Cattle and sheep raising and millet growing in the Longshan age in central China: Stable isotope investigation at the Xinzhai site

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ARTICLE INFO

ABSTRACT

Previous bone collagen stable isotope analyses conducted on faunal remains from archaeological sites from the Late Neolithic (Longshan) to the Bronze Age (Xia dynasty) in the Central Plains of China have revealed that C_4 plants — most probably cultivated millets — constituted a major part of cattle fodder and also contributed to sheep diet, although to a lower extent. In the present study, this difference between cattle and sheep diet management was investigated at the Xinzhai site (occupation phases 2 and 3, ca. 1800—1705 cal. BC), focusing on the seasonal scale through sequential $\delta^{13}C$ and $\delta^{18}O$ analysis in tooth enamel. This primary objective related to the reconstruction of Bronze Age husbandry practices required an effort in interpreting $\delta^{18}O$ sequences recovered from cattle and sheep molars: potential difficulty in the identification of the seasonal cycle could rise, inherent to a specific climatic regime. This region of China is nowadays under the influence of the East-Asian summer monsoon, whose strength undergoes variability on the annual scale, but also did in the past on decadal to century scales. At Xinzhai, all sheep teeth and one deer tooth delivered $\delta^{18}O$ sequences comparable to previously published sequences from locations were rainfall $\delta^{18}O$ is temperature controlled (no monsoon influence), revealing minimal influence of the summer monsoon over these animals' lifetime. Some cattle teeth delivered sequences with bimodal distribution of $\delta^{18}O$ values on the annual scale, potentially reflecting the influence of a summer monsoon. Such variability among domestic stock could relate to interannual/interdecadal variability in the monsoon intensity at the site location, or to differences in herding practices between sheep and cattle. Concomitant analysis of $\delta^{13}C$ values in deer molars confirmed a surrounding wild environment dominated by C_3 plants throughout the year, supporting the idea that a C_4 signal in cattle and sheep diets resulted from feeding practices involving cultivated millets. Furthermore, sheep had access to millet in late summer time while cattle were constantly foddered throughout the year, to a very high extent. Given the annual growth cycle of millet, with late summer maturity, a year round provisioning to cattle would suppose constitution of fodder. Constant provisioning could also have required cattle to be kept by the settlement all year round, inducing less investment in cattle herding, but in return, a necessarily important input to sustain cattle diet requirements at the daily scale. This could in fine be connected to the privileged status for cattle in social or ritual related activities at Xinzhai.

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1. Introduction

The Longshan Age (ca. 3000—2000 BC), especially the terminal stage, has always been regarded as a critical period for the formation of Chinese civilization (Yan, 1981; Li, 2005). Within this time span, a series of sociometric changes took place across China. As the geographic and cultural center of China, the Central Plains witnessed a series of transformations in aspects of agriculture and animal husbandry. The existing fauna structure predominated by the domestic pigs (*Sus scrofa domesticus*) continued but was modified by the introduction of cattle (*Bos taurus*) and sheep (*Ovis*

aries) (Yuan et al., 2007) with the latter playing increasingly important role in subsequent daily and ritual activities, especially in the case of cattle (Yao, 1984; Yuan et al., 2007). Millets, including the foxtail millet (*Setaria italica*) and broomcorn millet (*Panicum miliaceum*), were still the main cultivated cereals meanwhile rice and wheat remains were occasionally recovered (Zhao, 2007; Wang et al., 2012). All above not only provided food for the growing population but also revolutionized the land-use and social resources management system, which set the foundation for the formation of Chinese early states (Fitzhugh, 2001; Weisskopf, 2010).

In recent years, animal husbandry was investigated through stable isotope analysis at sites dating to a time span from late Longshan age to Xia dynasty (ca. 2070–1600 cal. BC), e.g. the Wadian (Chen et al., 2015) and Erlitou sites (Si, 2013) in He'nan province and the Taosi site in Shanxi province, respectively (Fig. 1). All of them consistently showed a contribution of C_4 plants to both cattle and sheep diets, but also much higher $\delta^{13}C$ values in cattle bone collagen than in sheep bones, suggesting a higher contribution of C_4 plants to cattle diets compared to sheep (Fig. 2a). This discrepancy trend was chronologically strengthened, from Taosi through Wadian to Erlitou site, with gradually larger variation in $\delta^{13}C$ values between cattle and sheep. This was inferred, to some extent, to be related with cattle increasingly high status. Given that natural environment in this area during the late Longshan age was dominated by C_3 plants (Liu et al., 2005) while C_4 cereals were widely raised by humans (Zhao, 2007; Weisskopf, 2010), the C_4 signal in the diets of both cattle and sheep were interpreted as primarily resulting from human feeding practices involving cultivated millets. Consequently, higher $\delta^{13}C$ values in the cattle bones than in sheep bones indicated that cattle were fed much more domestic C_4 crops.

The site of Xinzhai, located in Liuzhai County, Xinmi, Henan (Fig. 1), was first discovered in 1979 (Second team in Henan province, the Institute of Archaeology, Chinese Academy of Social Sciences (IA-CASS), 1981). Archaeological and radiocarbon dating evidences show that it was initially occupied in late Longshan age (Phase 1, ca. 1880–1850 cal. BC), continuing through the Xinzhai period (Phase 2, ca. 1800–1750 cal. BC), and lasted until the early Erlitou Culture age (Phase 3, 1735–1705 cal. BC). Due to its time span, location and archaeological features, the site of Xinzhai has been regarded as a key site to investigate the origin of Chinese first Dynasty, i.e. Xia dynasty (Xu, 2004; Zhao, 2004). Phytolith analysis indicated that millets, including the common millet and foxtail millet, were widely raised (Yao et al., 2007). Previous zooarchaeological research showed that domestic pig dominated the faunal assemblage, with increasing amounts of sheep and cattle since Phase 2 (Huang, 2008). Stable isotope analysis on animal (Dai et al., in press) and human bones (Wu et al., 2007) showed a similar pattern to that observed at the above cited sites: $\delta^{13}C$ values in cattle bone collagen were similar to those measured in humans, and clearly higher than those measured in sheep (Fig. 2b). Humans at the Xinzhai site consumed great amounts of millet as indicated by their high $\delta^{13}C$ values (−9.6 ± 1.5‰, n = 8). Cattle, with stable carbon isotope values averaging −9.8 ± 1.7‰ (n = 11), also relied intensively on C_4 plants, while sheep, with an averaged $\delta^{13}C$ value of −14.4 ± 1.6‰ (n = 8), displayed mixed diets with much more C_3 plants (over 60% estimated by the binary mixed model; Zhang, 2006). Obviously, at the Xinzhai site, millets were primary food for humans as well as staple fodder for livestock; however they clearly contributed to different extent to cattle and sheep diets, probably reflecting different husbandry strategies.

Different situations could lead to the observed pattern. One could be a contribution of C_4 plants to the diet of sheep and cattle throughout the year, but to a lower relative proportion in sheep compared to cattle. Another could be a difference in the timing of this contribution throughout the annual cycle, for example a seasonal contribution of C_4 plants to the sheep diet, *contra* a year round contribution to the cattle diet. This would reveal different organization schemes and may highlight differences in the scale of cattle and sheep herding. Indeed, a year round provisioning of cattle with considerable amounts of millet would require their keeping by the
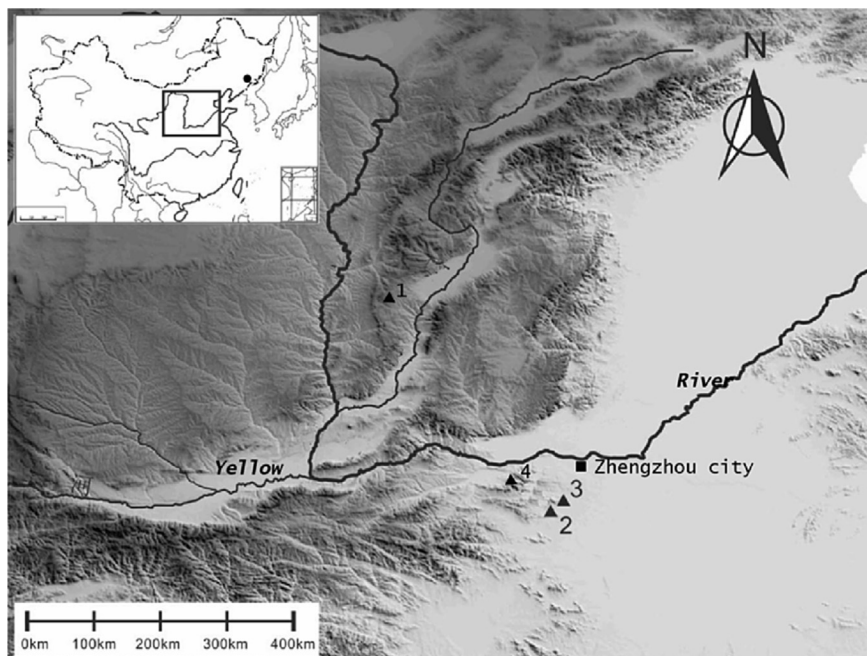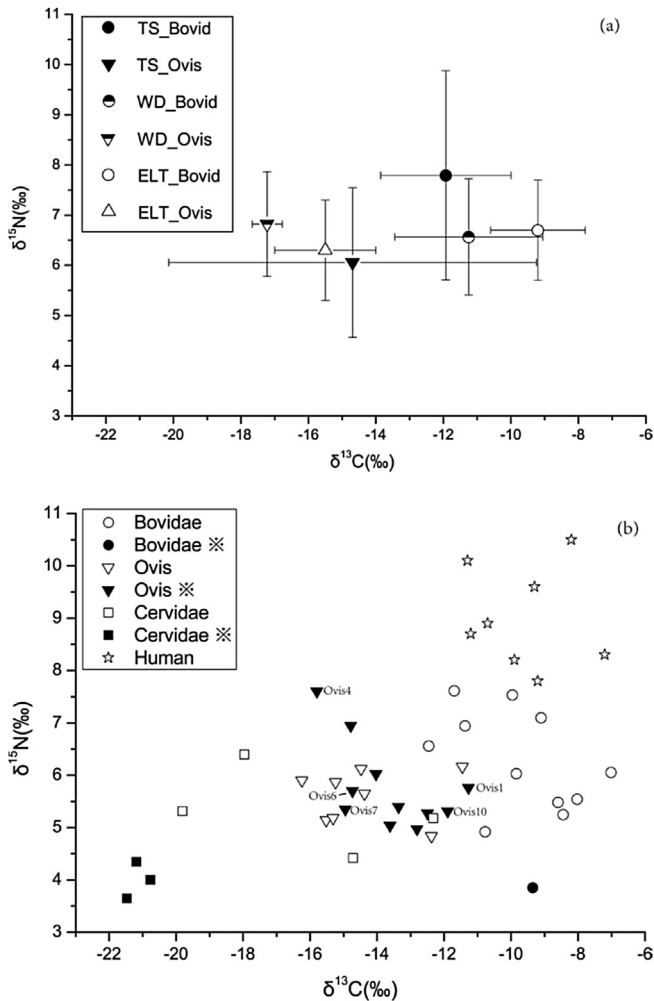

Fig. 1. Map of China with locations of the Zhengzhou city (■) and the archaeological sites (▲) cited in the text: 1 = Taosi site (TS), 2 = Wandian site (WD), 3 = Xinzhai site (XZ), 4 = Erlitou site (ELT); ● location of Sihailongwan lake in Jilin Province.

Fig. 2. (a): Stable carbon and nitrogen isotope values from bone collagen of Ovis and Bovid from sites dating from late Longshan age to Xia dynasty in the Central Plains of China (Chen et al., 2015; Si, 2013). TS = Taosi, WD = Wadian, ELT = Erlitou sites; (b): stable carbon and nitrogen isotope values from animals bone collagen from Xinzhai, China ("※"refer to this study; data on human bones are from Wu et al. (2007); all other data are from Dai et al., in press). In specimens Ovis 1, 4, 6, 7 and 10, molars were sequentially sampled for $\delta^{18}O$ and $\delta^{13}C$ analysis.

1981; Krueger and Sullivan, 1984; Lee-Thorp et al., 1989; Ambrose and Norr, 1993) and ingested water (e.g. Land et al., 1980; Longinelli, 1984; D'Angella and Longinelli, 1990). Unlike bone collagen, bioapatite incorporated in enamel during tooth formation is not replaced once mineralization is completed (Gage et al., 1989). Consequently, it holds a record of individual's stable isotope history over the time of tooth growth and mineralization. In large-sized terrestrial mammals with constant body temperature, the oxygen isotopic composition of skeleton bioapatite is mainly controlled by ingested water, reflecting local surface water, mainly related to precipitation (e.g. Land et al., 1980; Longinelli, 1984; Luz et al., 1984). The oxygen isotope composition in precipitation changes spatially and temporally, controlled by factors including water vapor source and transport patterns, ambient temperature, amount of precipitation, latitude and altitude (Dansgaard, 1964; Gat, 1980; Rozanski et al., 1993). Seasonal variations in the $\delta^{18}O$ of precipitation are recorded in tooth enamel during mineralization and can be reconstructed through sequential analysis along tooth growth axis (Fricke and O'neil, 1996). Concomitant analysis of enamel bioapatite $\delta^{13}C$ values, linked to diet (e.g. Krueger and Sullivan, 1984; Ambrose and Norr, 1993) permits to highlight potential seasonal changes in the relative proportion of C_3 and C_4 plants in diet. Intra-tooth sequential analysis of enamel $\delta^{13}C$ and $\delta^{18}O$ is now commonly used to investigate husbandry and animal diet management at the seasonal scale in past herds (e.g. Balasse et al., 2006, 2012a, 2014, in press).

In the present study, a similar approach was conducted in order to investigate at the seasonal scale the differences highlighted between sheep and cattle diet at the Xinzhai site. This primary objective related to the reconstruction of Bronze Age husbandry practices required a careful interpretation of $\delta^{18}O$ sequences in terms of the annual cycle. A potential difficulty is inherent to the very specific meteorological and pluviometric regime of Southeast Asia and China in particular, with consequences on the pattern of seasonal variations in $\delta^{18}O$ values of rainfall, and variations of this regime in the past. Whereas the great majority of previous studies involving sequential analysis of enamel $\delta^{18}O$ investigated mid- and high-latitudes locations where precipitation $\delta^{18}O$ values are mainly controlled by surface temperature, with ^{18}O-enriched rains in summer and ^{18}O-depleted rains in winter, this scheme may not be applied a priori to our study site.

China is set under a complex pattern of spatial and temporal distribution of stable isotope composition of precipitation, with air masses of different origins whose relative contribution in the curse of the annual seasonal cycle is modulated by the monsoon activity and the seasonal displacement of the Intertropical Convergence Zone, ITCZ (Araguas-Araguas and Froehlich, 1998; Johnson and Ingram, 2004). While at the sites located north of the maximum extent of the ITCZ, the temperature effect prevails to explain seasonal changes in rainfall $\delta^{18}O$, the amount effect prevails at sites from lower latitudes in the monsoonal domain, with contribution of ^{18}O-depleted rains in summer. However, in sites located close to the ITCZ (as is the case for the Xinzhai site), the temperature and amount effects apply conjointly to varying degrees (Johnson and Ingram, 2004). The situation preventing today in the location under study is illustrated from data measured at the closest meteorological station at Zhengzhou city (Fig. 1). Today, this specific region is under the influence of the Pacific monsoon system, where the amount of summer precipitation overshadows the influence of surface air temperature on summer rainfall $\delta^{18}O$ values: the monsoon rains brought in the summer are ^{18}O-depleted, despite higher ambient temperatures (Araguas-Araguas and Froehlich, 1998). This results in the bimodal pattern (highlighted in Fig. 3; IAEA/WMO, 2015), with minimal rainfall $\delta^{18}O$ values in summer (monsoon effect) and a second minimum in winter (temperature

village. Inversely, if a lower contribution of millet to sheep diets was explained by seasonally interrupted provisioning, this could potentially reveal extensive herding for part of the year. Defining precisely seasonal trends in millet provisioning would then contributed to a better understanding of how agriculture and husbandry were interwoven at the Xinzhai site. In particular, the reason behind contribution of millet to cattle and sheep diet could be related to field management, involving preventive grazing (Halstead, 2006), and/or soil fertilization. In return, or alternatively, cattle and sheep could be foddered crops of by-products in times of pasture shortage and/or due to crop surplus management. All strategies may induce different patterns in the seasonal round of millet contribution to sheep and cattle diet. All previous stable isotope analyses were conducted on bone collagen, reflecting long-term or even lifetime averaged diet (Schoeninger and Moore, 1992) and preventing further investigation in this sense. These patterns may be deciphered through sequential analysis of stable carbon and oxygen isotope ratios in tooth enamel.

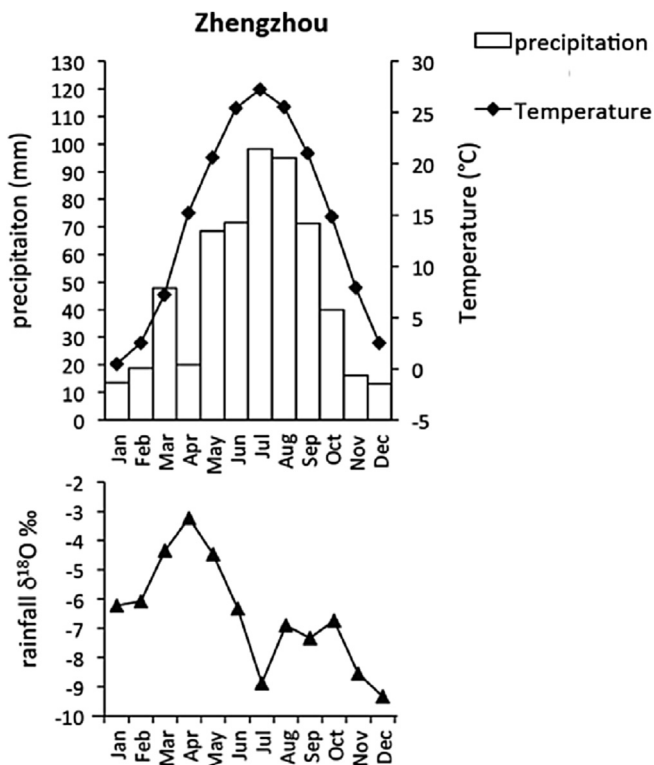Stable carbon and oxygen isotopic compositions of tooth enamel bioapatite are closely related to diet (e.g. Sullivan and Krueger,

Fig. 3. Monthly average precipitation, temperature and $\delta^{18}O$ values of meteoric water from 1985 to 1992 at the Zhengzhou city, China. IAEA/WMO (2015).

in the western part of the Loess Plateau, in response to which occurred a sudden reduction of establishments and contraction of the sites distribution area (An et al., 2005). Phases 2 and 3 of Xinzhai occupation, from which specimens were selected for the present study, span a time period from 1800 to 1705 cal. BC. These phases would therefore encompass the 3700 cal. BP (or 1750 cal. BC) event with minimal monsoon influence. In this case, with minimal contribution of ^{18}O-depleted summer rainfall, it is expected that surface air temperature is taking over for the control of variations in precipitation $\delta^{18}O$ values throughout the year (Araguas-Araguas and Froehlich, 1998). Animals reared under this regime would be expected to provide $\delta^{18}O$ sequences varying accordingly.

A diversity of schemes may therefore be present in the Bronze Age assemblage from Xinzhai, depending not only on decadal to century-scale changes in monsoon intensity/front positioning but also on interannual variability usually expected in a monsoon dominated system. A specific attention will be given to this point when interpreting $\delta^{18}O$ sequences retrieved from animal teeth. (1) Animals living under a monsoon climate are expected to deliver bimodal $\delta^{18}O$ sequences on an annual scale, with minimal values corresponding to summer and winter times, and reduced amplitude of annual variation. (2) Animals living at a time when monsoon influence was minimal are expected to deliver temperature controlled $\delta^{18}O$ sequences with unimodal distribution on an annual scale, minimal $\delta^{18}O$ values reached in wintertime and maximal values reached in summertime.

effect). The $\delta^{18}O$ sequences measured in the teeth from animals submitted to this climate regime are expected to vary accordingly.

An additional great difficulty is temporal variations in the Southeast Asian monsoon intensity and position of the summer monsoon front. Enhanced in the early Holocene, this monsoon regime also met variability within the Holocene, on different timescales including annual, decadal and century scales. A palaeohydrological reconstruction at the Lake Sihailongwan in Northeastern China (Fig. 1) revealed minima summer rainfall influence around 6400, 4900, 3700 and 2200 cal. BP (Schettler et al., 2006). Of special interest for the present study is the event around 3700 cal. BP. This distinct dry interval occurring shortly after 4000 cal. BP was evidenced in other palaeoclimatic records (including sedimentological, geochemical and palynological records) from north−central and Northeastern China (An et al., 2005; Schettler et al., 2006). This dry event is even thought to be responsible for a significant alteration of the landscape and ecology between 4000 and 3600 cal. BP

2. Materials

Fifteen mandibles (including 11 sheep, three deer, *Cervus* sp. and one cattle) from phases 2 and 3 were selected for stable carbon and nitrogen isotope analysis of bone collagen to enlarge the previous dataset and to confirm the observed pattern. Among those, five sheep mandibles (labeled in Fig. 2b) that delivered bone collagen among the lowest (Ovis 4, 6 and 7) and the highest $\delta^{13}C$ values (Ovis1 and 10) in the whole dataset were chosen for sequential analysis in tooth enamel, in order to explain the inter-individual variability in sheep. CXZ Ovis1, Ovis4, Ovis6 and Ovis7 gave one second molar (M_2) and one third molar (M_3). CXZ Ovis10 only delivered one M_2. Both M_2 and M_3 from the cattle mandible (CXZ Bos1) were sampled, and the cattle dataset was enlarged with two additional isolated M_3s (CXZ Bos2 and CXZ Bos3). Last, one sika deer (*Cervus nippon*) M_2 and two roe deer (*Capreolus pygargus*) M_3s were also included in order to check for the availability of C_4 plants in the surroundings at the seasonal scale. Details of all specimens for stable isotope analysis on bone collagen and/or tooth apatite are listed in Table 1.

Fig. 4. Enamel sampling in second and third molars from sheep (a), cattle (b) and deer (c).

Table 1
Specimens included in the stable isotope analysis.

Sample ID	Context	Phases	Species	Bone type	Sides	Teeth analyzed
CXZ Ovis1	CXAT6H65	2	*Ovis aries*	mandible	right	M2,M3
CXZ Ovis2	CXAT7③A	3	*Ovis aries*	mandible	left	
CXZ Ovis3	CXAT6④A	3	*Ovis aries*	mandible	left	
CXZ Ovis4	CXAT19H126	2	*Ovis aries*	mandible	left	M2,M3
CXZ Ovis5	CXAT3T6G2	2	*Ovis aries*	mandible	left	
CXZ Ovis6	CXAT12④	3	*Ovis aries*	mandible	left	M2,M3
CXZ Ovis7	CXAT4③	3	*Ovis aries*	mandible	left	M2,M3
CXZ Ovis8	CXAT5G2	2	*Ovis aries*	mandible	left	
CXZ Ovis9	CXAT7F5⑥	2	*Ovis aries*	mandible	left	
CXZ Ovis10	CXAT7F5⑪	2	*Ovis aries*	mandible	right	M2
CXZ Ovis11	CXAT8⑥	3	*Ovis aries*	mandible	left	
CXZ Cervus1	CXAT18H112	2	*Cervus nippon*	mandible	right	M2
CXZ Capreolus1	CXAT18H112	2	*Capreolus pygargus*	mandible	right	M3
CXZ Capreolus2	CXAT18H112	2	*Capreolus pygargus*	mandible	left	M3
CXZ Bos1	CXAT4S	2	*Bos taurus*	mandible	right	M2,M3
CXZ Bos2	CXAT5③	3	*Bos taurus*	/	right	M3
CXZ Bos3	CXAT4④A	3	*Bos taurus*	/	right	M3

The radiographic data of tooth formation of European breeds (Weinreb and Sharav, 1964) indicate that for sheep, M_2 starts to form during the second month of life and the whole crown is completed by the age of 12 months. The third molar (M_3) starts at approximately ten months and takes 12 months to form (Witter and Míšek, 1999). For cattle, the growth of M_2 begins soon after birth and is completed after one year; the M_3 starts forming around 9–13 months after birth and crown formation takes about 2–3 years (Brown et al., 1960). Coupled sequential analysis in M_2 and M_3 could provide a longer period of time, allowing to check the reproducibility of observed patterns from one year to another. In this research, both M_2 and M_3 were sampled unless tooth attrition was rather heavy.

3. Methods

3.1. Collagen extraction procedure

The bone surfaces were cleaned using a tungsten drill. The polished bone fragments were ground into powder. Collagen extraction procedure followed the one described in Bocherens et al. (1991). About 300 mg bone powder were weighed and treated in 0.1 M hydrochloric acid for 20 min, followed by a treatment in 0.125 M NaOH for 20 hours at room temperature and gelatinized in 0.01 M hydrochloric acid at 100 °C for 17 hours. The filtered final solutions were freeze-dried for 48 hours. Approximately 400–500 mg collagen were weighed for stable isotope analysis.

3.2. Tooth enamel sequential analysis

All tooth samples were prepared following the protocols described in Balasse et al. (2012a). The second and/or third molars were extracted from the mandibles. Enamel surfaces were cleaned with a brush and external surfaces were abraded with a tungsten drill in order to remove cementum. Sequential sampling was performed by drilling on the buccal side of the tooth, on the lobe with the greatest preserved height (Fig. 4). Each sample was located in tooth crown by its distance from the enamel–root junction (erj). Sampling covered the whole crown height with an interval of 1–1.5 mm. Between 5 and 8 mg of enamel powder were drilled out.

Enamel powders were treated in 0.1 M acetic acid for 4 hours (0.1 ml/mg enamel), rinsed with distilled water and freeze-dried. Bioapatite samples weighing 580–630 µg were analyzed on a Kiel IV device interfaced to a Delta V Advantage IRMS. Samples reacted under vacuum with 100% phosphoric acid [H_3PO_4] at 70 °C in individual vessels. The analytical precision, determined from analyses of the laboratory internal carbonate standard (Marble LM), vary for each run from 0.01‰ to 0.03‰ for $\delta^{13}C$ and from 0.02‰ to 0.05‰ for $\delta^{18}O$. Typically a run included 8 Marble LM.

3.3. Estimating relative contribution of C_4 plants to diet

A 5‰ ^{13}C-enrichment was applied between diet protein and collagen (Ambrose and Norr, 1993) and a +14.1‰ fractionation factor between diet and bioapatite (Cerling and Harris, 1999). All modern plant values were corrected by +1.5‰ to compensate for the fossil fuel effect (Freyer and Belacy, 1983; Francey et al., 1999). An average value of −26.5‰ was considered for the great majority of modern C_3 plants from open areas (Kohn, 2010). A pure C_3 diet should then be reflected in bone collagen values averaging −20‰. In modern ecosystems, C_3 plant $\delta^{13}C$ values comprised between −25.5‰ and −23‰ reflect in majority dry ecosystems (Kohn, 2010). This would lead to values comprised between −19 and −16.5‰ in archaeological bone collagen, and values comprised between −10.2 and −7.7‰ in archaeological enamel bioapatite. $\delta^{13}C$ values within this range may reflect dry C_3 environments or mixed contribution of C_3 and C_4 plants, while higher values must reflect contribution of C_4 plants. An et al. (2015) provide $\delta^{13}C$ values for archaeological seeds (−11.9 to −9.6‰) and modern leaves (−14.6 to −12.3‰) from common and foxtail millets, both present at Xinzhai. Using a mean value of −11‰ for archaeological millet, a pure millet diet should translate to +2.9‰ in enamel bioapatite.

4. Results

4.1. Stable isotopic compositions in bone collagen

The results for stable carbon and nitrogen isotopic ratios in bone collagen are listed in Table 2. Collagen yields vary from 1.2 to 12%. The C contents (31.7%–41.6%), N contents (11.3%–15.2%) and C: N ratios (3.1–3.3) all satisfy with criteria defining isotopically well-preserved collagen extracts (Ambrose, 1990).

Table 2
Results from stable carbon and nitrogen analysis in bone collagen from sheep, cattle and deer at the Xinzhai site, China

Sample ID	Bone powder (mg)	Yield (mg/g)	%N	%C	C/N	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)
CXZ Ovis1	310	98	14.9	41.0	3.2	5.8	−11.3
CXZ Ovis2	310	70	11.3	31.7	3.3	5.7	−14.7
CXZ Ovis3	340	86	15.0	41.2	3.2	5.0	−12.8
CXZ Ovis4	330	84	15.2	41.6	3.2	7.6	−15.8
CXZ Ovis5	310	94	14.9	41.0	3.2	5.3	−12.5
CXZ Ovis6	310	13	12.4	34.7	3.3	6.9	−14.8
CXZ Ovis7	310	21	12.7	34.5	3.2	5.3	−14.9
CXZ Ovis8	320	73	14.6	40.1	3.2	5.4	−13.4
CXZ Ovis9	340	97	15.1	41.6	3.2	6.0	−14.0
CXZ Ovis10	300	39	13.6	36.5	3.1	5.3	−11.9
CXZ Ovis11	300	86	14.8	40.5	3.2	5.0	−13.6
CXZ Bos1	330	12	11.9	32.8	3.2	3.9	−9.4
CXZ Cervus1	330	90	15.0	41.0	3.2	4.0	−20.8
CXZ Capreolus1	300	79	14.7	40.0	3.2	3.6	−21.5

Sika deer and roe deer show the lowest $\delta^{13}C$ values of the dataset (−21.5‰ to −20.8‰). Those indicate a wild ecosystem largely dominated by C_3 plants. The $\delta^{13}C$ values measured in the cattle mandible (−9.4‰) fall within those previously measured at the site (Fig. 2b), suggesting a major contribution of millet to cattle diet. The $\delta^{13}C$ values measured in sheep vary from −15.8‰ to −11.3‰ with an average of −14.4‰ (n = 11). They also fall within the range of the previous dataset (Fig. 2b) although CXZ Ovis 1 yielded the highest $\delta^{13}C$ values for sheep (−11.3‰). All of those reflect an important contribution of millet to the sheep diet,

although to a lower extent than what was observed in most cattle specimens.

### 4.2. Results from $\delta^{13}C$ and $\delta^{18}O$ analysis in tooth enamel bioapatite

The results for $\delta^{18}O$ and $\delta^{13}C$ measured in tooth enamel bioapatite are reported in Supplementary table and shown in Figs. 5 and 6. Stable oxygen isotope values vary between −8.2‰ and −1.3‰ in cattle (with amplitudes of intra-tooth variation around 2‰), between −5.4‰ and 2.5‰ in sheep (amplitudes of intra-tooth variation of 1.8‰–6.5‰) and between −6.2‰ and −2.9‰ in deer. All sequences of $\delta^{18}O$ values display intra-tooth variation close to a sinusoidal pattern, except in roe deer.

Stable carbon isotope values vary from −5.3‰ to 2.9‰ in cattle, from −11.4‰ to 0.2‰ in sheep and from −12.9‰ to −8.4‰ in deer. In all sheep, $\delta^{13}C$ values vary according to a pattern tuned to the cycle observed in the $\delta^{18}O$ values: the lowest $\delta^{13}C$ values are recorded when $\delta^{18}O$ values start to increase again just after reaching a minimum; the highest $\delta^{13}C$ values are measured when $\delta^{18}O$ values start to decrease again after reaching their maximum (Fig. 5).

The inter-individual variability on $\delta^{13}C$ values in sheep bone collagen is not reflected in a similar way in the sequential $\delta^{13}C$ values of bioapatite. Ovis 1 and 10, with $\delta^{13}C$ values in bone collagen (−11.3 and −11.9‰ respectively) among the highest for sheep at the site, display maximum $\delta^{13}C$ values in M_2 sequence, similar (about −1‰) to that measured in Ovis 6, which yielded a lower $\delta^{13}C$ value in bone collagen (−14.8‰). In CXZ Ovis 4 and 7, the
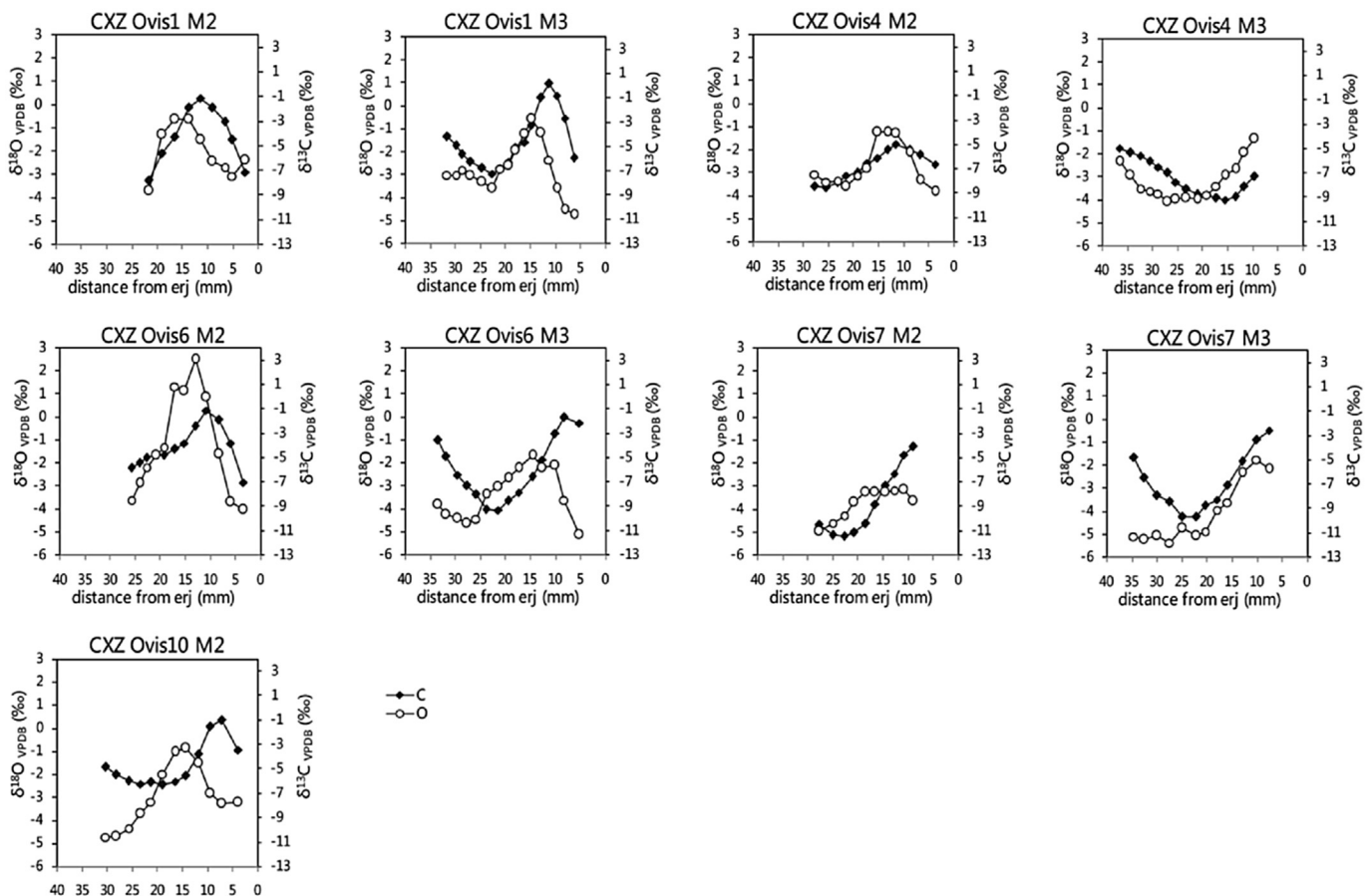
Fig. 5. Results from sequential analysis of stable carbon ($\delta^{13}C$, black symbols) and oxygen ($\delta^{18}O$, white symbols) isotope ratios in sheep tooth enamel bioapatite from the Xinzhai site, China. Samples are located in tooth crown by their distance from the enamel–root junction (erj).
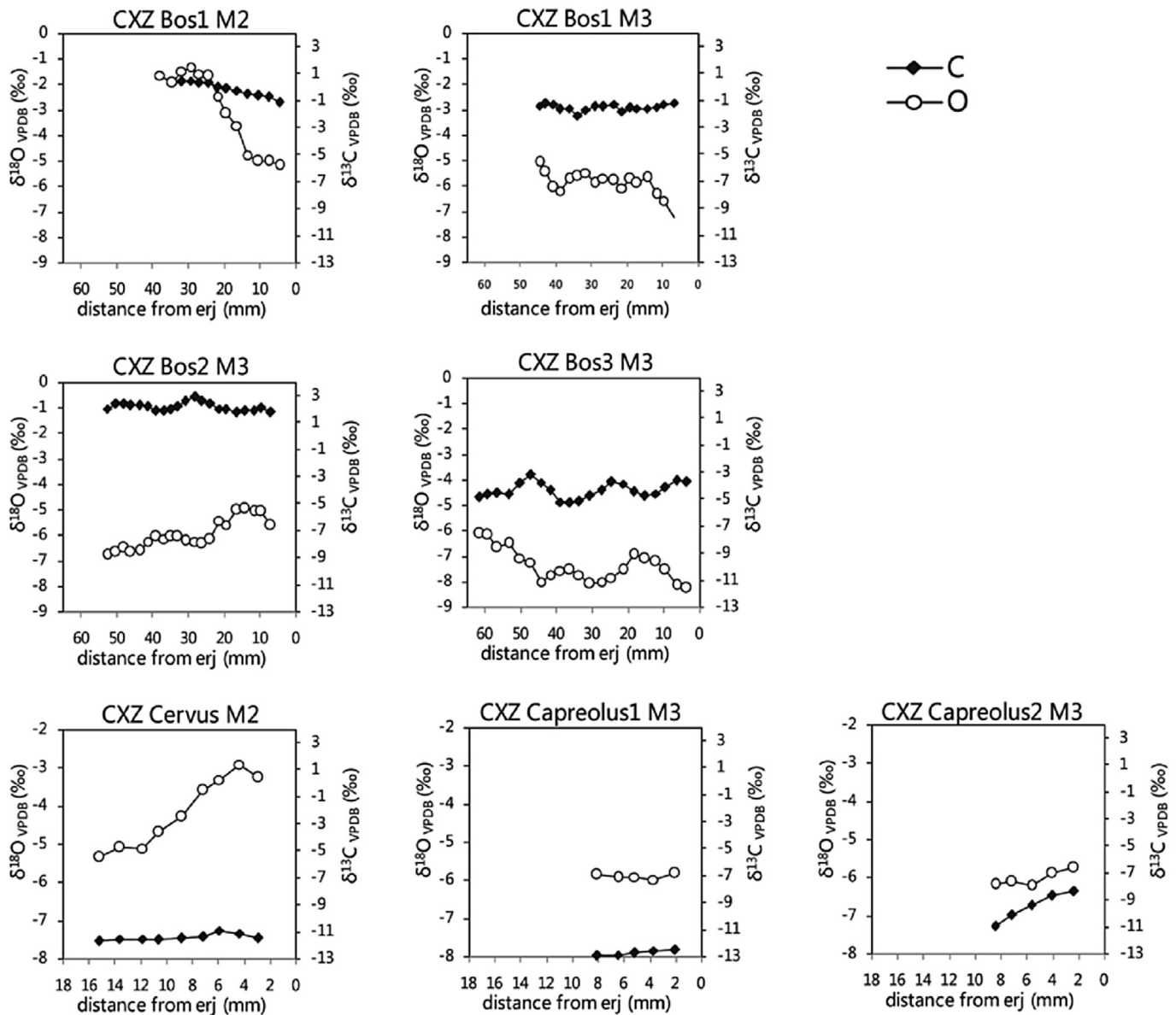
Fig. 6. Results from sequential analysis of stable carbon ($\delta^{13}C$, black symbols) and oxygen ($\delta^{18}O$, white symbols) isotope ratios in cattle and deer tooth enamel bioapatite from the Xinzhai site, China. Samples are located in tooth crown by their distance from the enamel−root junction (erj).

maximum $\delta^{13}C$ values in the M_2 sequence are much lower ($-5.0‰$ and $-4.1‰$ respectively) relative to the three other individuals.

A cyclical pattern may also be observed in $\delta^{13}C$ values measured in cattle teeth M_3s (CXZ Bos2M_3, CXZ Bos3M_3 and CXZ Bos1M_3: Fig. 6). This rhythmicity is the same as that observed in $\delta^{18}O$ values. However, in all cattle M_3s, $\delta^{18}O$ and $\delta^{13}C$ values vary inversely.

5. Discussions

5.1. Interpreting $\delta^{18}O$ sequences at the intra-tooth/infra-annual scale

Previous attempts at detecting influence of summer monsoon in fossil tooth enamel $\delta^{18}O$ sequences have relied on the identification of opposed intra-tooth variations in $\delta^{13}C$ and $\delta^{18}O$ values (Biasatti et al., 2010; Zhang et al., 2012). The rationale behind this is that higher $\delta^{13}C$ values reflecting higher relative contribution of C_4 plants would correspond to summertime, when hot and wet conditions are created by the monsoonal rains, the latter carrying $\delta^{18}O$ depleted water. Two $\delta^{18}O$ sequences measured in modern goat molars are presented respectively in the above-cited studies. Both show unimodal distributions of $\delta^{18}O$ values on an annual scale. In these sequences, the lowest $\delta^{18}O$ values were interpreted as reflecting summertime. Although opposed variations were indeed observed between $\delta^{18}O$ and $\delta^{13}C$ signals, in our opinion uncertainty remains in the identification of the seasons from the $\delta^{18}O$ sequences. Indeed, seasonal changes in modern rainfall $\delta^{18}O$ suggest an inverse scenario. The Qaidam basin, from which the modern goat specimen analyzed in Zhang et al. (2012) originated, is located North of the ITCZ, therefore outside of the monsoonal domain, where rainfall $\delta^{18}O$ is temperature controlled: the highest rainfall $\delta^{18}O$ values occur in summertime when temperature is the highest and the lowest $\delta^{18}O$ values occur in wintertime (data from the nearest GNIP station: Zhangye; IAEA/WMO, 2015). Similarly, although the Linxia basin, from where the modern goat analyzed in Biasatti et al. (2010) originated, lies at the limit of the maximum
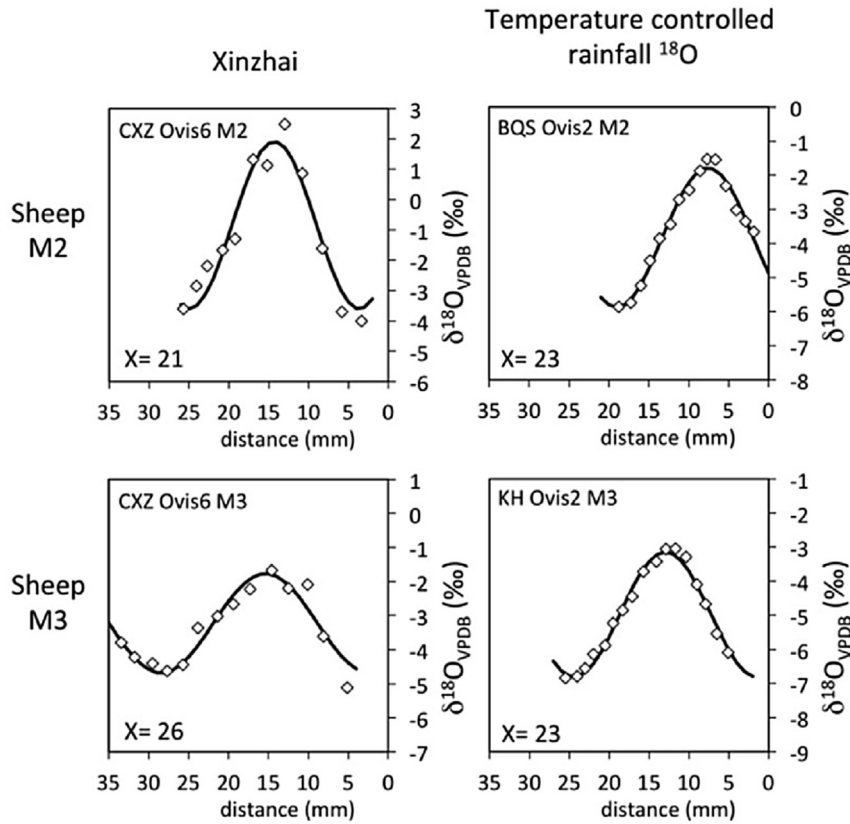
Fig. 7. Comparison of sheep δ18O sequences measured at Xinzhai and similar datasets from locations where rainfall δ18O is controlled by surface air temperature: BQS = Bercy (northern France; 4th mil cal BC; Balasse et al., 2012a); KH = Knap of Howar (Orkney; 4th mil cal. BC; Balasse et al., 2006). X = period of the cycle, as defined from the modeling.

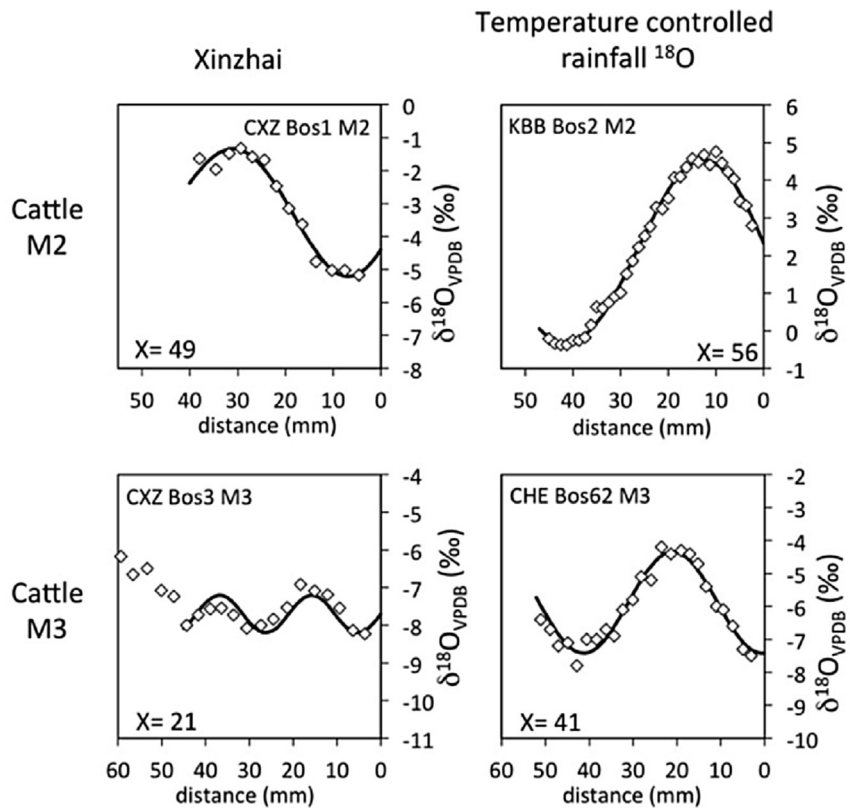**Fig. 8.** Comparison of cattle δ18O sequences measured at Xinzhai and similar datasets from locations where rainfall δ18O is controlled by surface air temperature: CHE = Cheia (Romania, 5th mil cal BC; Tornero et al., 2013) and KBB = Kasteelberg (South Africa; Late Stone Age; Balasse, 2002). X = period of the cycle, as defined from the modeling.

extent of the ITCZ and is under summer monsoon influence, the closest GNIP station (Lanzhou) evidences temperature controlled rainfall $\delta^{18}O$ (Biasatti et al., 2010; IAEA/WMO, 2015). Given these uncertainties, on the one hand, and given a location further west of the above-mentioned study sites compared to Xinzhai, on the other hand, these examples may not be relevant modern analogs for animals raised under monsoonal regimes in the area under consideration in the present study.

Age site of Kasteelberg in South-Africa (Fig. 8). Similarly, the $\delta^{18}O$ sequence measured in the sika deer M_2 (Fig. 6) is strictly comparable to those measured in modern red deer from Northwestern Europe (Stevens et al., 2011). All this suggests minimal influence of summer monsoon over the time of formation of these teeth. Consequently, in these specimens, the highest and the lowest $\delta^{18}O$ values were interpreted as reflecting respectively summertime and wintertime.

Table 3
Results from the modeling of the $\delta^{18}O$ sequences measured in sheep and cattle molars from Xinzhai (CXZ), Bercy (BQS, France), Cheia (CHE, Romania), Bordusani-Popina (PBORD, Romania), Knap of Howar (KH, Scotland) and Kasteelberg (KBB, South Africa).

Specimen	Sequence	X(mm)	A(‰)	x_0(mm)	M(‰)	Data
CXZ Ovis1 M2	$\delta^{18}O$	17.5	1.4	14.7	−1.8	this study
CXZ Ovis4 M2	$\delta^{18}O$	20.3	1.3	13.0	−2.6	this study
CXZ Ovis6 M2	$\delta^{18}O$	21.3	2.8	14.3	−0.8	this study
CXZ Ovis10 M2	$\delta^{18}O$	25.5	1.9	15.0	−2.9	this study
BQS Ovis2 M2	$\delta^{18}O$	22.8	2.0	7.6	−3.8	Balasse et al., 2012a
CHE Ovis 1 M2	$\delta^{18}O$	26.8	−2.7	19.2	−5.7	Tornero et al., 2013
CXZ Ovis1 M3	$\delta^{18}O$	20.0	1.9	15.5	−2.9	this study
CXZ Ovis6 M3	$\delta^{18}O$	26.1	1.5	15.4	−3.2	this study
CXZ Ovis7 M3	$\delta^{18}O$	25.4	1.6	9.7	−3.4	this study
PBORD Ovis 72 M3	$\delta^{18}O$	29.7	2.8	14.8	−4.2	Balasse et al. in press
KH Ovis2 M3	$\delta^{18}O$	22.9	1.8	13.0	−5.0	Balasse et al., 2006
CXZ Bos1 M2	$\delta^{18}O$	48.8	2.0	31.6	−3.2	this study
CHE Bos 35 M2	$\delta^{18}O$	59.9	2.0	30.2	−5.7	Balasse unpublished
KBB Bos2M2	$\delta^{18}O$	56.4	−2.4	41.5	2.1	Balasse et al., 2003
CXZ Bos3 M3	$\delta^{18}O$	21.1	0.5	15.8	−7.7	this study

Instead, in the present study, a summer monsoon influence was investigated from the shape of $\delta^{18}O$ cycles on the annual scale, i.e. bimodal distribution in monsoonal system *versus* unimodal distribution in a temperature controlled system. In order to do so, comparisons were conducted with $\delta^{18}O$ sequences retrieved from secure temperature controlled systems. In locations where the predominant factor for annual variations in rainfall $\delta^{18}O$ values is ambient temperature, $\delta^{18}O$ sequences measured in cattle and sheep molars may be modeled following an equation based on a cosine function (Balasse et al., 2012b):

$$\delta_m = A. \cos(2\Pi(x - x_0)/X) + M$$

where δ_m is the modelled $\delta^{18}O$ or $\delta^{13}C$ sequence, x is the distance from the enamel−root junction; X is the period (in mm), corresponding to the length of tooth crown formed over a complete cycle. A is the amplitude [= (max. − min.)/2] (in‰) and depends on the amplitude of the isotopic signal; x_0 is the delay (mm) − $\delta^{18}O$ attains its maximum value when $x = x_0$; M is the mean [= (max. + min.)/2] expressed in ‰.

This approach was attempted to the sheep and cattle molars from Xinzhai. Only the sequences presenting a cycle with at least two consecutive optima (one maximum and one minimum values) were modeled. The best fit of the different parameters of the model to the measured data was determined using an iterative method, and a minimization of the sum of the square of the difference between modeled and measured data (the method of least squares). The calculations were carried out using Microsoft Excel software. This model could be successfully applied to the sheep M_2s and M_3s and to the cattle M_2. In Xinzhai sheep, the period of the cycle varies from 17.5 to 25.5 mm in sheep M_2s, from 20.0 to 26.1 mm in sheep M_3s (Table 3). These figures are similar to those measured in sheep teeth from diverse European locations (Table 3 and Fig. 7) where rainfall $\delta^{18}O$ is controlled by surface air temperature. In the unique cattle M_2 (CXZ Bos1M_2), the period of the modeled cycle (~49 mm) is of the same extent as the sole sequence published to date from a cattle second molar, from the Late Stone

On the other side, the third molars from CXZ Bos1, CXZ Bos2 and CXZ Bos3 show a very different pattern from that usually observed in Europe (Fig. 8) and strongly resembling the one observed in present day annual variations in rainfall $\delta^{18}O$ values at Zhengzhou (Fig. 3). Setting the hypothesis that the pattern observed in these cattle third molars mimics the one from a pluviometric regime under summer monsoon influence (Fig. 3), we defined the period of this sequence in the cattle M_3 in order to define whether it was likely to have formed over a year. The period was defined from calculation of the intersection between the least square regression line (calculated from the sequence minima and maxima) and the measured sequence (Fig. 9). In CXZ Bos2 and CXZ Bos3, the calculated period was respectively 37.1 mm and 37.3 mm. This approach could not be applied to CXZ Bos1 whose $\delta^{18}O$ sequence is more difficult to read. However, visual observation does suggest a period of a similar extent for this tooth (Fig. 6). These estimations compare directly with the period of cycles measured in European cattle M_3 (Fig. 8 and Table 3), suggesting that the bimodal $\delta^{18}O$ sequences measured in Xinzhai cattle M_3 were indeed formed over a period of a year. This pattern could therefore reflect the typical pattern of annual changes in precipitation $\delta^{18}O$ values in a system controlled by the Pacific monsoon, with ^{18}O-depleted summer rainfall. These cattle teeth would have been formed over strong monsoon years, whereas all sheep teeth would have been formed over weak − or absent − monsoon years, possibly around the time of the 3700 cal. BP monsoon minima. It is striking to note that in CXZ Bos1, the M_2 delivered a $\delta^{18}O$ sequence similar to that measured under no monsoon influence, whereas the M_3 delivered a signal suggesting strong monsoon influence (Fig. 6). Given that the stable isotope record over the M_2 and M_3 would span two consecutive years, this could suggest great inter-annual variability in the strength of the summer monsoon in the site location, or a change of residence (between the time of mineralization of M_2 and M_3) between locations crossing the monsoon front.

Potential physiological factors and/or differing husbandry practices were also considered as alternative explanations to this difference between the pattern of $\delta^{18}O$ measured in all sheep on the
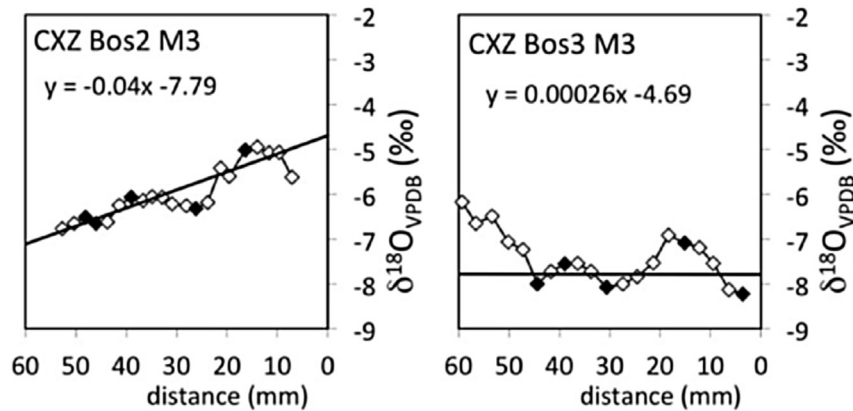
Fig. 9. Slope and intercept for the least square regression (calculated from the sequence minima and maxima, highlighted in black) of the measured sequences. The period is calculated from the intersection between this regression line and the measured sequence.

one side and most cattle teeth on the other side. A considerably shorter growth rate (= a longer time for tooth formation) for the third molar of Xinzhai cattle compared to prehistoric European cattle is difficult to support given the similarity between both as long as the M_2 is concerned. Another explanation could be a pattern of mobility (at the seasonal scale, over the time of formation of the third molar) inducing a break in the cycle of seasonal changes in $\delta^{18}O$ values of drinking water at the local scale. However, given the very high contribution of C_4 plants (most probably cultivated millet) to cattle diets all year round, it is very unlikely that this diet management strategy could be maintained with mobility: foddered cattle had to be kept by the settlement. In this regard, it may be envisaged that their penning could have been accompanied by provisioning with water from a specific source, including well water. But still, contribution of well water could dampen seasonal variation of the $\delta^{18}O$ values in the bioapatite (Kirsanow et al., 2008), however it should not induce increased periodicity in variations of $\delta^{18}O$ values. Still, the fact that a "monsoon" signal was only observed in cattle teeth (3 out of 4 teeth) when sheep (12) and deer (1) teeth show another pattern may cast doubt on the climatic explanation to it. However, given the small sample size, a strong monsoon regime only detected in only three cattle third molars could be attributed to chance.

For the moment, an ^{18}O-depleted summer monsoon rainfall signal remains the most likely possible explanation for interpretation of the sequences measured in cattle M_3s, although, this hypothesis would be beneficiated to be tested on teeth from cattle securely submitted to a monsoon system, and where both the temperature effect and the amount effect apply. Under this hypothesis, the $\delta^{18}O$ minima would be related to winter and summer, while the $\delta^{18}O$ maxima would indicate spring and autumn.

5.2. A wild environment heavily dominated by C_3 plants throughout the year

The gradual increase in $\delta^{18}O$ values measured in CXZ CervusM_2 reflects a time period of approximately half a year, from winter to summer. The time period covered by the stable isotope recorded in CXZ Capreolus1M_3 and CXZ Capreolus2M_3 is more difficult to evaluate given the shortness of the sequence and the absence of clear pattern of variation in $\delta^{18}O$ values (Fig. 6 and Supplementary Table).

C_4 plants did not contribute, even at a seasonal scale, to the diet of CXZ Cervus ($\delta^{13}C$ values from −11.7‰ to −10.9‰) or to the one of CXZ Capreolus1 (−12.9‰ to −12.5‰). On the other side, CXZ

Capreolus2M_3 delivered seasonally higher values (up to −8.4‰). This may either reflect a dry summer, or a small contribution of C_4 plants. Roe deer have opportunistic ecological behaviors and it would not be surprising that they could have fed on the cultivated millets in the unprotected croplands. This could explain a seasonal contribution of C_4 plants to their diet, without contradicting the idea that wild C_4 plants, which are favored in warm rainy summer (Yao et al., 2011), would not have been available to a significant extent whether in an annual or seasonal scale, as suggested both by bone collagen and enamel bioapatite $\delta^{13}C$ values. As a conclusion, the C_4 plant signal was primarily considered as reflecting feeding practices with cultivated millets.

5.3. A late summer contribution of millet to the sheep diet

In sheep, the $\delta^{13}C$ sequences vary accordingly to the $\delta^{18}O$ sequences, with a short time lag. This would suggest maximal contribution of C_4 plants to sheep diet in late summer, corresponding with maturity of C_4 crops (He, 2010). When a maximum $\delta^{13}C$ value may be identified at the annual scale (i.e. in CXZ Ovis1 M2&M3, CXZ Ovis4M2, CXZ Ovis6 M2&M3 and CXZ Ovis10M2: Fig. 5) the estimated values for diet vary from −18.8‰ to −13.7‰, suggesting the proportions of millet in diets vary from 45% to 81%. When minimal $\delta^{13}C$ value were identified (in CXZ Ovis1M3, CXZ Ovis4 M2&M3, CXZ Ovis6M3, CXZ Ovis7 M2&M3 and CXZ Ovis10M2: Fig. 5), they were converted to $\delta^{13}C$ values for diet varying from −25.1‰ to −20.2‰ indicating diets composed of 0%–35% millet. These estimations were based on $\delta^{13}C$ values for millet seeds: the overall millet contribution could have been higher if it was given in the form of leaves with lower $\delta^{13}C$ values than grains (An et al., 2015). Nevertheless, it must be kept in mind that these estimations are biased due to the time lag in enamel mineralization inducing attenuation, in the enamel record, of the amplitude of these seasonal changes (Balasse, 2002): contribution of millet may have been higher than estimated in summer time and lower in winter time. As a consequence, although it is not possible to conclude to no contribution of millet to the sheep diets in late winter/early spring when minimal $\delta^{13}C$ values are attained, except in CXZ Ovis7M_2 (where millet contribution could not be lower: 0% C_4 plant in diet), contribution of millet could have been very light to absent at this time of the year.

The domestic millets could be accessible to sheep in two different forms, i.e. human deliberate feeding practice or sheep spontaneous eating. It was recorded in an agricultural book titled < *Ma shou Nong yan* (马首农言)> in Qing dynasty (1636–1911

AD) (Qi, 1999) that in the central region of Shanxi province, which is northwest to Henan province where the Xinzhai site is located, sheep usually grazed in mountain in the spring and were brought back closer to the farmland in autumn. In particular, they were allowed into croplands after harvesting and penned in the fields for fertilizing during the night. In addition to human deliberate feeding practices, sheep could run into unprotected farmland to eat millets and such an episode was recorded in a historical book dating to Han dynasty (九章算术, 206BC − 220 AD) (Bai, 1983) that a sheepherder was required to compensate for the millets eaten by the sheep that run into the farmland. The systematic pattern of a maximal contribution of millet in late summer time, in all sheep and both molars (i.e. over two successive years), more probably resembles a deliberate husbandry practice. Millet reaches maturity in late summer. A late summer contribution of the crop to the sheep diet could therefore either correspond to a direct contribution of the fresh harvest as fodder (seeds or leaves), or be explained by the setting of the sheep in the fields after harvest time, where they could graze on the stubble, while fertilizing the soil.

5.4. Year round provisioning of millets to cattle

The amount of millets consumed by cattle varied seasonally in ranges from 65 to 86%, 92−100% and 43−58‰ for CXZBos1, CXZBos2 and CXZBos3 respectively. It can be noted that the contribution of millet to cattle diet was not significantly different in monsoon and non-monsoon years (see CXZ Bos1 M2/M3: Fig. 6). Again, these estimations made using $\delta^{13}C$ values for millet seeds may be underestimated if millet was mostly consumed in the form of leaves. In all instances, millets contributed as a major part to cattle diets all year round, and even almost exclusively to the diet of CXZ Bos2 over the time of formation of its third molar. Given the annual growth cycle of millet, with late summer maturity, a year round provisioning to cattle would suppose constitution of fodder, and restitution to cattle beyond the period with availability of the fresh crops. Constant provisioning with fodder/fresh crops would require cattle to be kept by the settlement all year round. This would induce less investment in cattle herding, if those were not brought to pasture. In return, the necessary input to sustain cattle diet requirements at the daily scale may have been important, unless this type of cattle husbandry was conducted either at a small scale or by highly centralized management.

Cattle, introduced to the Central Plains from western Eurasia about 4500 BP (Yuan et al., 2007; Lv et al., 2014), only account for a small percentage (5.1% in NISP, 3.9% in MNI) in the faunal assemblage at Xinzhai, as well as at several other Longshan-era sites (Yuan et al., 2007; Brunson et al., in press). No evidence was found for exploitation of cattle milk, strength or transportation. However, stable isotopic analysis on cattle bone collagen indicated that they could have been an important part of meat sources for the local residents (Dai et al., in press). In addition, beyond the meat resource, cattle may have been more valuable to the inhabitants: they may have symbolized wealth and acted importantly in sociopolitical activities especially during the three dynasties, i.e. Xia, Shang and Zhou (Liu, 2014; Lv et al., 2014). Cattle occupied the highest position in the ritual activities as documented in some ancient Chinese literatures. For example, the Chinese phrases of "Tailao" (太牢), composed of cattle, sheep and pig, and "Shaolao" (少牢), composed of sheep and pig, are two kinds of high-level sacrifice activities, among which cattle have a higher social status than the sheep or pigs as stated in Da dai Li ji (大戴礼记), "Da Dai's Book of Rites" (Dai, 100−0 BC) (Zheng, 2001). High $\delta^{13}C$ values, resulting from annually abundant millet fodder provision, may indeed reflect cattle very special status. Considering the intensive input, in terms of time and labor, in order to sustain cattle diet requirements at the

daily scale, it is likely that cattle husbandry was conducted on a small scale, possibly through penning, and may have been in the charge of new emerging elites. The connections between specialized cattle husbandry and early urbanism would need further investigation.

6. Conclusion

This new dataset confirms conclusions from previous studies highlighting differences in cattle and sheep husbandry practices in late Longshan age and early Xia dynasty in China. At Xinzhai, the difference in the level of contribution of cultivated millet to cattle and sheep diet is explained by provisioning of cattle with subsequent amounts of millet throughout the year (in certain instances, millet constituted 92−100% of cattle diet over the year), whereas sheep had more variable access to this resource seasonally. A daily scale supplying of cattle with millets would probably require cattle to be kept by the settlement all year round, but also a significant input in terms of labor for constitution of dry fodder, unless this effort was conducted either at a small scale, potentially at the household level, or by highly centralized management, given the low relative importance of cattle at the site in number of remains contra a high socio-symbolic status. In sheep, if this contribution was mostly occurring in late summer time, after the harvest, it may as well be linked to the practice of fertilization of cultivated soils, by allowing sheep to graze on stubble while providing manure in return. Depending the intensity of manuring, this could induce elevated $\delta^{15}N$ values in cereals grown on these soils (Bogaard et al., 2007; Fraser et al., 2011). In return, animals fed these cereals could inherit elevated $\delta^{15}N$ values. This direction of research should be followed in the future, on bone assemblages specifically selected for this purpose. The proposed identification of the seasonal round in sheep and cattle diet management depends partly upon correct interpretation of $\delta^{18}O$ sequences retrieved from their molars. Our interpretation of these sequences as reflecting variability (at the interannual or decadal scales) in the influence of the summer monsoon in this location at the time of occupation considered here (ca. 1800−1705 cal. BC) must be confirmed with analyses of cattle and sheep molars securely submitted to a monsoon climate regime.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2016.02.035.

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