* and *Medicago* are more ubiquitous in the piedmont assemblages compared to the lakeside assemblages (**Figures 3**, **6E**). *Carex,* in particular, is sometimes seen as an indicator of field irrigation due to its adaptation to open and well-watered soils (Rühl et al., 2015; Motuzaite Matuzeviciute et al., 2020).

The isotopic and archaeobotanical evidence, therefore, suggests two distinct barley cultivation strategies co-existing in eastern Tianshan. Barley crops were grown in stressful conditions near the saline lakes, while crops were relatively well-looked after in the piedmont zone. As mentioned, archaeologically visible irrigation channels are absent in this region, but water management can be achieved by small-scale modifications or strategic planting without leaving traits in projected archaeology. Ethnographic records in Tuva, for example, demonstrated the application of simple channels for irrigating fields among southern Siberian pastoralists (Vainshtein, 1980). Some piedmont fields in modern-day Barkol are irrigated by simple ditches bringing glacial water from the top of the mountain.

## Conclusion

The data presented in this paper allows two inferences. First, our results indicate that different cultivation strategies were employed at different ecosystems. Plant isotope results show, unequivocally, water management at hill sites to meet barley's growing demand in an otherwise arid environment. However, barley fields near the lake shores were stressed due to soil salinity.

The second inference concerns changing cultivation strategies over time. Stable carbon and nitrogen isotope compositions and archaeobotanical results combined suggest a shift in barley cultivation from the Bronze Age to the historical period manifested by the difference between SRZIV and SRZIII. The former likely represents a labour-intensive system with water management, application of animal manure or midden for soil improvement, and potentially frequent weeding activities during 1300 BCE and 800 BCE. The latter is associated with an extensive cultivation strategy with diminished input in irrigation, manuring, and weeding between 400 BCE and 300 CE, corresponding to the development of nomadic lifeways during this time that has been discussed elsewhere (Ma, 2014; Ning et al., 2019; Li et al., 2021).

These findings shed light on an extensification trend of barley cultivation from the late Bronze Age to the historical period. During this later period, with communities increasingly relying on pastoral activities as the main subsistent strategies, intensive cultivation with high labour input per area seen in the Bronze Age was partially diminished. The latter was given way to an extensive approach in which productivity is driven by the size and expansiveness of herds, pastures and cultivation, a trend that has been speculated by scholars but we provided tangible evidence here. Of course, there are limitations. We began our interpretation with carbon isotope evidence that is quite clear; the nitrogen isotope compositions also present clear trends but are more enigmatic in distinguishing natural and anthropogenetic drivers; the archaeobotanical data, however, has more than one interpretation. This is where the ambiguity begins, and we draw attention to the value of context-based assemblage formation process in future research.

## Data availability statement

The original contributions presented in this study are included in the article/**Supplementary material**, further inquiries can be directed to the corresponding authors.

## Author contributions

XLiu, DT, and YS conceptualised the research with MMR's contribution and wrote the draft which was read and further edited by all authors. YS, XLing, and XLiu conducted the isotopic analysis. DT and ZZ carried out macrofossil analysis and sample selection. TX, MRen, JM, and JW led excavations and archaeological surveys. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2022.966366/full#supplementary-material

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