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Pastoralism and Millet Cultivation During the Bronze Age in the Temperate Steppe Region of Northern China

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Eastern and Western Asia were important centers for the domestication of plants and animals and they developed different agricultural practices and systems. The timing, routeway and mechanisms of the exchanges between the two centers have long been important scientific issues. The development of a mixed pastoral system (e.g., with the rearing of sheep, goats and cattle) and millet cultivation in the steppe region of northern China was the result of the link between the two cultures. However, little detailed information is available about the precise timing and mechanisms involved in this mixture of pastoralism and millet cultivation. To try to address the issue, we analyzed the pollen, fungal spores and phytolith contents of soil samples from the Bronze Age Zhukaigou site in the steppe area of North China, which was combined with AMS ^{14}C dating of charcoal, millet and animal bones. A mixed pastoralism and millet agricultural system appeared at the site between 4,000 and 3,700 cal yr BP, and the intensity of animal husbandry increased in the later stage of occupation. Published data indicate that domestic sheep/goats appeared across a wide area of the steppe region of northern China after ~4,000 cal yr BP. A comparison of records of sheep/goat rearing and paleoclimatic records from monsoon area in China leads us to conclude that the mixture of pastoralism and millet cultivation was promoted by the occurrence of drought events during 4,200–4,000 cal yr BP. Moreover, we suggest that mixed rainfed agriculture and animal husbandry increased the adaptability and resilience of the inhabitants of the region which enabled them to occupy the relatively arid environment of the monsoon marginal area of northern China.

Keywords: Zhukaigou site, 4.2 cal kyr BP, sheep/goat rearing, rainfed agriculture, human adaptation

INTRODUCTION

The domestication of plants and animals greatly enhanced human adaptability to environmental changes and at the same time profoundly affected human cultural development and ultimately large urban centers (Zeder, 2008; Lv et al., 2009; Yuan, 2010). Western Asia, Eastern Asia and Central America were important centers for the early domestication of plants and animals. Barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), cattle (*Bos taurus*), sheep (*Ovis aries*) and goats (*Capra aegagrus*) were originally domesticated in Western Asia. Rainfed agriculture, rice cultivation, together with the domestication of dogs (*Canis familiaris*) and pigs (*Sus domestica*) originated in Eastern Asia (pigs were also domesticated in SW Asia), while maize and alpacas were first domesticated in Central America (Cruz-Uribe, 1987; Fuller et al., 2010; Yuan, 2010; Lv, 2018). The exchange and mixture of different agricultural systems during the Holocene enabled humans to adapt to different environments and to environmental fluctuations. The timing, pathways and mechanisms of early agricultural cultural interactions (also known as food globalization) have long been considered an important topic in archaeology and global changes (Jones, 2007; Liu et al., 2019).

The Eurasian steppe is an important routeway of cultural exchanges between the East and West (Frachetti et al., 2012; Qu et al., 2020). Botanical archaeological research has revealed that wheat and barley cultivation spread to the Altay region of the Eurasian steppe as early as 5,200 cal yr BP (Zhou et al., 2020), and subsequently appeared in the Hexi Corridor and in the Shandong Peninsula in China between 4,300 and 4,000 cal yr BP (Dodson et al., 2013; Long et al., 2018). Millet cultivation was practiced in southeast Kazakhstan in Central Asia at ~4,700 cal yr BP, and then spread westward at ~4,000 cal yr BP (Betts et al., 1995; Jones, 2007; Miller et al., 2016; Wang et al., 2017; Hermes et al., 2019).

The spread of pastoralism represented by sheep/goat and cattle rearing provides important evidence for cultural interactions between the East and West. Domesticated sheep/goats appeared in the Mongolian steppe and then spread eastward and southward by at least 5,200 cal yr BP (Li and Song, 2018; Wilkin et al., 2020). Domestic cattle rearing can trace back to 5,500–5,300 cal yr BP at the Houtaomuga site in Northeast China (Cai et al., 2018). The earliest evidence for sheep rearing in China may be from the Shizhaocun and Hetaozhuang sites in the western Loess Plateau (Yuan, 2010). The context of the cultural layer indicated that the interval of sheep rearing was 5,000–5,600 cal yr BP, but the sheep bone have not yet been directly dated (Yuan, 2010). Two important questions regarding this evidence are how this animal husbandry was introduced to Eastern Asia, and whether it was imported together with wheat or other crops. More specially, the transmission mechanism of these agricultural practices, the timing of the domestication of sheep/goats and cattle, and the routeway of their dispersal are unknown.

The steppe of northern China is located in the eastern part of the Eurasian steppe belt, and it includes the steppe regions of the Northeastern Plain, the Inner Mongolia Plateau, the Ordos Plateau, and the Loess Plateau. Overall, these regions have long had a mixed agricultural and pastoral economy due to the arid and semiarid climate, with millet cultivation and animal husbandry (e.g., sheep, goats and cattle) being major components. The combination of millet cultivation, pig rearing and hunting and gathering was the dominant subsistence strategy of the region since before the mid-Holocene, which differs substantially from the agriculture practiced in the region today (Hu and Sun, 2005). The rearing of sheep, goats and cattle, together with other forms of animal husbandry, began to appear in the middle and late Holocene, eventually resulting in the development of a mixed agricultural system based on rainfed cultivation and animal husbandry. The development of this agro-pastoral system enabled the inhabitants of the region to adapt to its climate from wet to dry. However, there is a lack of detailed research on the relationship between the timing of the development of this agro-pastoral system and the environmental background (Zhao, 2006).

To attempt to address this knowledge gap we studied a section at the Zhukaigou (ZKG) site in the steppe region of northern China. Analyses of pollen, phytoliths, and the stable isotope composition of animal bones, combined with AMS^{14}C dating and reference to published botanical and zoological archaeological evidence, enable us to determine the timing of the appearance of this mixed agricultural economy in the study area. We also compare the findings with records of the regional climatic and environmental evolution and develop a possible link between the development of agro-pastoralism and climate change.

STUDY REGION

The Bronze Age site of ZKG is located in the eastern part of the Ordos Plateau in southern Inner Mongolia (**Figure 1**). The archaeological site was discovered in 1974, and so far it has been excavated four times. Archaeological excavations have revealed the remains of houses, ash pits, tombs, other relics, a large amount of pottery, stone artifacts, numerous bone artifacts, bronze artifacts, and abundant animal remains. The pottery type series include tripod jars, basins, pots, spindle whorls and so on. The stone artifacts include axes, chiels, knives and adzes. The Bronze ware includes the famous Ordos bronze dagger, a bronze knife and ornaments (Institute of Cultural relics and Archaeology, Inner Mongolia Autonomous region, 2000). The domestic animal remains excavated at the site include pigs, sheep, cattle and dogs, and wild animals include badger (*Meles*), bear (*Ursus* sp.), leopard (*Panthera pardus*), roe deer (*Capreolus*), red deer (*Cervus elaphus*), and goral (*Noemorhedus goral*) (Huang, 1996). In recent years, the study of archaeobotany has revealed that the inhabitants of the ZKG site grew common millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) (Bao et al., 2018).

Most of the Ordos Plateau, where the ZKG site is located, is a mixed agricultural-pastoral area, while the subsistence strategy in the Mu Us sandy land to the southwest is dominantly animal husbandry. The zonal vegetation is typical steppe dominated by *Stipa bungeana* and *Stipa krylovii*. Due to erosion, desertification

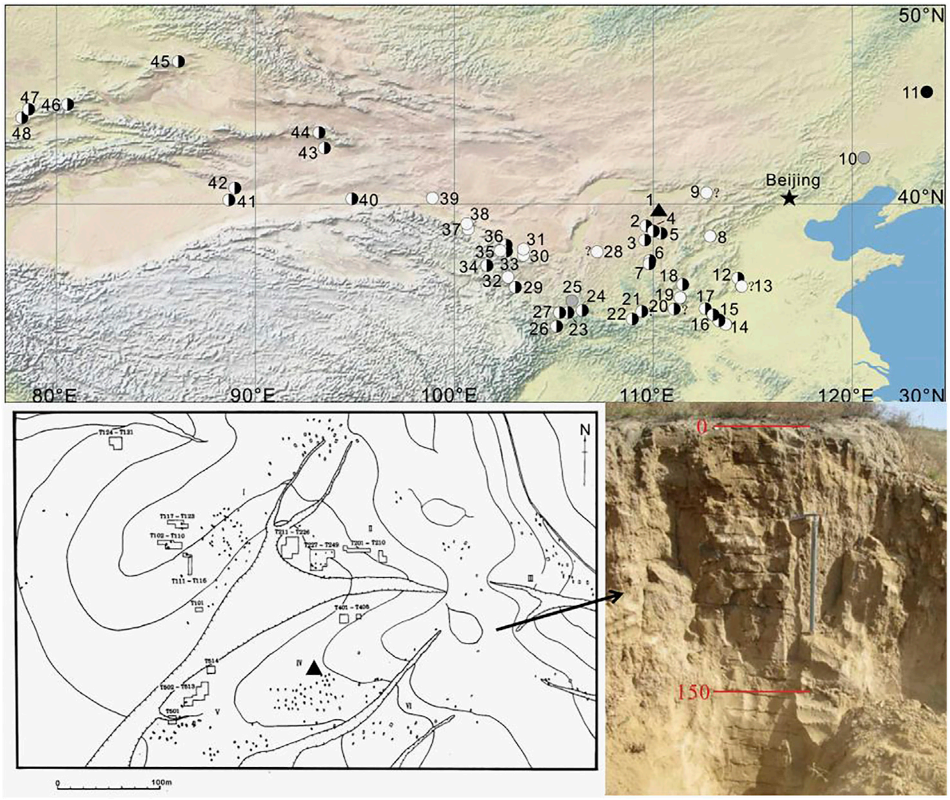

FIGURE 1 | Location of the Zhukaigou site and other sites mentioned in the text. White and black circles indicate sites with the remains of domestic sheep/goat and cattle, respectively. Grey circles indicate sites without the remains of domestic sheep/goat and cattle. "?" indicates a site where it is uncertain whether the sheep/goat or cattle were domesticated. The sites names represented by the numbers are shown in **Table 1**. The Zhukaigou section and its location in the Zhukaigou site. The location map of Zhukaigou site was cited from the Institute of Cultural relics and Archaeology, Inner Mongolia Autonomous region, (2000).

and long-term human activities, desert vegetation has replaced the native steppe vegetation in most of the area. The main plant taxa are: *Artemisia ordosica*, *Caragana*, *Sabina vulgaris* Ant and Salicaceae. The annual average temperature of the region is 5.3–7.5°C and the annual precipitation is 270–400 mm. The climate is arid and semiarid.

MATERIALS AND METHODS

Stratigraphy of the Zhukaigou Section

The ZKG section (39°6′N, 110°3′E) located in the southern of the site, which is 155 cm-deep (**Figure 1**) and contains evidence of human activities, such as pottery and charcoal. According to the color and structural characteristics of the sediments, the section is divided into four layers: 1) 0–40 cm: Light gray sandy silt with abundant charcoal fragments, large calcium carbonate nodules, and small pebbles. 2) 40–70 cm: Light yellow sandy silt with less charcoal than above; abundant larger calcium carbonate nodules, small gravel clasts and gray clay pottery. 3) 70–100 cm: Light gray sandy silt containing occasional charcoal fragments, small calcium carbonate nodules, pebbles and animal remains. 4) 100–155 cm: Pale yellow sandy silt layer containing a small amount of charcoal, fine gravel and gray clay. The natural soil layer is below the depth of 155 cm. In order to determine the age of the sedimentary section, charcoal and grains of millet were selected at the depths of 145 cm, 105 and 60 cm for AMS ^{14}C dating.

AMS ^{14}C Dating of Domesticated Animal Remains at the ZKG Site

Huang, (1996) suggested that the domesticated animals at the ZKG site consist of pigs, sheep and cattle, and they estimated the age of the remains based on AMS ^{14}C dating of charcoal recovered from the strata. So far, however, there has been no direct AMS ^{14}C dating of the remains of domesticated animals at the site, and therefore we selected animal bones from different cultural periods for AMS ^{14}C dating. The AMS ^{14}C dating was conducted at the Beta Laboratory, United States. The dated samples included two pig bones, two sheep bones and one cattle bone, from different cultural layers. The AMS ^{14}C dating results were calibrated using IntCal20 in OxCal 4.3 software (Reimer et al., 2020).

3.3 Pollen and Phytolith Analysis

Fifteen pollen samples of ~30 g weight were analyzed using conventional heavy liquid separation. A known number of

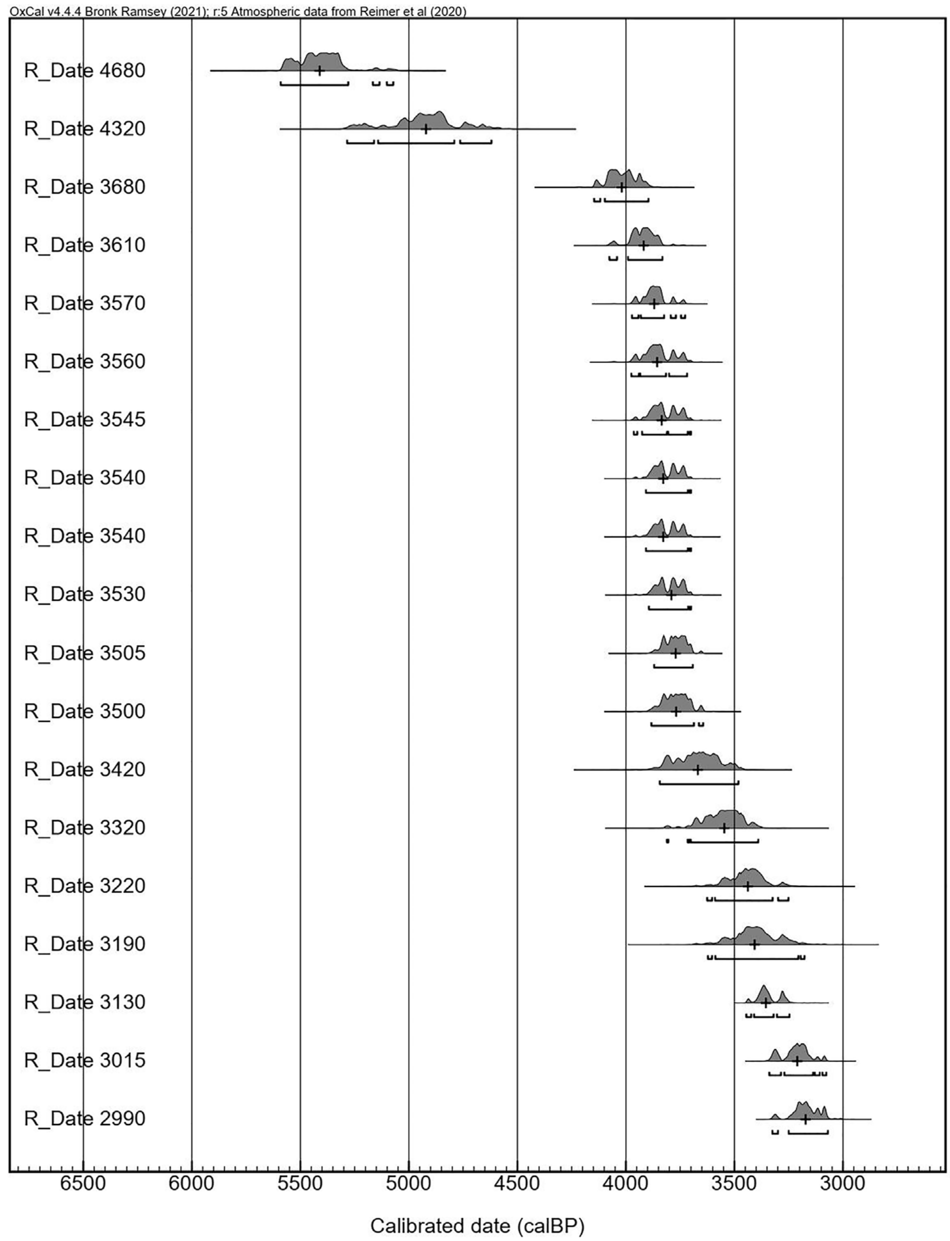

FIGURE 2 | AMS 14C dating results for the samples from the ZKG site. "+" indicates the median age. The ages were determined using OXCAL 4.3 software with the INTCAL20 curve correction (Reimer et al., 2020).

Lycopodium spores was added prior to the preparation to calculate pollen concentrations. The identification of pollen and fungal spores was based on atlases of pollen morphology (Taylor, 1988; Xi and Ning, 1994; Wang et al., 1995; Van Geel et al., 2003; Tang et al., 2016). A pollen and fungal spores diagram was drawn and statistical zonation was conducted using CONISS implemented in Tilia 2.0 (https://www.tiliait.com/). The charcoal content was estimated using point counting. Fifteen samples of ~10 g weight were used for phytolith analysis following the conventional wet oxidation method. Phytoliths were identified with reference to the phytolith key of Wang and Lv (1993), and a phytolith diagram was drawn using Tilia software.

RESULTS

AMS ^{14}C Dating Results

The AMS ^{14}C dating results for the materials from the ZKG are illustrated in **Figure 2** and listed in **Table 1**. The age of charcoal fragments at the depth of 145 cm in the ZKG section is 3,718–3,975 cal yr BP (OZQ360); and that of the depth of

TABLE 1 | The sites names represented by numbers in **Figure 1** and their abbreviations in this study.

Number	Archaeology sites	Abbreviation	Species	Age (cal yr BP)	Reference
1	Zhukaigou	ZKG	*Ovis aries; Bos taurus*	3,247–3,972[a]	This study
2	Muzhuzhuliang	MZZL	*Ovis aries; Bos taurus*	3,800–4,000	Chen et al. (2015)
3	Huoshiliang	HSL	*Ovis aries; Bos taurus*	3,800–4,200	Hu S. M. et al. (2008); Dodson et al., 2014
4	Xinhuacun	XHC	*Ovis aries*; *Bos taurus*	3,820–4,150	Sun et al. (2002)
5	Shimao	SM	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,800–4,300	Hu et al. (2016)
6	Hongliang	HL	*Ovis aries; Capra aegagrus hircus; Bos taurus*	4,186–4,407[a]	Hu, (2021)
7	Jingbianmiaoliang	JBML	*Ovis aries; Capra aegagrus hircus; Bos taurus*	4,151–4,406[a]	Hu, (2021)
8	Youyao	YY	*Ovis aries*	4,000–4,300	Dodson et al. (2014)
9	Shihushan	SHS	*Ovis* sp.	6,000–6,700	Dodson et al. (2014)
10	Xinglonggou	—	—	7,500–8,000	Zhao, (2005)
11	Houtaomuga	—	*Bos taurus*	5,300–5,500	Cai et al. (2018)
12	Yinxu	YX	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,400	Institute of Archaeology, Chinese Academy of Social Sciences, (1994)
13	Baiying	BY	Caprinae	3,500–4,200	Zhou, (1983)
14	Xinzhai	XZ	*Ovis aries/Capra aegagrus hircus*	3,500–3,800	Huang, (2008)
15	Wadian	WD	*Ovis aries; Bos taurus*	3,500–4,300	Lv et al. (2007)
16	Wangchenggang	WCG	*Ovis aries; Bos taurus*	3,700–4,000	School of Archaeology and Museology, Peking University, (2007)
17	Erlitou	ELT	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,500–3,800	Cai et al. (2010)
18	Taosi	TS	*Ovis aries; Bos taurus*	~4,000	Chen et al. (2012)
19	Dongxiafeng	DXF	*Ovis aries*	3,500–3,700	Dodson et al. (2014)
20	Miaodigou	MDG	Caprinae; Bovinae	5,500–6,000	Institute of Archaeology, Chinese Academy of Sciences, (1959)
21	Lingkou	LK	Caprinae; Bovinae	6,100–6,700	Shaanxi Institute of Archaeology, (2004)
22	Kangjia	KJ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	4,000–6,000	Liu et al. (2001)
23	Xishanping	XSP	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,800–4,200	Institute of Archaeology, Chinese Academy of Social Sciences, (1999); Yuan, 2010
24	Qinweijia	QWJ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,800–4,200	Gansu Task Force, Institute of Archaeology, Chinese Academy of Sciences, (1975)
25	Dadiwan	-	-	7,350–7,800	Liu et al. (2004)
26	Xihelanqiao	XHLQ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	2,877–3,450[a]	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
27	Shizhaocun	SZC	*Ovis aries/Capra aegagrus hircus; Bos taurus*	5,000–5600,3800–4,200	Institute of Archaeology, Chinese Academy of Social Sciences, 1999; Yuan, 2010
28	Haba Lake	HBL	*Ovis* sp.	4,500–4,900	Dodson et al. (2014)
29	Dahezhuang	DHZ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,400–3,800	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
30	Shuikou	SK	*Ovis aries/Capra aegagrus hircus*	3,932–4,142[a]	Yang et al. (2019)
31	Guojiashan	GJS	*Ovis aries/Capra aegagrus hircus*	3,500–4,400	Yang et al. (2019)
32	Hetaozhuang	HTZ	*Ovis aries*	5,000–5,600	Yuan, (2010)
33	Mozuizi	MZZ	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,073–3,316[a]	Yang et al. (2019)
34	Changning	CN	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,800–4,200	Cai et al. (2010)
35	Lijiageleng	LJGL	*Ovis aries/Capra aegagrus hircus*	3,588–3,810[a]	Yang et al. (2019)
36	Huangniangniangtai	HNNT	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,600–4,400	Wei, (1978)
37	Donghuishan	DHS	*Ovis aries/Capra aegagrus hircus*	3,481–3,823*	Xu and Zhang, (1995)
38	Xihuishan	XHS	*Ovis aries/Capra aegagrus hircus*	3,481–3,823[a]	Yang et al. (2019)
39	Ganguya	GGY	*Ovis aries/Capra aegagrus hircus*	3,362–3,821[a]	Yang et al. (2019)
40	Dadunwan	DDW	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,218–3,442[a]	Yang et al. (2019)

(Continued on following page)

TABLE 1 | (*Continued*) The sites names represented by numbers in Figure 1 and their abbreviations in this study.

Number	Archaeology sites	Abbreviation	Species	Age (cal yr BP)	Reference
41	Xiaohe	XH	*Ovis aries; Bos taurus*	~4,000	Yang et al. (2014)
42	Gumugou	GMG	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,800–3,900	Wang, (1983)
43	Tianshanbeilu	TSBL	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,300–4,000	Wang et al. (2017)
44	Shirenzigou	-	*Ovis aries; Capra aegagrus hircus; Bos taurus*	~2,300	You et al. (2014)
45	Tongtian cave	TTC	*Ovis aries; Capra aegagrus hircus; Bos taurus*	3,200–5,200	Zhou et al. (2020)
46	Adunqiaolu	ADQL	*Ovis aries/Capra aegagrus hircus; Bos taurus*	3,200–3,850	Cong et al. (2013)
47	Dali	—	*Ovis aries; Capra aegagrus hircus; Bos taurus*	4,700	Hermes et al. (2019)
48	Begash/Tasbas	—	*Ovis aries; Capra aegagrus hircus; Bos taurus*	4,200–4,500	Hermes et al. (2019)

[a]*indicate the ages of the AMS,* ^{14}*C dating of the remains of sheep/goat or cattle bones from the archaeology sites and other ages were deduced from the context of the cultural layer.*

105 cm is 3,700–3,908 cal yr BP (Beta 563,896); the age of carbonized seeds at the depth of 60 cm is 3,700–3,908 cal yr BP (Beta 563,895); and the age of cattle remains is 3,727–3,972 cal yr BP (median age of 3,870 cal yr BP, the same below). The ages of sheep and pig remains from the second cultural stage are 3,700–3,908 cal yr BP (3,828 cal yr BP) and 3,700–3,894 cal yr BP (3,791 cal yr BP). The age of sheep remains from the third cultural stage is 3,247–3,445 cal yr BP (3,355 cal yr BP). The age of pig remains from the fourth cultural stage is 3,070–3,325 cal yr BP (3,172 cal yr BP). Thus, the age range of the remains of domestic animals at the site is 3,070–3,972 cal yr BP. The published AMS ^{14}C ages for the ZKG site are between 4,100 and 3,100 cal yr BP, except for two ages that are older than 4,500 years (**Figure 2**; **Table 2**).

Pollen Analysis

A total of 4,445 pollen grains, comprising 18 families and genera, were identified from the 15 samples analyzed from the ZKG section (**Figure 3**). The main tree pollen types are *Pinus*, *Betula*, *Ulmus* and Fagaceae; and the main shrubs and herb pollen types are *Artemisia*, Chenopodiaceae, *Ephedra*, Asteraceae, Leguminosae, *Tamarix*, *Polygonum*, and Apiaceae. Ferns are rare and include Monoletes, Triletes and Polypodiaceae. The fungal spores are mainly *Sporormiella* and *Srodaria*. The pollen diagram (**Figure 4**) was divided into three zones according to CONISS, and are described below.

Pollen Assemblage Zone I (*Artemisia*-Chenopodiaceae): 155–130 cm. The zone is dominated by herbaceous pollen which is dominated by *Artemisia* (53.7–61.2%; average of 57%), followed by Chenopodiaceae (33.3–43.3%; average of 36.7%. Poaceae is relatively poorly represented (1.5–8.8%; average of 4.3%). The content of *Sporormiella* fungal spores is 0–1.1% (average of 0.6%). The charcoal concentration is low, with an average of 0.9×10^{-2} cm^2 g^{-1}.

Pollen Assemblage Zone II (*Artemisia*-Chenopodiaceae-Poaceae): 130–60 cm. There are substantial changes in the herbaceous taxa compared with Zone I, with a major decrease in Chenopodiaceae (10.4–39.2%; average of 20.8%) and an increase in Poaceae (5.5–49.3%; average of 23.5%). However, *Artemisia* is still well represented (23.9–63.9%; average of 48.4%). The content of fungal spores is slightly higher than in Zone I, including *Sporormiella* (0.0–2.7%; average of 0.8%) and *Sordaria* (0.0–3.6%; average of 0.7%. The concentration of charcoal particles is higher than in the Zone I (1.2–61.8 $\times 10^{-2}$ cm^2 g^{-1}; average of 26.9×10^{-2} cm^2 g^{-1}).

Pollen Assemblage Zone III (*Artemisia*-Chenopodiaceae-Poaceae): 60–0 cm. *Artemisia* (34.7–48.3%, average of 39.6%) and Chenopodiaceae (13.3–26.2%; average of 21.8%) are well represented. The representation of Poaceae (12.5–39%, average of 22.7%) is similar to that of Zone II. There is a substantial increase in the representation of fungal spores, including *Sporormiella* (0–4.5%; average of 1.8%) and *Sordaria* (1.3–3.4%; average of 2.5%). The concentration of charcoal fragments is substantial higher than in Zone II (93–968 $\times 10^{-2}$ cm^2 g^{-1}).

Phytolith Analysis

A total of 9,630 phytoliths were identified in the 15 samples from the ZKG section, comprising 16 taxonomic categories (**Figure 3**). The main morphotypes are: Elongate psilate, Elongate dendritic, Rectangle, Square, Acicular hair cell, Sponge spicules, Saddle, Cuneiform bulliform, Elongate echinate, Tooth type, "Y" type, Fusiform, Bilobate, Triangular prism, and common millet and foxtail millet. The morphotypes for common millet and foxtail millet are "η" and "Ω", repectively (Lv et al., 2009). And they come from husks. There are few other Panicoideae phytoliths in the samples. The phytoliths are dominated by Elongate psilate (25.1–49.9%) and Acicular hair cell (11.2–50.6%). The phytoliths of common millet and foxtail millet occur within the depth interval of 70–135 cm; the lowest representation is 0.2% at a depth of 70 cm and the highest is at 105 cm, representing 33.4 and 41.1% of total phytoliths, respectively. Based on the cluster analysis, the phytolith records can also be divided into three zones (**Figure 5**):

TABLE 2 | ^{14}C dates for the ZGK site.

LabID	Sample ID	Material	^{14}C age (yr BP)	Calibrated age (cal yr BP)	Median age (yr BP)	δ13C ‰	δ15N ‰	C/N	wt.% C	wt.% N	Reference
Beta - 572,544	T246-5	Cattle bone	3,570 ± 30	3,727–3,972	3,870	−15.9	6.6	3.2	41.10	14.93	This study
Beta - 572,543	T232-4	Sheep bone	3,540 ± 30	3,700–3,908	3,828	−17.1	5.6	3.2	41.94	15.28	This study
Beta - 572,542	T231-4	Pig bone	3,530 ± 30	3,700–3,894	3,791	−7.8	6.6	3.2	41.61	15.07	This study
Beta - 572,541	T102H8	Sheep bone	3,130 ± 30	3,247–3,445	3,355	−17.7	5.4	3.2	41.35	14.95	This study
Beta - 578,540	T249-2	Pig bone	2,990 ± 30	3,070–3,325	3,172	−7.1	6.4	3.2	41.03	15.14	This study
Beta - 563,895	ZKG60	Millet seed	3,540 ± 30	3,700–3,908	3,828	−10	—	—	—	—	This study
Beta - 563,896	ZKG105	Charcoal	3,540 ± 30	3,700–3,908	3,828	−25.8	—	—	—	—	This study
OZM232	ZGK4	Human bone	3,680 ± 40	3,896–4,147	4,019	−7.9	8.2	3.2	44	16	Atahan et al. (2014)
OZM221	ZKG Human 2	Human bone	3,500 ± 40	3,644–3,883	3,769	−8.4	9.7	3.2	44	16	Atahan et al. (2014)
OZQ354	ZKG1	Fruit shell	3,610 ± 35	3,832–4,076	3,918	—	—	—	—	—	Bao et al. (2018)
OZQ360	ZKG-S-29	Charcoal	3,560 ± 40	3,718–3,975	3,856	—	—	—	—	—	Bao et al. (2018)
OZQ355	MILLET ZKG2	Millet seeds	3,545 ± 35	3,700–3,964	3,835	—	—	—	—	—	Bao et al. (2018)
OZN201	SI1573	Bone	3,505 ± 30	3,692–3,870	3,771	—	—	—	—	—	Bao et al. (2018)
OZN202	SI1575	Bone	3,015 ± 30	3,077–3,339	3,211	—	—	—	—	—	Bao et al. (2018)
BK79053	IIIT23(5)	Charcoal	4,320 ± 90	4,620–5,285	4,921	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
BK80028	V(2)H5018	Charcoal	3,320 ± 70	3,390–3,811	3,547	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
WB84-76	I(3) H1071,1073	Charcoal	3,220 ± 70	3,251–3,626	3,438	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
WB84-77	I(3)H1055	Charcoal	3,190 ± 85	3,177–3,622	3,407	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
WB84-78	IIT228(4)	Charcoal	4,680 ± 80	5,072–5,591	5,411	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)
WB84-79	I(4)H1058	Charcoal	3,420 ± 70	3,482–3,844	3,669	—	—	—	—	—	Institute of Archaeology, Chinese Academy of Social Sciences, (1983)

Zone I (155–130 cm). The total numbers of phytoliths in zone I are 1,483. Elongate psilate type (37.8–45%) and Acicular hair cell type (40.1–50.6%) are the most common phytoliths. Common millet (1.2%) occurs in a single sample at the depth of 135 cm.

Zone II (130–60 cm). The total numbers of phytoliths in zone II are 5,571. Elongate psilate type (25.1–49.9%) remains the most common phytolith type, and there is a decrease in the Acicular hair cell type (9.6–38.7%). There are increases in the common millet (0–35.1%) and foxtail millet phytolith types (0–7.9%).

Zone III (60–0 cm). The total numbers of phytoliths in zone III are 2,734. The Elongate psilate type (25.3–41.3%) and Acicular hair cell type (24–27.8%) continue to decrease. Square (14.7–32.3%) and Rectangle (7.4–15.4%) increase substantially, and there is a slight increase in the Cuneiform bulliform type. However, the common millet and foxtail millet types disappear.

DISCUSSION

The Agro-Pastoral Economy at the ZKG Site

Phytoliths are tiny siliceous bodies precipitated in plant cells and deposited in the soil. They have distinct morphological characteristics due to differences in plant cell structure and soil type, and moisture and climatic conditions. As an important biological indicator, phytoliths have been widely used in research in palaeovegetation, palaeoecology and agricultural archaeology (Lv et al., 2009).

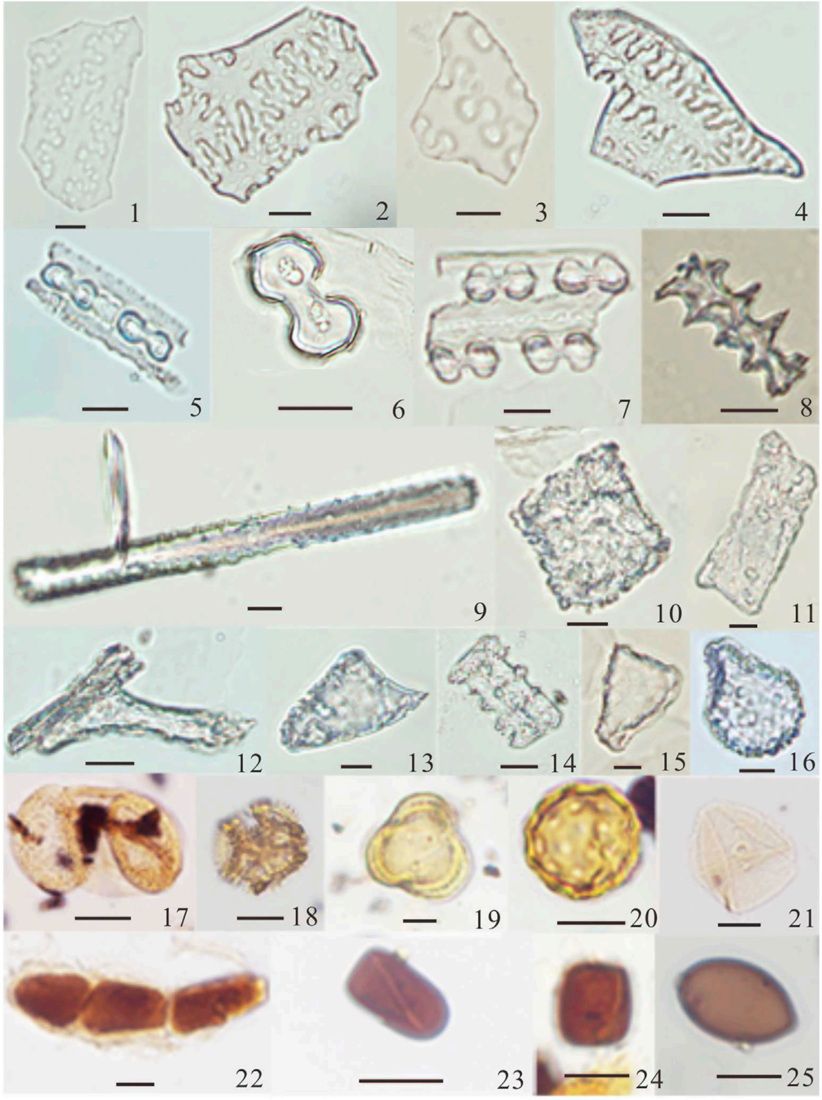

FIGURE 3 | Phytoliths, pollen and fungal spores from the ZKG section. 1, 2, 4, Broomcorn millet husk; 3, Foxtail millet husk; 5-7, Bilobate; 8, Elongate dendritic; 9, Elongate psilate; 10, Square; 11, Rectangle; 12, "Y" type; 13, Acicular hair cell; 14, Tooth type; 15, Fusiform; 16, Cuneiform bulliform; 17, Pinus; 18, Compositae-Taraxacumtype 19, Artemisia; 20, Chenopodiaceae; 21, Poaceae; 22–24, Sporormiella; 25, Sordaria (black lines indicate 10 μm).

The phytoliths of common millet and foxtail millet in the section are direct evidence of the cultivation of the parent plants at the site, and are consistent with the discovery of millet seeds and associated agricultural tools at the site (Institute of Cultural relics and Archaeology, Inner Mongolia Autonomous region, 2000; Bao et al., 2018). The AMS ^{14}C ages of two crop seeds from the ZKG site are 3,700 and 4,000 cal yr BP (median ages of 3,835 and 3,828 cal yr BP, respectively). There is a relatively high abundance of phytoliths in the sediments within this period, indicating that millet was cultivated in the vicinity of the site, and that there was a high intensity of planting activity (**Figure 6**). Phytoliths are absent from the sediments above 60 cm in the ZKG section, which may have been caused by a reduction in rainfed agriculture at the site.

The life cycle of fungal spores is closely related to the activity of herbivores. After breaking dormancy in the intestinal tract of animals, the spores are excreted and then propagate (Van Geel et al., 2011). Many studies have shown that fecal fungal spores can be used as indicators of domestic herbivores (Van Geel et al., 2003; Zhao et al., 2013; Huang et al., 2020, 2021). Therefore, the occurrence of fungal spores in the sediments of the ZKG site indicates the local presence of herbivorous domestic animals, which is consistent with the large quantity of domestic animal remains excavated from the site (Huang, 1996). The distribution of fungal spores in the strata is characterized by low percentages below the depth of 60 cm, indicating limited cattle and sheep rearing at that time, while the increased percentages above 60 cm indicate that animal husbandry increased (**Figure 6**).

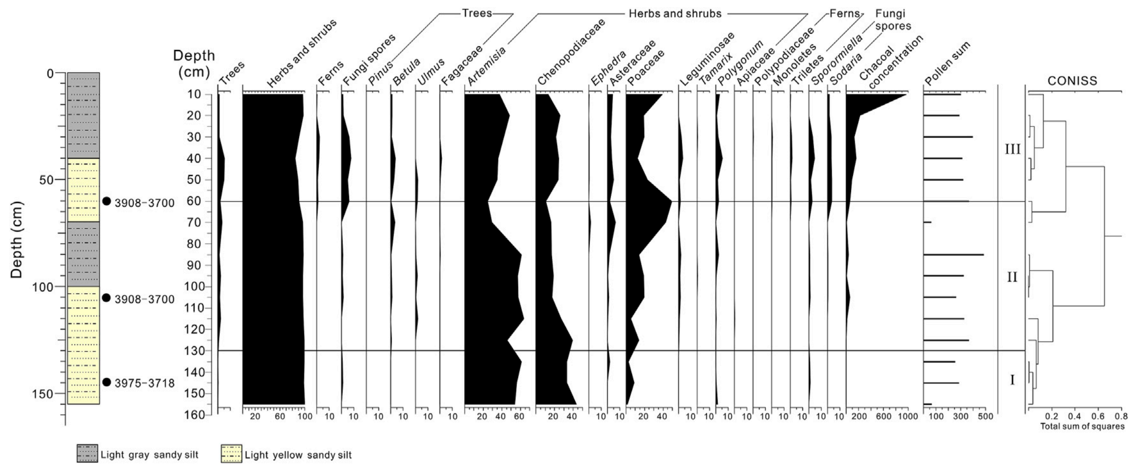

FIGURE 4 | Pollen percentage diagram for the ZKG section (only the major taxa are shown). The contents of fungal spores and charcoal particles are also shown.

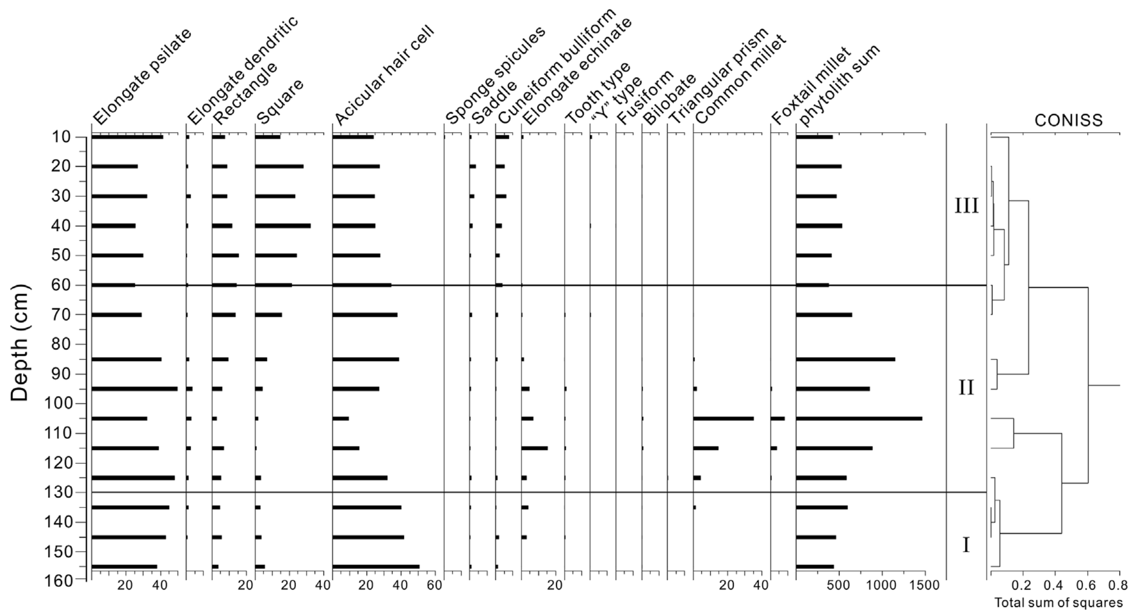

FIGURE 5 | Percentage diagram of the main phytolith types for the ZKG section.

The carbon isotope composition ($\delta^{13}C$) of the bones of domesticated pigs, cattle and sheep can reflect their diet and hence human feeding strategies (Hu S. M. et al., 2008; Chen et al., 2012). The $\delta^{13}C$ values of carbon isotopes of two pig bones from the ZKG site are −7.1‰ (3,791 cal yr BP) and −7.2‰ (3,172 cal yr BP), which indicates that their food was dominated by C_4 plant types. The $\delta^{13}C$ values of pigs are similar to those of human bones at the ZKG site (Atahan et al., 2014) (**Table 2**); moreover, the $\delta^{13}C$ values of the bones of humans and domestic pigs in North China are similar (Hu Y. W. et al., 2008). The $\delta^{13}C$ values of cattle and sheep indicate that C_3 plants were the dominant plant types consumed by these animals at the ZKG site. The $\delta^{13}C$ of cattle is also ~1‰ more positive than that of sheep, which may be related to the consumption of cultivated millet and millet byproducts. The Taosi site in the Central Plains is an important symbol of Chinese large urban centers (**Figure 1**; **Table 1**). The $\delta^{13}C$ values (average −11.25‰) of cattle bones at the Taosi site are indicative of a diet dominated C_4 plants, which may reflect the supply of fodder by humans (Chen et al., 2012). However, the $\delta^{13}C$ values of cattle bones at ZKG indicates that a lower proportion of C_4 plants was consumed than at the Taosi site.

The evidence provided by the contents of phytoliths and fungal spores of the section, combined with the archaeological evidence, reveals that a mixed agro-pastoral economy consisting of rainfed millet cultivation and animal husbandry (cattle and sheep) appeared at the ZKG site some 4,000 years ago. However,

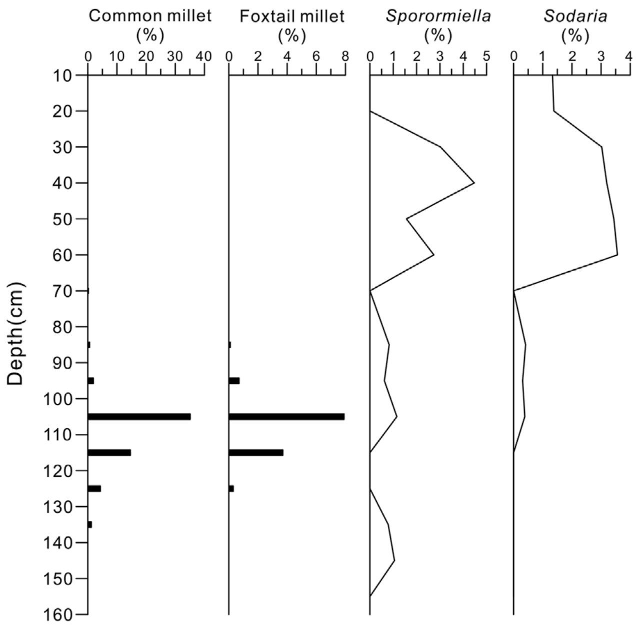

FIGURE 6 | Contents of common millet and foxtail millet phytoliths and fungal spores inthe ZKG section.

there were changes in the relative proportions of rainfed millet cultivation and pastoralism over time. Rainfed millet cultivation accounted for a high proportion of the agricultural activity in the early phase, but the proportion of pastoral activity increased subsequently. The nitrogen isotope composition ($\delta^{15}N$) of two human bones from ZKG were 8.2 and 9.7‰ (median ages of 4,019 cal yr BP and 3,769 cal yr BP, respectively). The 1.5‰ difference between the two indicates an increase of the nitrogen intake and hence an increase in animal husbandry (Atahan et al., 2014). Pig bones dating back 3,200 years have been found at the ZKG site, and pig rearing is direct evidence of settled agriculture. Although there may have been cultural or genetic exchanges with the Andronovo culture (Institute of Cultural relics and Archaeology, Inner Mongolia Autonomous region, 2000; Jeong et al., 2020; Wang et al., 2021), the area remained dominated by a settled agro-pastoral economy from the middle to the late Bronze Age (4,000–5,000 cal yr BP).

Agro-Pastoralism in the Steppe Region of Northern China

In the early mid-Holocene, human activity in the forest and steppe region of northern China mainly took the form of rainfed agriculture and pig rearing. For example, millet cultivation appeared at the Xinglonggou site in the West Liaohe River Basin between 8,000 and 7,500 cal yr BP (Zhao, 2005), and at the Dadiwan site, in the western part of the Loess Plateau, at 7,800–7,350 years cal yr BP (Liu et al., 2004). Pig rearing was also conducted at both sites. Agricultural tools have been excavated from Shihushan (6,700–6,000 cal yr BP), Wangmushan (5,300–4,900 cal yr BP), Xiyuan (5,000–4,800 cal yr BP) and Ashan (4,400–3,800 cal BP) in the northern Loess Plateau and in the Hetao area of the Ordos Plateau (Yang, 1997; Bao et al., 2018; Feng and Wei, 2018). We speculate that they are related to millet agriculture. But usewear and residue analyses on food processing stone tools from these sites have shown that plants including tubers are dominant (Liu et al., 2014; 2016). The seeds have been found from Xiaojiamao, Dakou, Zhaimao, Zhukaigou, Shimao sites (Bao et al., 2018). Millet, a C_4 plant, was an important food source for humans in the steppe region of northern China during 2,500–5,000 cal yr BP, then the ratio of C_3 plants in the diet began to increase after 2,500 cal yr BP (Atahan et al., 2014).

Evidence of cattle and sheep rearing gradually appeared in the region in the middle and late Holocene (from the time of the Longshan culture to the Bronze Age). For example, AMS ^{14}C ages of the remains of domestic cattle at Houtaomuga of 5,500–5,300 cal yr BP were obtained (Cai et al., 2018). AMS ^{14}C ages of 4,577–4,454 cal yr BP were obtained for cattle remains at the Ashan site, but it is unclear if they were domesticated (Bao et al., 2018). The latest AMS ^{14}C dating of cattle bone from the Hongliang site were 4,406–4,186 cal yr BP (Hu, 2021). The first directly cattle bones for the Hexi Corridor region, with the samples dating to 3,850–3,700 cal yr BP (Brunson et al., 2020). The earliest evidence of domestic sheep/goats in China may be at the Shizhaocun and Hetaozhuang sites in the western Loess Plateau; the estimated age range is 5,600–5,000 cal yr BP based on the archaeological context, but no direct AMS ^{14}C ages were reported (Yuan, 2010).

So far, published AMS ^{14}C ages for the remains of the earlist domesticated sheep/goats come from the Youyao (4,292–4,029 cal yr BP) site (Dodson et al., 2014). AMS ^{14}C ages of 4,406–4,151 cal yr BP were obtained for three sheep bones at the Jingbianmiaoliang site (Hu, 2021). An AMS ^{14}C age of 3,925 cal yr BP was obtained for sheep skin at Gumugou in Xinjiang (Wang, 1983). The dating results for mixed human and sheep bones from Xihe Lanqiao in Gansu Province are 3,450–2,877 cal yr BP (Chinese Archaeological Radiocarbon Collection, 1983). In addition, the AMS ^{14}C dating results for sheep/goat bones from Hexi Corridor are 4,413–3,073 cal yr BP (Yang et al., 2019). Other dates for sheep or cattle remains have been obtained for the sites of Shimao (4,300–3,800 cal yr BP), Muzhuzhuliang (~4,000 cal yr BP) and Zhengzemao (~4,800 cal yr BP) in Shaanxi Province; Yongxingdian in Zhunger Qi in Inner Mongolia Province (4,450–3,950 cal yr BP); Dakou (4,200–3,500 cal yr BP) and Taosi in Shanxi Province (~4,000 cal yr BP); and Yuanqu Shangcheng (3,300–2,800 cal yr BP), Tongtian cave (5,200–3,200 cal yr BP), Adunqiaolu (3,850–3,200 cal yr BP), Xiaohe (4,000 cal yr BP) and Shirenzigou (2,300 cal yr BP) in Xinjiang. However, no direct AMS ^{14}C dating has been reported (**Figure 6**) (Wei, 2000; Cong et al., 2013; You et al., 2014; Yu et al., 2018).

Opposite to the eastern end of the Eurasian steppe (including the steppe region of northern China), the Yamnaya culture (5,300–4,200 cal BP) originated in the western part of the Eurasian steppe and practiced an economy based on hunting and grazing. The Yamnaya people spread eastward and reached Lake Baikal, which

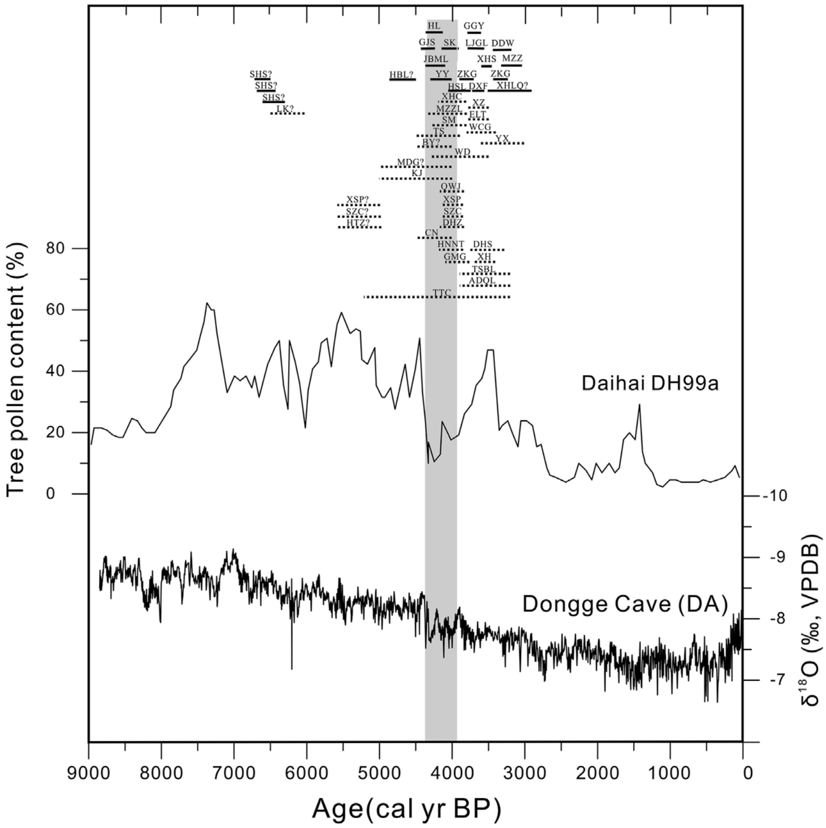

FIGURE 7 | Ages of the remains of domestic sheep at sites in North China (solid line indicates AMS 14C ages, dashed line indicates age inferred from the cultural context, and "?" indicates that it is uncertain whether the sheep were domesticated). Also shown are tree pollen percentages from Daihai (Xiao et al., 2004) and the oxygen isotope record from Dongge cave (Wang et al., 2017). The grey shading represents drought events at ~4,200 cal yr BP. The full names of the sites are shown in **Table 1**.

was the eastern limit of their extension (Zhou et al., 2020; Wang et al., 2021; Narasimhan, et al., 2019). The Afanasyevo culture (5,000–3,500 cal yr BP), which was believed to have been formed by the eastward spread of the Yamnaya culture (Cong and Jia, 2020; Honeychurch et al., 2021). And the Afanasyevo culture which appeared in the central Eurasian steppe, was characterized by sheep/goat and cattle rearing (Honeychurch et al., 2021). During the middle and late Bronze Age, the Andronovo culture (1900–1,500 cal yr BP) developed in the central Eurasian steppe. Several studies have proposed that practiced a sedentary from of animal grazing, and raised animals such as horses, sheep/goat and cattle (Kuzmina, 2008).

According to recent ancient DNA research, during the early Bronze Age there was a possible cultural connection between the populations of Yamnaya and the Eastern Eurasian steppe (Wang et al., 2021). The economy of the steppe of northern China at this time was dominated by rainfed agriculture and pig rearing. Cattle and sheep/goat were also raised sporadically, but did not play the dominant role. By the middle to late Bronze Age, cattle and sheep/goat rearing had increased substantially, similar to the subsistence economy of the Andronovo culture, but horse raising was uncommon. According to this study, the mixed economy of rainfed agriculture and cattle and sheep/goat rearing in the steppe region of northern China was practiced as early as 4,000 years ago. In addition to cultural influences from the central and western steppe areas, climatic and environmental changes were an important factor that must be considered when interpreting patterns of subsistence activity, which is discussed below.

Climatic Influence on the Mixture of Pastoralism and Millet Cultivation in the Steppe Region of Northern China

The steppe region of northern China, dominated by arid and semiarid ecosystems, is located on the margin of the zone of influence of the Asian summer monsoon. A shift in the East Asian monsoon occurred some 4,000 years ago and it had an important impact on the environment of East Asia. Stalagmite records from Dongge Cave show that the intensity of the Asian summer monsoon weakened from 4,400 years BP to 3,900 years BP corresponding to a decrease in North Atlantic sea surface temperatures (Bond et al., 1997; Demenocal et al., 2000; Wang, 2017) (**Figure 7**). Pollen records and quantitative palaeoclimatic reconstructions from Gonghai in Taihang Mountain and

Tianchi in Liupan Mountain indicate a substantial decrease in precipitation in the monsoon margin zone at ~4,000 years BP (Zhang et al., 2010; Chen, 2015; Li et al., 2017). Additionally, the pollen percentages of Chenopodiaceae increased significantly during 4,400–3,350 cal yr BP at Hulun Lake, indicating arid climatic conditions (Wen et al., 2010).

According to a comprehensive study of environmental and archaeological records (Cui et al., 2019; Sun et al., 2019), the decline of major Neolithic cultures in China was closely related to the weakening of the monsoon some 4,000 years ago. Neolithic cultures, such as the Qijia, Laohushan, Hongshan, Longshan and Liangzhu, all declined and ended in or after this period (Wu and Liu, 2001; Mo et al., 2003; An et al., 2005; Yang et al., 2015).

Major drought events at ~4,000 cal yr BP and their impacts may have been of global extent. The drought event during 4,200–3,900 years BP caused the abrupt decline of the Akkadian empire in Mesopotamia; and large urban centers in Egypt, on the Nile, and in India, on the Indus, also declined at the same time. Moreover, large urban centers in Anatolia, Aegean and Levant also developed during the Bronze Age (Weiss et al., 1993; Weiss and Bradley, 2001). The occurrence of severe droughts is suggested to have been a major cause of the declines of these large urban centers, on the one hand, and on the rise of a nomadic culture in steppe regions (Weiss and Bradley, 2001).

Tree pollen percentages in the Daihai DH99 drill core decreased substantially during 4,450–3,950 cal yr BP, while herb pollen types increased, indicating a pronounced cold and dry interval in the marginal area of the summer monsoon zone (Xiao et al., 2004) (**Figure 7**). The pollen record from the Zhukaigou site also suggests typical steppe vegetation, dominated by *Artemisia* and Chenopodiaceae, that would have favored the development of cattle and sheep rearing. Sheep/goats and cattle may have appeared in northern China some 5,000 years ago, but they were not universally raised. The period after the 4,200 years BP drought event, with substantially decreased precipitation and the expansion of steppe vegetation, coincided with a substantial increase in the numbers of domestic cattle and sheep (**Figure 7**). The low crop yields during this arid period may have been insufficient to support the population, while on the other hand the steppe vegetation benefited a pastoral economy. It is evident that the inhabitants of the region were able to adapt to these major environmental changes and adopt a modified economic structure which enabled the population carrying capacity of the land to be maintained. Therefore, we suggest that the combination of rainfed agriculture and pastoralism increased the adaptability of the inhabitants of northern China to arid conditions and increased their socioeconomic resilience.

CONCLUSION

A combined analysis of fungal spores, pollen and phytoliths of a sedimentary section at the Bronze Age ZKG archaeological site, combined with the results of AMS ^{14}C dating of domestic animal remains, reveals that the inhabitants of the site relied on millet cultivation and pastoralism. The intensity of pastoralism increased from the early to the late stage at the site. The mixture of pastoralism and millet cultivation was common in the steppe region of northern China after ~4,000 cal yr BP. The 4,200 years BP climatic event was likely an important factor responsible for the development of a mixed agro-pastoral economy in the region.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the animal study in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

YaZ and KZ did the research and wrote the article. YiZ identified the animal materials. SH and XZ participated in the research and offered suggestions for the article. LL participated in the identification of phytoliths experiment. JL participated in stable isotope experiment. XL guided the experiment and offered suggestions for the article.

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