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The Circulation of Ancient Animal Resources Across the Yellow River Basin: A Preliminary Bayesian Re-evaluation of Sr Isotope Data From the Early Neolithic to the Western Zhou Dynasty

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Many questions still remain regarding the acquisition and circulation of ancient domesticated animals across the Yellow River Basin, one of the key areas for the development of complex societies in ancient China. Here, we re-evaluate previously published strontium isotope data (^{87}Sr/^{86}Sr, $n = 167$) from tooth enamel of domesticated animals at 10 archaeological sites in the Yellow River Basin to shed new light on the transition between the Neolithic (7000–5000 BCE) and the Western Zhou Dynasty (1046–771 BCE). The results show that from the Late Neolithic to the Western Zhou Dynasty, some domesticated animals, mostly cattle and sheep, were increasingly sourced from non-local areas. We employed Bayesian methods to define an isoscape of bioavailable Sr for the Yellow River Basin and to show the considerable diversity in the origins of non-local domesticated animals, some of which may have come from locations hundreds of kilometers away from the site as early as the Late Neolithic. The increasingly variable ^{87}Sr/^{86}Sr ratios of domesticated animals from the Neolithic to the Western Zhou Dynasty are consistent with that of associated human remains, and also match the archaeological and zooarchaeological evidence for increased circulation of animal products in the Yellow River Basin. Therefore, we infer that local economies increasingly incorporated non-local animals as part of wider circulation networks that emerged with the development of complex societies since the Late Neolithic.

Keywords: strontium isotopes, isoscape, zooarchaeology, Yellow River Basin, animal mobility

INTRODUCTION

The Yellow River Basin is often considered the birthplace of ancient Chinese civilization, making this area the focus of archaeological research for decades (e.g., Liu and Chen, 2012; Chen et al., 2016; Dong et al., 2017; Li et al., 2020). As the geographic and cultural center of China, the Yellow River Basin hosted increasingly complex societies dating from the Neolithic to the Bronze Age, including the first agricultural villages and the earliest state-level and urban societies in China (Liu and Chen, 2003; Liu, 2009). Archaeological evidence from these periods revealed that settlement patterns, subsistence practices, mortuary customs, and circulation networks dramatically changed from the Early Neolithic (7000–5000 BCE) to the Western Zhou Dynasty (1046–771 BCE), laying the foundation for the subsequent development of ancient civilizations in China (Chang, 1986; Liu and Chen, 2012; Underhill, 2013; Shelach-Lavi and Jaffe, 2014; Zhang et al., 2020).

Through these different time periods, animals remained a consistent and essential part of the subsistence, ritual, and economic lifeways of past societies living within the Yellow River Basin (Yuan, 2002, 2015; Yuan and Flad, 2005; Dong and Yuan, 2020). As a result, information from zooarchaeological remains related to changes in animal communities, management, and origins can be immensely important indicators of economic and societal changes, providing a major contribution to our growing understanding of the societal transitions in the Yellow River Basin. Previous zooarchaeological research within the Yellow River Basin has mainly focused on the history of animal domestication and exploitation strategies. This revealed that pigs were domesticated independently in China (Cucchi et al., 2011; Dong et al., 2020), while sheep and goats were introduced into the middle and lower Yellow River Basin from West Asia during the Early Longshan period (ca. 2500 BCE, Flad et al., 2007; Cai et al., 2011), quickly being distributed within the basin during the Late Longshan period (2500–1900 BCE) and the Bronze Age (1900–500 BCE, Liu and Ma, 2017). Domesticated cattle firstly appeared in northern China between 3000 and 2000 BCE, and later was widely dispersed through the entire Yellow River Basin (Cai et al., 2014; Liu and Ma, 2017). Horses were introduced to China by the second millennium BCE and were adopted by the Shang elite as a prestige animal used in sacrificial activities (Yuan and Flad, 2005). With increasing social complexity and political centralization within northern China starting at the Late Neolithic, sheep/goats and cattle not only complemented pigs and dogs for meat consumption and ritual activities, but also provided secondary products, such as transportation of goods, wool, milk, and traction (Owlett et al., 2018; Yuan et al., 2020). Evidence of sheep kill-off patterns at Taosi and Erlitou suggested that sheep were used as a source of traded secondary products, such as wool exploitation (Li, 2014; Li et al., 2014; Brunson et al., 2016). The increasingly important use of these animals lead to a marked rise in the number of animals buried in sites from the Late Neolithic. For instance, the number of sheep bones clearly increased (almost in equal proportion with pigs) at Taosi between the middle and late periods (Tao, 2007; Brunson, 2008). During the early periods of Erlitou, cattle and sheep accounted for more than 25% of the zooarchaeological assemblage, and by the late periods rose to more than 42%, a trend that continued throughout the Bronze Age within the basin (Li et al., 2014).

Zooarchaeological evidence can also provide useful insights into ancient networks of circulation, here understood as the human behaviors associated with the acquisition, trade, and exchange, of animals between and among different villages and communities (Yuan and Flad, 2005; Liu and Chen, 2012). With an increase in the demand for animal resources to be employed in more diverse set of roles during the Late Neolithic and Bronze Age, long-distance circulation of animal resources are believed to have led to an increase in imports from areas surrounding and beyond the Yellow River Basin (Flad et al., 2007; Liu and Chen, 2012; Cao, 2014; Yuan, 2015). However, zooarchaeological evidence for mobility may be insufficient (e.g., Shimao, Owlett et al., 2018) and unlikely to offer a precise geographical origin for animals within vast regions such as those managed by past human societies across China.

Strontium isotope ($^{87}Sr/^{86}Sr$) analysis has been widely used to identify and source non-local animals in prehistoric and historical zooarchaeological assemblages (Ericson, 1985; Bentley, 2006; Britton et al., 2011). Strontium has four stable isotopes ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr. Among them, ^{87}Sr is radiogenic, as it is produced by the β-decay of rubidium (^{87}Rb). The relative abundance of ^{87}Sr compared to ^{86}Sr varies across geologic materials, according to their age and the original bedrock $^{87}Rb/^{86}Sr$ ratios (Faure, 1986). Since strontium has an electron configuration similar to calcium, strontium released from weathered rocks enters into the soil, water, and plants, and becomes incorporated into animal skeletal tissues. Once absorbed into plant and animal tissues, strontium acts as a substitute for calcium and has a small mass-dependent fractionation which can be corrected during mass spectrometric analysis (Bentley, 2006; Moynier et al., 2012). In the case of human teeth, $^{87}Sr/^{86}Sr$ of tooth enamel which formed during childhood does not change over the course of a lifetime, meaning that the method can be employed to assess the geological location of an individual's early childhood (Montgomery, 2010; Thornton, 2011). Although the underlying geology predominately determines the Sr isotopic compositions of biosphere materials, there are many factors that influence the $^{87}Sr/^{86}Sr$ of the biosphere, including atmospheric deposition, different weathering rates of minerals within rocks, anthropogenic disturbances to the environment and general topographic processes (Graustein and Armstrong, 1983; Evans et al., 2009; Hartman and Richards, 2014; Thomsen and Andreasen, 2019). Therefore, when establishing $^{87}Sr/^{86}Sr$ ratios for a given area, it is necessary to measure bioavailable $^{87}Sr/^{86}Sr$ ratios in biosphere materials instead of predicting ratios exclusively based on bedrock geology.

Strontium isotopes have been used to investigate early hominin landscape use and to examine the influence of climate change on early human mobility strategies (e.g., Copeland et al., 2011; Lugli et al., 2019). In later time periods, strontium isotopes have been used to inform archaeological perspectives on different modes of social organization in the ancient world (e.g., Knipper et al., 2017; Mittnik et al., 2019) and to assess the movement patterns in different animal species within paleoecological and archaeological studies (e.g., Pleistocene extinct megafauna, bird and fish species, domesticated animals such as pig mobility at Stonehenge) (Hoppe et al., 1999; Brennan et al., 2019; Madgwick et al., 2019).

To date, thousands of sites with abundant faunal materials have been excavated across the Yellow River Basin (Campbell et al., 2011; Bao, 2014). Previous strontium isotopic studies preliminarily distinguished between non-local and local animals at a given site (Yin, 2008; Zhao et al., 2011a,b; Zhao et al., 2015, 2016a,b; Lan, 2017; Fang, 2018; Wu, 2018; Zhao, 2018; Zhao et al., 2018; Wu et al., 2019). Although these studies provided useful insights it is also relevant to notice that:

(1) Most of the studies were published in local Chinese journals and rarely translated into English;
(2) The studies are often focused on a single site and lack a discussion on the acquisition and circulation of animals across time;
(3) The studies lack an in-depth discussion of the geographic origins of exotic animals as there is no baseline map available for the Yellow River Basin.

In this paper, we re-evaluate previously published animal strontium isotope data to investigate animal resource circulation from the Neolithic until the Western Zhou Dynasty across the Yellow River Basin. We establish a bioavailable Sr baseline map for the Yellow River Basin using a novel Bayesian modeling method (AverageR) which, in turn, allow us to employ another Bayesian model (LocateR) to determine the place of origin of animals and thus offer insights into their movements and circulation across the landscape.

MATERIALS AND METHODS

Archaeological Sites

In this study, we compiled $^{87}Sr/^{86}Sr$ data from 167 animal enamel samples (including pig, cattle, sheep/goat, horses, and dogs) from 10 archaeological sites distributed across the Yellow River Basin (**Supplementary Table 1**) and dating from the Early Neolithic until the Western Zhou Dynasty. Investigated sites cover Jiahu, an Early Neolithic (7000–5000 BCE) village, a series of sites dating to the Middle to the Late Neolithic (5000–2000 BCE), Qingliangsi, Lajia, Jiaojia, Taosi, and Shimao, Erlitou and Wangjinglou dating to the Erlitou-Erligang periods (1900/1800–1250 BCE), Yinxu dating to the Late Shang Dynasty (1250–1046 BCE), and finally, Zaoshugounao dating to the Predynastic-Zhou and Western Zhou Dynasty (1046–771 BCE). Most of these sites are located along the middle reaches of the Yellow River (**Figure 1**), while Lajia is the only site from the upper course of the river and Jiaojia is located in the lower reaches of the river. Most of the sites are located in areas with similar geological backgrounds. Information concerning the excavation of these sites is given in **Supplementary Information**.

Modeling Methods for $^{87}Sr/^{86}Sr$ Baseline and Place of Origin

Within isotopic studies of past mobility, when the $^{87}Sr/^{86}Sr$ ratios for ancient human or animal tooth enamel formed during early lifetime differ from an established $^{87}Sr/^{86}Sr$ baseline at the location of their burial, it is assumed that this likely indicates that investigated human and animals migrated from regions with different isotopic signatures for bioavailable $^{87}Sr/^{86}Sr$ ratios (Evans et al., 2010; Montgomery, 2010). However, distinguishing

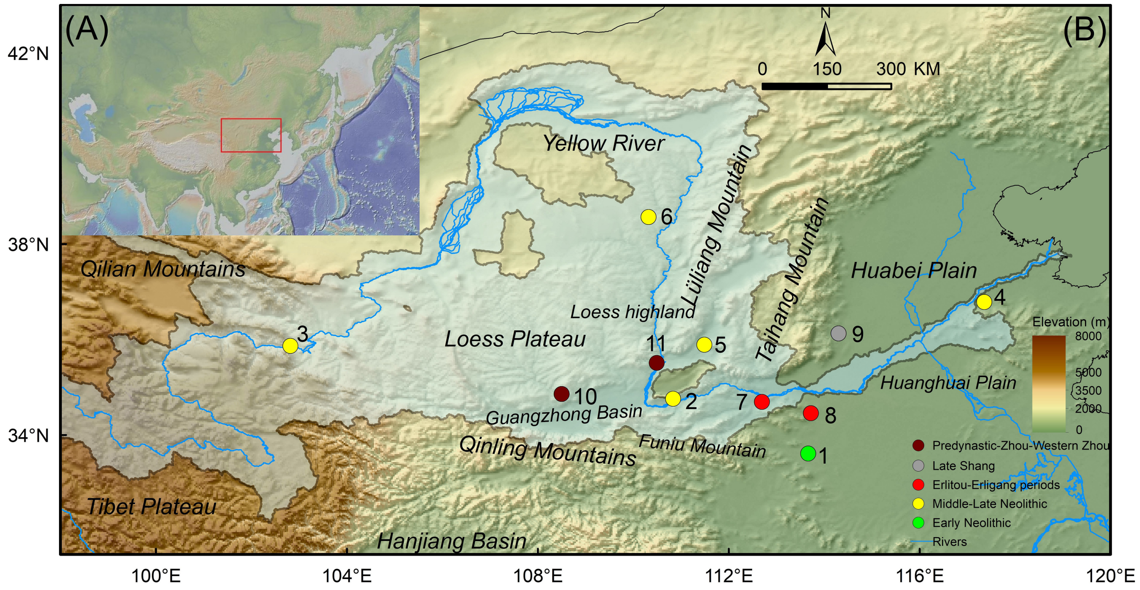

FIGURE 1 | (A,B) shows the current Yellow River drainage basin (blue shaded area) and its surroundings, as well as the archaeological sites referred in the study. (1) Jiahu; (2) Qingliangsi; (3) Lajia; (4) Jiaojia; (5) Taosi; (6) Shimao; (7) Erlitou; (8) Wangjinglou; (9) Yinxu; (10) Zaoshugounao; (11) Ruicheng. **(A)** was created using the software GeoMapApp (http://www.geomapapp.org) (Ryan et al., 2009).

non-locals from locals and identifying their possible geographic place of origin are challenging and require an accurate baseline map showing the distribution of bioavailable $^{87}Sr/^{86}Sr$ across a wide region (Bataille et al., 2020; Wang and Tang, 2020). In practice, directly sampled environmental materials, such as soil leachates, surface and groundwater, plants, and animal skeletons, form the basis of bioavailable $^{87}Sr/^{86}Sr$ maps (Bentley and Knipper, 2005; Maurer et al., 2012; Ventresca Miller et al., 2017; Snoeck et al., 2020). Recent advances in computational modeling, such as multi-source mixing models and random forest regression models employed a combination of baseline data and geological information to produce large-scale $^{87}Sr/^{86}Sr$ maps for the USA, Europe, the circum-Caribbean region, and also to assess global scale $^{87}Sr/^{86}Sr$ variability (e.g., Bataille and Bowen, 2012; Bataille et al., 2012, 2014, 2018, 2020; Willmes et al., 2018; Hoogewerff et al., 2019).

Unfortunately, the absence of a bioavailable $^{87}Sr/^{86}Sr$ map for the Yellow River Basin has hindered the use of strontium isotope methods for archaeological provenance studies in the region. To remedy this situation, we relied on previously published measurements on biosphere samples (**Supplementary Table 2**), including surface water, shallow groundwater, plants, snail shells, loess leachates, and low-mobility animals. From this data we employed Bayesian modeling to generate a $^{87}Sr/^{86}Sr$ baseline map across the Yellow River Basin and probability density maps to identify possible spatial origins for archaeological animals. This baseline map and assignment of animal origins are highly dependent on the density and types of analyzed samples that are currently available for the Yellow River Basin (Maurer et al., 2012; Willmes et al., 2018). To improve the reliability of spatial modeling, some samples were removed prior to analysis: (1) if measurement standards deviated considerably from reference values (>0.00003) or these were not reported; (2) if river samples may have been influenced of modern pollution; (3) using spatial statistical analysis to detect outliers. We calculated the global spatial autocorrelation (Moran's I) to test the spatial autocorrelation of $^{87}Sr/^{86}Sr$ data, which revealed a positive spatial autocorrelation (z-scores: 29.27, p-value < 0.05). A cluster/outlier analysis using Anselin's Local Moran's I was applied to test for local spatial autocorrelation to remove outliers (Anselin, 1995) following the method described by Pellegrini et al. (2016) and Scaffidi and Knudson (2020). Spatial statistical analysis was conducted using ESRI ArcMAP 10.2.

We produced a Bayesian spatial $^{87}Sr/^{86}Sr$ isoscape from 477 published samples using the Bayesian model AverageR available as an R-based (R Core Team, 2013) Open Access app, developed within the Pandora & IsoMemo initiatives (https://www.isomemoapp.com/). AverageR is a generalized additive mixed model that uses a thin plate regression spline (Wood, 2003). This spline smoother uses a Bayesian smoothing parameter governing the smoothness of the surface which is estimated from the data and a trade-off bias against variance to make the optimal prediction for new, unseen data (Wood, 2003; Groß, 2016; Rosenstock et al., 2019). By introducing a random intercept for the site, intra-site as well as the inter-site variation was employed in estimating uncertainty, expressed as a standard error of the mean. More specifically, we employ the following modeling formula:

$$Y_{ij} = s\left(\text{longitude}, \text{latitude}\right) + u_i + \varepsilon_{ij}$$

where:

Y_{ij}: independent variable for site i and individual j
s (longitude, latitude): spline smoother (Wood, 2003)
$u_i \sim N(0, \sigma_u)$: random intercept for site i.
$\varepsilon_{ij} \sim N(0, \sigma_\varepsilon)$: residual error for individual j in site i

The posterior distribution (P_x) generated by AverageR is given as:

$$P_x(y|\text{long}, \text{lat}) \sim N(\mu\left(\text{long}, \text{lat}\right), \sigma(\text{long}, \text{lat}))$$

To identify the place of origin for archaeological animals, we employed the Bayesian model LocateR, also developed within the Pandora & IsoMemo initiatives (https://www.isomemoapp.com/). Let x^* be an observed measurements with unknown location. Within the model LocateR, a measure of likelihood that a certain value x^* originates from a specific location is then the density of the posterior distribution P_x at point x^*:

$$P_x(x^*|\text{long}, \text{lat})$$

If the value x^* inherits some uncertainty σ_x^*, i.e., $x^* \sim N(\mu^*, \sigma^*)$, then we look for the overlap of both distributions, i.e., area of overlap. In practice this can be computed by simulating from $N(\mu^*, \sigma^*)$ and averaging over the corresponding posterior distribution values. This similarity index is then computed for each location of interest, giving a spatial map of similarity or locational likelihood for the observed measures.

RESULTS

Strontium Isotope Variations Across the Yellow River Basin

The resulting baseline map shows significant geographical variation in $^{87}Sr/^{86}Sr$ between the Yellow River Basin and surrounding areas (**Figure 2A**), with relatively homogeneous ratios (~0.7108–0.7118) within the basin and higher ratios (>0.712) distributed in the Qilian and Qinling Mountains, largely reflecting the influence of the underlying geology. Thick deposits of Quaternary loess cover the Loess Plateau of China (Liu, 1985; Ding et al., 2002), and much of this sediment is carried down into the Yellow River Basin. Since these areas are covered in thick deposits of loess or reworked loess, the $^{87}Sr/^{86}Sr$ signature for the region is relatively homogenous, with $^{87}Sr/^{86}Sr$ ratios slightly lower in the drainage basin than in the surrounding mountains. This hinders the identification of animals transported within most areas of the Yellow River Basin and from other areas: as far north as Yinshan Mountain, as far south as the Guanzhong Basin, as far west as the northeast of the Tibet Plateau, and as far east as the Huanghuai Plain. However, the underlying geologies and bioavailable $^{87}Sr/^{86}Sr$ ratios for the regions outside this area are sufficiently varied to enable the detection of animal and human movements into the Yellow River Basin.

The Qilian Mountains, close to the northwest of the upper Yellow River Basin, exhibit higher $^{87}Sr/^{86}Sr$ ratios (>0.712) than

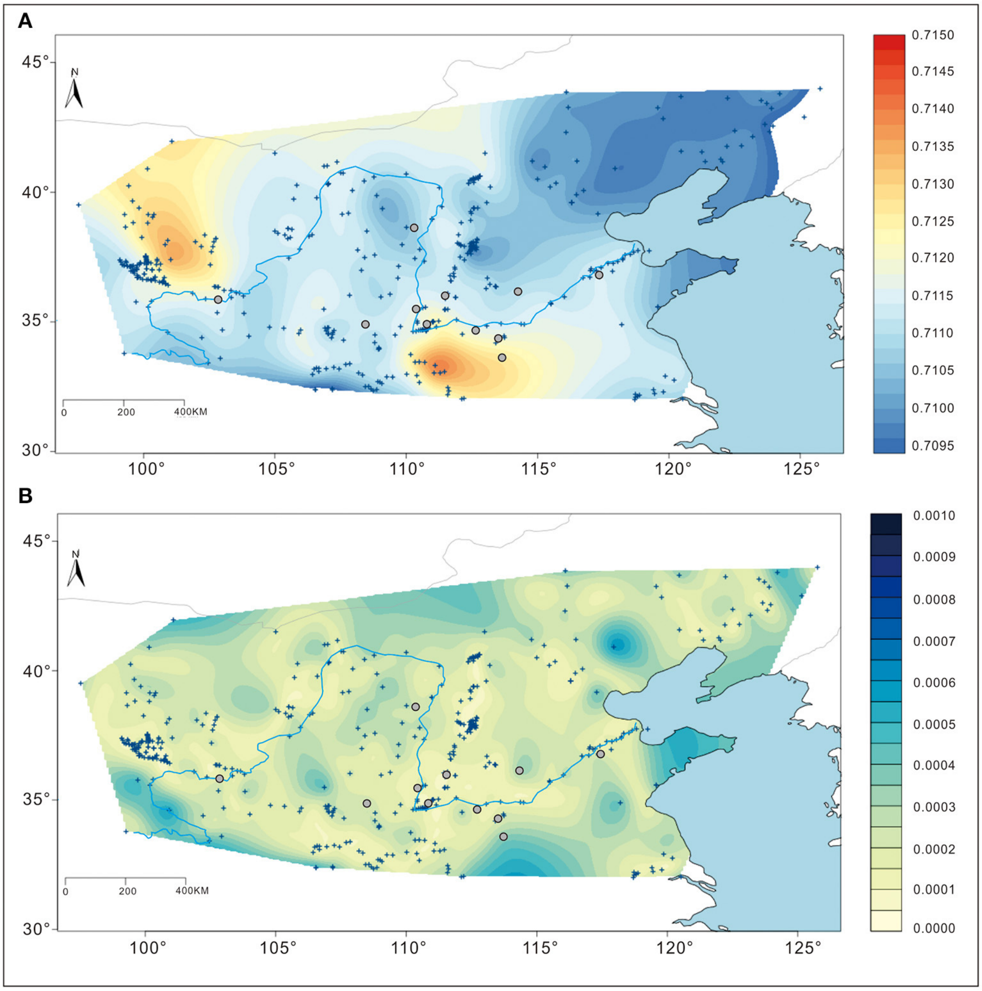

FIGURE 2 | (A) Bayesian mapping of bioavailable $^{87}Sr/^{86}Sr$ ratios for the Yellow River Basin and its surrounding areas; **(B)** Map of standard error of the mean map for predicted $^{87}Sr/^{86}Sr$ ratios.

the basin. This is mainly due to the presence of the Archean and Paleoproterozoic metamorphic rocks and granites (**Figure 3**) (Wu et al., 2010). In the south, the $^{87}Sr/^{86}Sr$ ratios in the Qinling Mountains, near the middle and lower reaches of the Yellow River, also show higher $^{87}Sr/^{86}Sr$. These ratios are likely the results of the presence of the Mesozoic granites and Precambrian rocks in the Qinling Mountains (Wang et al., 2013). Thus, long-distance movements of animals between Qilian or the Qinling Mountains and sites within the Yellow River Basin should be distinguishable using $^{87}Sr/^{86}Sr$ analysis (**Figure 2A**).

The baseline map (**Figure 2A**) also shows differences in the $^{87}Sr/^{86}Sr$ ratios for investigated archaeological sites. Most locations (Jiaojia, Qingliangsi, Shimao, Taosi, Lajia, Yinxu, and Zaoshugounao) have lower ratios (∼0.7108–0.7118), probably due to the influence of the underlying loess and other Cenozoic sediments. The remaining three other sites, located adjacent to the northern edge of the Qinling Mountains (Wangjinglou, Erlitou, and Jiahu) exhibit slightly higher $^{87}Sr/^{86}Sr$ ratios (>0.7118), probably influenced by the geology of the Qinling Mountains. The standard error of the mean for predicted $^{87}Sr/^{86}Sr$ (**Figure 2B**) obtained through Bayesian modeling are generally lower than 0.0006 across the mapped region.

Defining the Local $^{87}Sr/^{86}Sr$ Signature

While having great potential, methods for establishing local Sr isotopic signature still vary and remain complex. In general, two methods have been suggested (Scaffidi and Knudson, 2020). The commonly used method is to measure the $^{87}Sr/^{86}Sr$ ratio of enamel or bones in archeological low-mobility animal species (e.g., snail shells, rodents, and pigs) which will likely average Sr isotopes within their dwelling area (Bentley et al., 2004). However, different low-mobility animal species may vary in $^{87}Sr/^{86}Sr$ ratios given a variability in dietary preferences, species-specific dwelling ranges, trade, animal husbandry and herding practices (Price et al., 2002; Montgomery, 2010). The second approach is to use the $^{87}Sr/^{86}Sr$ of various types of local environmental samples, such as bedrock, soil leachate, plants, and water (Evans et al., 2010; Lugli et al., 2019). In this

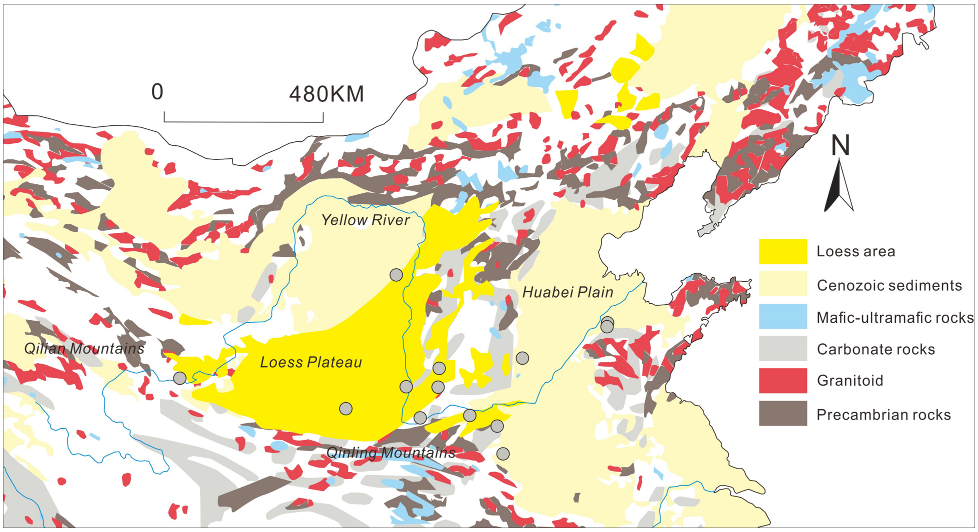

FIGURE 3 | Geological map of the study area (Modified after Ma et al., 2002).

case, comparisons of $^{87}Sr/^{86}Sr$ measurements on environmental samples revealed variations among materials since these are the results of different depositional and biochemical process, and thus may not match with the $^{87}Sr/^{86}Sr$ ratios for tissues of local animals and humans (Maurer et al., 2012). Therefore, it is recommended that reliable local $^{87}Sr/^{86}Sr$ reference ratios should be established by extensive field collections (Grimstead et al., 2017; Britton et al., 2020). In our study area, published $^{87}Sr/^{86}Sr$ ratios for local samples (especially plants) are scarce and unevenly distributed around most of the archaeological sites for which $^{87}Sr/^{86}Sr$ animal data are available. Here, we define local ranges for $^{87}Sr/^{86}Sr$ ratios by taking the mean and two standard deviations (2SD) of $^{87}Sr/^{86}Sr$ ratios measured in local low-mobility animals.

Pigs may be employed as a good reference for local $^{87}Sr/^{86}Sr$ ranges in migration studies as they are often raised near settlements and consume human by-products such as table scraps and crop wastes which can average bioavailable Sr isotope signals for the areas within which local residents utilize food resources (Bentley and Knipper, 2005). Previous zooarchaeological studies have shown that domesticated pigs in China were present at the Jiahu site as early as the Early Neolithic period and played an important role in food consumption and sacrificial activities in ancient China in both prehistorical and historical times (Cucchi et al., 2011; Yuan, 2015; Brunson et al., 2016). In contrast, some studies have shown that pigs were also subject to trade by past societies and thus can possibly originate from areas distant from their burial location (Shaw et al., 2009; Madgwick et al., 2019). In view of this, we compared the $^{87}Sr/^{86}Sr$ ratios measured on pigs with those from bioavailable baseline map. The $^{87}Sr/^{86}Sr$ ratios of pigs obtained from the 10 sites range from 0.710842 to 0.712388, and fall within the ranges for the Yellow River Basin and Qinling Mountains. Furthermore, the variability of $^{87}Sr/^{86}Sr$ ratios for archaeological sites is relatively small, suggesting that they moved within a narrow geographic area. Thus, the local $^{87}Sr/^{86}Sr$ ranges for each site in this study is defined by the mean ratio (± 2SD) for pig tooth enamel, providing the local ranges for Jiahu (0.71220–0.71242), Qingliangsi (0.71118–0.71171), Lajia (0.71080–0.71106), Jiaojia (0.71097–0.71173), Taosi (0.71103–0.71133), Shimao (0.71107–0.71129), Erlitou (0.71189–0.71227), Wangjinglou (0.71182–0.71203), Yinxu (0.71132–0.71174), and Zaoshugounao (0.71085–0.71161).

Identifying Non-local Domesticated Animals

Domesticated animals other than pigs ($n = 93$, mostly cattle and sheep/goats) have $^{87}Sr/^{86}Sr$ ranging from 0.709431 to 0.712844. The presence of non-local domesticated animals appears as early as the Late Neolithic with three sheep found at Shimao and Taosi as well as a cattle sample from Lajia (**Figure 4**). The most radiogenic ratios are observed in a Late Shang horse from Yinxu (0.712844) and a cattle sample from Erlitou (0.712593), and the lowest ratios are present in a separate horse from Yinxu (0.709431) and a predynastic Zhou-Western Zhou sheep from Zaoshugounao (0.709995), all of which have ratios well-beyond the local range defined by pigs for each of these sites.

Although the majority of the non-pig domesticated animals yielded strontium isotope ratios that are consistent with the baseline map (**Figure 4**), 24 animal samples are classified as isotopic outliers. These outliers include three sheep and one cattle from sites dating to the Middle to Late Neolithic (4/25), five sheep and six cattle recovered from the Erlitou-Erligang period sites (11/30), five horses from Yinxu during the Late Shang Dynasty (5/10), as well as two sheep, one dog and one cattle from a predynastic Zhou-Western Zhou site (4/18), which shows a slight increase in the percentage of non-local animals after the Late Neolithic. These "outliers" plot on both sides of the strontium isotope baseline at sites dating from the Erlitou-Erligang periods to the West Zhou Dynasty, suggesting that these non-local animals may have diverse geographic origins.

Excluding pigs, the variability in $^{87}Sr/^{86}Sr$ ratios for domesticated animals increases through time (**Figure 5**, 1 SD for sites dating to the Middle-Late Neolithic: 0.000087–0.000296;

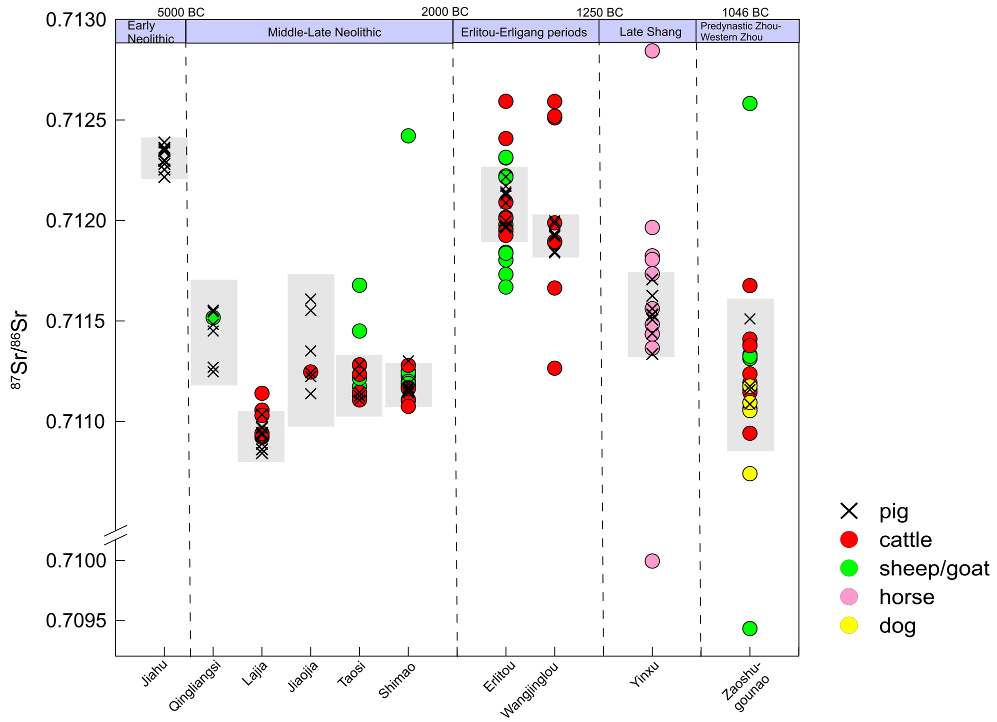

FIGURE 4 | $^{87}Sr/^{86}Sr$ ratios for animal tooth samples from 12 archaeological sites. Gray intervals represent the $^{87}Sr/^{86}Sr$ range for pigs at each site.

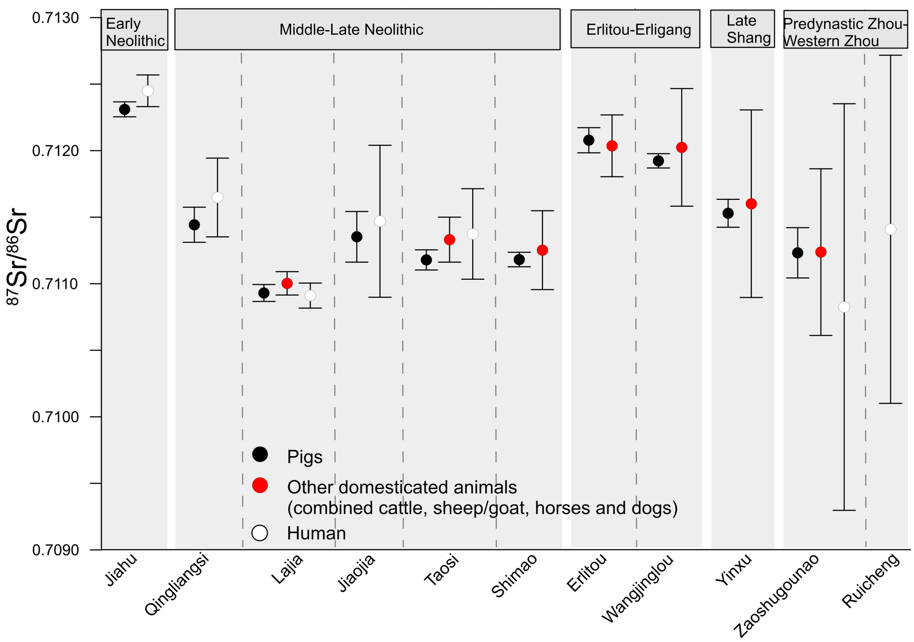

FIGURE 5 | Mean and standard deviation of $^{87}Sr/^{86}Sr$ ratios for pigs, other domesticated animals, and human samples from archaeological sites across different periods within the Yellow River Basin.

Erlitou-Erligang: 0.000232–0.000442; Late Shang: 0.000704; Predynastic Zhou-Western Zhou: 0.000626). Notwithstanding the limited sample size for some periods, there is a clear increase in the variability of animal circulation from the Middle-Late Neolithic to the Western Zhou Dynasty. Particularly at sites dating to the Late Neolithic (Shimao), the Late Shang Dynasty (Yinxu), and the Predynastic Zhou-Western Zhou Dynasty (Zaoshugounao), two sheep (0.709431 and 0.712421, respectively) and two horse teeth (0.709995 and 0.712884, respectively) have $^{87}Sr/^{86}Sr$ ratios that are significantly different from the local isotopic signature and that are rarely observed within the Yellow River Basin.

The high variability in $^{87}Sr/^{86}Sr$ ratios for animals, excluding pigs, may also result from the herding of animals across areas showing large $^{87}Sr/^{86}Sr$ variation within relatively short distances which may occur in vertical transhumance (Montgomery, 2010). The Yellow River Basin is located at a transitional zone between agriculturalist and agro-pastoralist lifeways (Cao et al., 2020). This transitional zone shifted northward or southward as a result of climate change and/or human adaptions (e.g., establishing irrigation farming such as Tuntian (屯田) in the north or due to territorial changes arising from conflicts with nomadic populations) (Han, 2012). Ancient local populations within the region relied primarily on production activities such as crop farming or livestock husbandry albeit with temporal variations. Therefore, we cannot exclude the possibility of animal herding within the basin, which could have resulted in $^{87}Sr/^{86}Sr$ signatures differing from local site ranges. To further investigate this possibility, intra-tooth sequential sampling work could be performed. Additionally, the larger variability in $^{87}Sr/^{86}Sr$ ratios in cattle, goats and sheep compared to that of pigs can also result from different human feeding practices involving cultivated millets and C_3-based plants within the Yellow River Basin. Previous research employing carbon and nitrogen isotopes have suggested that pigs were mainly fed on C_4-based foods (e.g., millets) while other domesticated animals consumed a mix of C_3 and C_4 foods from the Late Neolithic onward (Chen et al., 2016; Dai et al., 2016; Wang et al., 2018). In this respect, different types of plants within a certain region may show variable $^{87}Sr/^{86}Sr$ ratios as a result of different physiologies and water utilization strategies (e.g., depth of the root uptake) or growth in different landscape (e.g., valleys vs. foothills) (Poszwa et al., 2004; Montgomery, 2010; Reynolds et al., 2012), it is possible that non-local pigs with more diverse fodders yield larger variations. However, several examples of extreme $^{87}Sr/^{86}Sr$ outliers in Shimao, Zaoshugounao and Yinxu are well-beyond the isotopic ranges observed within the basin, indicating that people were circulating animals between and among different remote regions.

Human vs. Animal Mobility

Strontium isotope analysis in the Yellow River Basin was also previously carried out on human teeth (Yin, 2008; Chen, 2012; Zhao et al., 2016b; Lan, 2017; Fang, 2018; Wu, 2018). Human samples from the Early Neolithic indicate that their ratios are mostly similar to their local baseline reference and show little variability (**Figure 5**). A larger variation of $^{87}Sr/^{86}Sr$ in human samples is observed during the Middle-Late Neolithic compared to the Early Neolithic, and an even larger variation in human $^{87}Sr/^{86}Sr$ ratios is found at the two archaeological sites dating to the Predynastic Zhou-Western Zhou Dynasty (1 SD of humans for sites dating to the Neolithic: 0.000094–0.000571; Predynastic Zhou-Western Zhou: 0.001308–0.001527), a result that is consistent with the variability observed in animals. This suggests that the introduction of animals into these sites from a wider geographic range during the later periods is likely related with shifts in human mobility.

Origins of Non-local Domesticated Animals

We took as reference the $^{87}Sr/^{86}Sr$ baseline map and employed the model LocateR to map the probability of origin at different locations for outlier animals, that is, those that had the most extreme $^{87}Sr/^{86}Sr$ ratios when compared to the two-sigma range observed at the different sites (**Figure 6**). As mentioned previously, 24 outliers are identified from all sites and most of these ($n = 19$) have $^{87}Sr/^{86}Sr$ ratios similar to those found in or near the surroundings of the Yellow River Basin. In this case, we cannot identify if these animals were raised nearby the site or brought from afar within the basin or the Loess Plateau. For example, the six non-local cattle and five non-local sheep that date to the Erlitou-Erligang periods have $^{87}Sr/^{86}Sr$ ratios between 0.711265 and 0.712593. The likely geographical sources for these extreme ratios are all found in vicinity to the site or within the larger basin region for which similar baseline $^{87}Sr/^{86}Sr$ ratios are observed (**Figure 6**). Future research should employ a multi-proxy approach (e.g., $^{87}Sr/^{86}Sr$ in combination with oxygen or sulfur isotopes) under which it will likely be possible, using LocateR, to achieve a higher spatial constraint for place of origin.

For some extreme outliers ($n = 5$), the Bayesian modeling results suggest a place of origin which can be at large distances from the archaeological sites where the animal remains were found. For instance, one sheep sample from the Late Neolithic site of Shimao has a $^{87}Sr/^{86}Sr$ ratio (0.712421) similar to those observed at the Qinling or Qilian Mountains, located at a distance larger than 400 km from the site. Two horse samples from the Late Shang Dynasty have extreme $^{87}Sr/^{86}Sr$ ratios (0.712844 and 0.709995) which differ considerably from the site reference. The likely source for the horse with the upper extreme ratio is within areas located at least 200 km from the site (e.g., northern Qinling Mountains). For the horse with the low extreme ratio, the place of origin is likely the northern part of the Huabei Plain and northeastern China at a distance of over 150 km from the site. From the Zaoshugounao site, which dates to the predynastic Zhou-Western Zhou Dynasty, the likely origins of the high $^{87}Sr/^{86}Sr$ ratio from a sheep (0.712582) are the Qinling or the Qilian Mountains, while the low ratio of another sheep (0.709431) fits well with the $^{87}Sr/^{86}Sr$ ratios observed within the Hanjiang Basin located in the south of the Qinling Mountains, as well as extended sections of northern part of the Huabei Plain and northeastern China, around 150 km distant from the site.

DISCUSSION

$^{87}Sr/^{86}Sr$ Evidence for Animal Circulation

The statistical analysis of the animal isotopic data and the modeling results demonstrate the circulation of animal resources

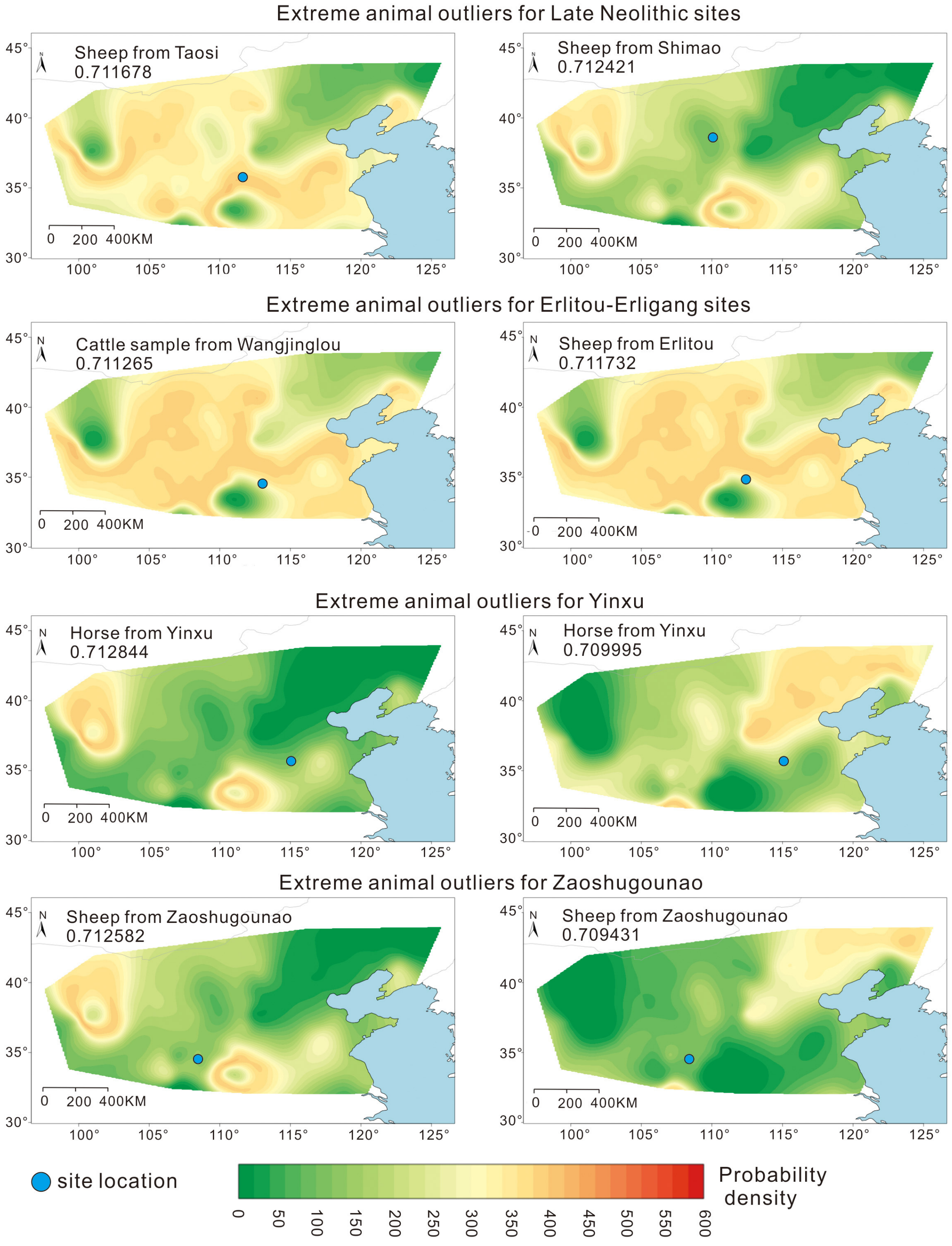

FIGURE 6 | Probability density map for Bayesian estimates on the possible geographical origins for extreme outlier ^{87}Sr/^{86}Sr ratios observed in animals at different archaeological sites. Points show the site location and a color scale is used to represent the probability of origin across the map.

from the Late Neolithic onwards that could have been driven by inter-regional networks that extended beyond the Yellow River Basin. From the Late Shang to the Western Zhou Dynasty, an increasingly higher number of animal resources may have arrived at investigated sites through long-distance circulation networks. This temporal pattern revealed by animal ^{87}Sr/^{86}Sr data matches the zooarchaeological evidence which shows an increase of the regional exchange of animal resources after the Neolithic (see discussion below). With more socially complex societies and stronger hierarchical systems emerging after the

Neolithic, domesticated animals filled an increasingly diverse set of roles, not only as food sources and ritual goods, but also as sources of secondary products (e.g., traction, dairy products) for humans. This rise in the demand for domesticated animals led to a temporal increase in the number of animals imported into the basin through various means, such as war, trade, tribute, and different animal management strategies.

During the Early-Middle Neolithic period, domesticated pigs served as a main source of meat and were frequently sacrificed for ritual purposes (Kim et al., 1994; Yuan, 2015; Dong and Yuan, 2020). After pigs, dogs were the second most important sacrificial offering and were also used as a hunting aid during the Neolithic period (Dong et al., 2020) and later were more routinely sacrificed in ritual ceremonies during the Shang Dynasty, particularly in the lower Yellow River Basin. Following the introduction of sheep/goats and cattle into north China during the Middle-Late Neolithic, these domesticated animals were frequently used in social and economic activities complemented with pigs and dogs (Flad et al., 2007; Yuan, 2010; Lu et al., 2017). During the Shang and Zhou Dynasties, with the increase in social complexity and the consolidation of social hierarchies, cattle and sheep replaced the pig dominated zooarchaeological assemblages that typified the Neolithic in some regions (Li, 2012; Brunson, 2015; Ren, 2019). As for animal consumption, the contribution from cattle increased from the Erlitou period onward, growing from 5 to 20% between 1850 and 1400 BCE and jumping to 50% after only a century before stabilizing during the Shang Dynasty (Cao, 2014). During ritual activities, the Zhou king established a hierarchical system of animal sacrifice, revealing that cattle and sheep were only represented at the top two hierarchical systems (Sun, 1989). A large number of cattle and sheep were required for sacrifice in ancestral worship ceremonies and according to *Yizhoushu·Shifujie*, the Zhou king sacrificed about 500 cattle to the heavens and about 2,700 sheep, dogs, and pigs to nature (Huang, 2007). Therefore, it is possible that these early states secured external supplies to meet the huge demand for consumption and ritual activities involving animals within cities.

Unlike other domesticated animals, people deemed horses a prestige animal throughout the Bronze Age, particularly during the Late Shang period when this kind of animal had just been introduced to China and were used in warfare and as sacrifices in the tombs of kings (Xie, 1959; Yuan and Flad, 2005). Many adult horses were found in excavations at Yinxu, but were rarely found in the surrounding regions, indicating that, except for locally raised horses, some of these horses were probably brought to Yinxu from distant regions. Based on zooachaeological evidence and on unearthed mortuary goods (e.g., chariots and horse fittings) some outposts were likely sources of horses, such as Gaohong (Shanxi, ^{87}Sr/^{86}Sr $\sim$ 0.7110), Zhangying (Beijing, ^{87}Sr/^{86}Sr $\sim$ 0.7100) and northeastern China (^{87}Sr/^{86}Sr < 0.7100) (Yang, 2006a; Cao, 2014). From the probability density map (**Figure 6**), the nearest sources for the ^{87}Sr/^{86}Sr ratios observed for Late Shang horses are the north and west parts of the Huabei Plain (including Shanxi and Zhangying), about 100 km way from the site, indicating that Yinxu had interregional interactions with these regions, a hypothesis supported by the presence of trade goods like bronze vessels, gold ornaments, and bronze weapons also from this region (Cao, 2014). Beyond consumption and sacrifice, these animals were used by the military, for agriculture, the transportation of goods, and as a source of traded secondary products (e.g., wool exploitation) since the Late Neolithic (Li, 2014; Li et al., 2014).

Written Evidence for Animal Circulation

Written records (e.g., oracle bone inscriptions, see Guo, 1978–1983) dating to the Late Shang Dynasty are a useful source of information regarding ancient animal circulation networks. Although these are ritual texts from high-ranking elites, it is evident that animals were imported to the capital city by trade, tribute, or as the spoils of war during the Late Shang (Yang, 1999). For instance, high-ranking elite Zi (子) sent envoys to inquire among professional traders, who usually traveled long distances, on the source of horses which were considered valuable exotic animals in ancient China (Guo, 2010). However, these written records contain few details on the locations or distances to the sources of exotic animals. One oracle bone inscription mentioned that to “get” cattle from Cha, the western outpost probably in the Linfen Basin, was about a 10 days’ journey away from the capital city Anyang (*HJ* 8977). Another inscription recorded that Cha and Zhi Guo (probably persons or places from modern Shanxi) delivered horses to Anyang (*HJ 8797*), and some Shang vassal states (e.g., Weifang, modern Shandong) also supplied cattle to the capital city (*HJ* 32896, Cao, 2014). Yet another inscription mentions that the Shang court ordered an inspection of sheep/goats in the western land where they might intend to import sheep/goats from west (*HJ* 8777).

Additionally, there are multiple oracle bone inscriptions referring to animals as tribute. One group mentions that someone “offers” (供or 登), “turns in” (入) and “presents” (见,similar to 献) animals to the Shang king (e.g., *HJ* 10405, *HJ* 19875, *HJ* 1606, *HJ* 5685, and *HJ* 102). The other group shows that the Shang king ordered his subjects to “get” (取), “bring” (来) animals (e.g., horse) for him (e.g., *HJ* 945, *HJ* 8979, and *HJ* 8966). The described animals include cattle, horse, sheep, dog, pig and other wild animals. The largest number of cattle for tribute mentioned in inscriptions is once about four hundred (e.g., *HJ* 8965), followed by sheep at three hundred (e.g., *HJ* 8959), dogs at two hundred, horse at thirty (e.g., *HJ* 500), (e.g., *HJ* 8979), and for pig only two (e.g., *HJ* 11432). Those who gave offerings included professional traders, foreign statelets, vassals, or elite-officials. Additionally, in the records from the early Western Zhou bronze *Xiao Yu Ding* (小盂鼎), a commander *Yu* is said to have captured a large number of domesticated animals (355 cattle and 28 sheep/goats) and chariots in two campaigns against the Guifang (in northern Shaanxi and Shanxi), and presented them to the king (Li, 2006).

Animal Circulation and Social Complexity

The ^{87}Sr/^{86}Sr evidence presented in this study offered detailed insights into changes in animal mobility and circulation networks from the Early Neolithic to the Western Zhou Dynasty. Domesticated animals showed a temporal increase in non-local origins starting with the Late Neolithic. A greater number of outliers for later periods also observed for humans, probably indicates that human movement expanded the use of animal resources across wider geographic areas. This shift was probably not only a consequence of increased social complexity but also it reflected the increased network of linkages between China's different regions.

During the Neolithic, most domesticated animals have $^{87}Sr/^{86}Sr$ ratios indicating that these resided within the Yellow River Basin. Animals that have ratios which are extreme outliers are found only at large Late Neolithic sites, indicating that the initial period of extensive animal circulation might have begun during the Late Neolithic. The Early Neolithic reveals a mixed economy that combined hunting and gathering, raising domesticated animals (pig and dog), and cultivating domesticated plants (millet and rice) in the Yellow River Basin (Liu et al., 2005; Hu et al., 2006; Underhill and Habu, 2006). During this period, the settlement pattern of the region consisted of small villages scattered within the major river valleys and ceramics were hand molded into relatively simple shapes (Underhill, 2013; Shelach-Lavi, 2015).

However, during the Middle-Late Neolithic (e.g., Late Yangshao and Longshan periods), particularly the Late Neolithic, Neolithic society witnessed an increase in social complexity and developed early forms of urbanism with political, religious, and economic functions: mortuary goods showing remarkable signs of social hierarchy (Underhill, 2002; Liu and Chen, 2012), regional centers built with walled enclosures (Liu and Chen, 2012), an increase in population density, settlement numbers, and size (Liu et al., 2005), the introduction of sheep and cattle (Barnes, 1999; Flad et al., 2007), more elaborate shapes and production techniques of ceramics and jade and their long-distance circulations (Shelach-Lavi, 2015), exotic trade and exchange items (e.g., turtle shells and ivory artifacts) (Barnes, 1999; Li, 2015), the use of bronze and copper artifacts (Liu, 2004), greater inter-polity conflict and warfare, and early writing system (Liu, 2004). Painted potteries were developed around the middle region of the Yellow River during the Yangshao period and later spread into other regions, such as the Wei River region, northeast China, and into the lower region of the Yellow River (Underhill, 2002). High quality eggshell and fine black ceramics typical of sites in the Shandong area during the Longshan period were found in some large sites in the middle region of the Yellow River, such as Wangchenggang (Shelach-Lavi, 2015). Jade artifacts provide further evidence for interactions among societies with many sites in the Yellow River Basin revealing the presence of Liangzhu-style jades such as *cong* 琮 and *bi* 璧 (from the lower Yangtze Basin), probably representing the elite-controlled exchange of prestige items (Liu and Chen, 2012; Shelach-Lavi, 2015).

Larger variability in $^{87}Sr/^{86}Sr$ ratios for animals from the Erlitou-Erligang periods indicates that animal resources were increasingly transported from more diverse regions, consistent with political and economic shifts documented at this time. As suggested by Liu (2009), the Erlitou period is often described as exhibiting the earliest state-level societies in China based on a mono-centered and highly integrated political system that spread across a wide region. However, some opposing archaeological views hold that the first state-level states in China emerged during the Late Neolithic which may have included the Liangzhu and Taosi cultures (e.g., Allan, 2007; Shelach-Lavi and Jaffe, 2014; Renfrew and Liu, 2018). The peripheral regions provided the dominant center (Erlitou and Erligang) with raw materials and exotic goods as tribute to support urban growth and technological production, contributing to the formation and maintenance of hierarchical social and political structures. Many goods and natural resources, such as timber for building palaces, kaolinic clay for making white pottery, salt for daily use, lead, tin, and copper for making bronzes, lithic materials for stones tools, were imported into Erlitou (Liu, 2003) which is located on alluvial plains and is poor on natural resources (Liu and Chen, 2001; Chen et al., 2010; Li, 2011). However, most of these resources could have been acquired from the surrounding regions within radii of 20 to 200 km (Liu and Chen, 2003). For instance, stone resources were abundant in the Mangling Hills (200 km to the southwest of the site) and Sangshan Mountains (40 km to southeast of the site) (Liu and Chen, 2003). The Hedong Salt Lake, located ∼160 km to the northeast of Erlitou, was the only salt source for Erlitou (Liu and Chen, 2012). Considering that other goods and resources were moved from exotic locales as well (Yang, 2006b), it is unsurprising that the $^{87}Sr/^{86}Sr$ signatures of the domesticated animals reveal that some of these were imported from regions far off from the Yellow River Basin.

The Late Shang was characterized by a multicentre political landscape and multiple overlapping regional economies (Liu and Chen, 2012; Dreyer, 2015). The forms of interaction between the Shang state and its surroundings became more complex through exchange, warfare, and tribute (Chang, 1980; Yang, 1999). According to the historical records and archaeological evidence, a number of exotic goods, raw materials, animals for sacrifice and other resources were imported from the peripheries, or, in some cases, remote locations (Bagley, 1999; Chen et al., 2019). A remarkable development during the Late Shang Dynasty was the introduction of horses. Unlike other animals such as cattle or sheep/goats commonly used for consumption and sacrifice, horses were an important means of transport for both people and goods, in long distance trade, warfare, and as a prestige animal sacrificed for royal tombs (Yuan and Flad, 2005). High-quality horses, in particular, were always desirable to the elite class and were often obtained from remote regions and thus it is unspringing that the horses at Yinxu have extreme $^{87}Sr/^{86}Sr$ ratios (Cao, 2014).

A chronological comparison reveals that the largest variability in animal $^{87}Sr/^{86}Sr$ ratios took place during the Western Zhou Dynasty. The Western Zhou adopted a feudal political system 分封制 in which the king enfeoffed his relatives and non-cognate meritorious generals and leaders by granting them land and these in returned had to heed the king's commands and pay a regular tribute (Li, 2008). The kings strengthened royal rule over nearby territories, established strict relationships with feudal lords, and increased the kingdom's territory through military conquest. This contributed to the multi-directional flow and re-distribution of materials and resources through trade, tribute and war (e.g., bronze vessels, jades, and animals;

Underhill, 2002; Shelach-Lavi, 2015). New technologies, such as bronze or iron casting, and religious innovations easily crossed political boundaries and were commonly adopted throughout the Zhou world (von Falkenhausen, 2006; Chastain, 2019). Bronze vessels became ornate artistic products during the Western Zhou Dynasty. In comparison to the Late Shang Dynasty, there was a larger production of bronze vessels and also a greater diversity in shapes and styles (Chastain, 2019). Bronze vessels are commonly found in elite burials and caches from the early Western Zhou Dynasty onward. A later development was the adoption of the sumptuary system known as *lie ding* (列鼎), in which the types and quantities of bronze vessels buried with the deceased were strictly prescribed by rank. This system was used throughout the Zhou territory (Shelach-Lavi, 2015; Jaffe, 2016).

CONCLUSIONS

Our study builds on previous archaeological and zooarchaeological discussions on the circulation of animal resources within the Yellow River Basin from the Neolithic until the Bronze Age. We address outstanding questions regarding the interconnectedness of animal circulation networks by mapping bioavailable $^{87}Sr/^{86}Sr$ across China. In our meta-analysis, we employed previously reported strontium isotopes measured in tooth enamel from domesticated animals (cattle, sheep/goats, horses, and dogs) to investigate animal movement and circulation across the Yellow River Basin over extended time periods. A few strontium isotope ratios outliers for animals from large Late Neolithic sites reveals the initial expansion of animal circulation systems which likely took place during Late Neolithic and Erlitou-Erligang periods. Our data also revealed that from the Late Shang period until the Western Zhou Dynasty there was an increase in the proportion of animals originating from regions with a higher degree of social complexity. This was likely the result of the adoption, at later time periods, of considerably more complex and interconnected economic and social systems. Nonetheless, the huge time span and area covered in our study plus the relatively small size of the presented dataset hinders a deeper discussion on the factors that influenced animal circulation. To overcome these limitations, future work is necessary to systematically increase the size of animal samples from across different periods plus the employment of multi-isotope methods. Nonetheless, our study provides a solid foundation for the use of strontium isotopes as a powerful tool in animal mobility studies within China.

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/s.

AUTHOR CONTRIBUTIONS

XW, PR, ZT, and RF conceived the project. RF and XW conducted data analysis. All authors shared ideas, contributed to the interpretation of the results, and to the writing of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021.583301/full#supplementary-material

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