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Spatiotemporal Changes in Prehistoric Land Use in Upper and Middle Reaches of Yellow River Valley

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Abstract: During the Holocene, the upper and middle reaches of the Yellow River valley in China were pivotal areas for agricultural development. Quantitatively reconstructing the spatiotemporal changes in prehistoric human land use is essential for understanding, from a long-term perspective, the interactions among evolutions of climate, agriculture, and human activities. Based on 327 archaeological sites and the PLUM (prehistoric land use model), we quantitatively reconstructed human land use changes from 6 to 3 ka BP (thousands of years before the present) in the Tao River valley, the second-largest tributary in the upper reach of the Yellow River valley. The results indicated that regional land use areas increased from 571 km^2 to 1468 km^2, with spatial expansion from the lower reach to the upper–middle reach of the Tao River valley. A comparison of the five areas distributed across the upper and middle reaches of the Yellow River valley revealed two different trends of increasing land use from 8 to 3 ka BP within these areas. The first group (the Wei River and Yiluo River valleys) exhibited rapid and substantial growth before 5 ka BP, while the second group (the Huangshui River and Tao River valleys, and the Yunlin district) showed a much slower and less significant increase before 5 ka BP, but a more obvious increase thereafter. The asynchronous increases in these areas indicate an expansion of land use from the southeastern part of the upper and middle reaches of the Yellow River Valley to across the entire region between 8 and 3 ka BP, which was primarily driven by agricultural development and cultural communication.

Keywords: cultivation; climate change; culture development; Holocene

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1. Introduction

In terms of the origins and development of agriculture, China has been recognized as one of the most important centers in the world [1,2]; human cultivation greatly impacted regional land cover during the Holocene [3–6]. The emergence and progression of various Neolithic and Bronze Age cultures across China resulted in substantial spatial variations in human activity and associated land use changes [7,8]. Investigating the spatiotemporal changes in prehistoric human land use across different regions of China is imperative, as this will enhance our understanding of the interplay between climate evolution, cultural development, and long-term human activity [9–11].

Numerous studies have focused on the roles that climate change and cultural development played in driving human activity during the Holocene [12–14]. In the early stage, population- and agriculture-based development were usually controlled by climate events [15], and cultural decline or prosperity often corresponded to the deterioration or optimization of climate conditions. However, human activity responses to climate change became diversified with the enhanced social resilience during the middle–late Holocene [16]. Currently, most studies rely on comparing climatic and cultural/human activity variable curves. While, over time, the correlations between these variables have been widely confirmed [17–20], they cannot reveal the responses of human activity to climatic and cultural factors from a spatial perspective. Even though several studies have utilized spatial evolution information from archaeological records, these are always point records that cannot provide sufficient quantitative information to reflect the spatial variations in human activities [21,22]. Therefore, the quantitative reconstruction of spatiotemporal changes in human land use provides new data for overcoming the aforementioned research shortcomings.

Until now, various types of human activity records have been applied in quantitative reconstructions of human land use during the Holocene. On a global scale, historical land use data have been extrapolated to prehistoric periods using population growth models, as well as the relationships among the modern population, land use, and environmental variables' distributions. This approach revealed an outline of the spatiotemporal changes in global land use since 12 ka BP [23–25]. However, due to the lack of direct evidence regarding prehistoric human activity, the resolution and accuracy of these reconstructions still need further improvement. At a regional scale, pollen data have been utilized to develop land cover reconstruction models, which have been applied in Europe and China [26,27]. Nevertheless, identifying several cereal pollen types at the species level remains challenging, hindering our ability to distinguish between anthropogenic biotypes and natural plant communities. The application of archaeological data (direct evidence of prehistoric human activity) in land use studies can enhance the accuracy of reconstructions of both land use size and distribution [28], as these control points can more accurately reflect the temporal fluctuations and spatial migration of prehistoric human activity. Some efforts have been made to establish and apply prehistoric land use models based on archaeological data in several areas of China [3–5] and western Africa [29].

In China, the Prehistoric Land Use Model (PLUM) has been successfully developed and applied in typical dry or rice cultivation areas [3–5]. The number and size of archaeological sites and the cultural parameters related to cultivation have been used to improve the accuracy of land use area reconstructions; the relationship between the distributions of archaeological sites and environmental variables has been adopted to reconstruct the spatial patterns of land use. This model has also been validated based on modern observed land use data and prehistoric archeological sites in the Yiluo River and Yangtze River valleys. First, the comparison between observed and reconstructed modern land use distribution patterns showed no systematic bias, and the spatial distributions of about 80% of cultivated and non-cultivated areas were both correctly simulated. Second, the percentage of observed archaeological sites distributed in the high-potential areas predicted by PLUM was high (>83%), confirming the ability of the model to simulate the spatial distributions of prehistoric human activities [3,5].

Compared with other regions in China, quantitative reconstructions of prehistoric land use based on archaeological data are most often made in the upper and middle reaches of the Yellow River valley (e.g., the Yulin region, the Huangshui, Wei, and Yiluo River valleys) [3,4,6,30], as they have been the key dry cultivation (millet) centers. However, the spatial variation in prehistoric land use across the upper and middle reaches of the Yellow River valley remains unclear. More systematic and comprehensive studies providing a good base for further mechanism analyses are needed.

Here, the prehistoric land use in the Tao River valley, the second-largest tributary in the upper reach of the Yellow River valley, was first reconstructed to further improve the spatial coverage of land use reconstructions in the upper and middle reaches. Then, the prehistoric land use changes (8–3 ka BP) from different areas of the upper and middle reaches of the Yellow River valley were compared to reveal their spatial variations and potential linkages.

2. Materials and Methods

2.1. Study Region and Period

The upper and lower reaches of the Yellow River valley are located in northern China, and their area accounts for 97% of the entire Yellow River valley [31] (http://www.yrcc.gov.

cn/zwzc/ghjh/202312/t20231220_365000.html, accessed on 20 February 2024). Since the early Holocene, the area has gradually formed two major agricultural and cultural regions (the Ganqing Cultural region in the upper reach of the Yellow River valley, and the Central Plains Cultural region in the middle reach) (Figure 1) [7]. The cultures in each region developed independently, formed their own sequences, and influenced each other [32,33] (Table 1).

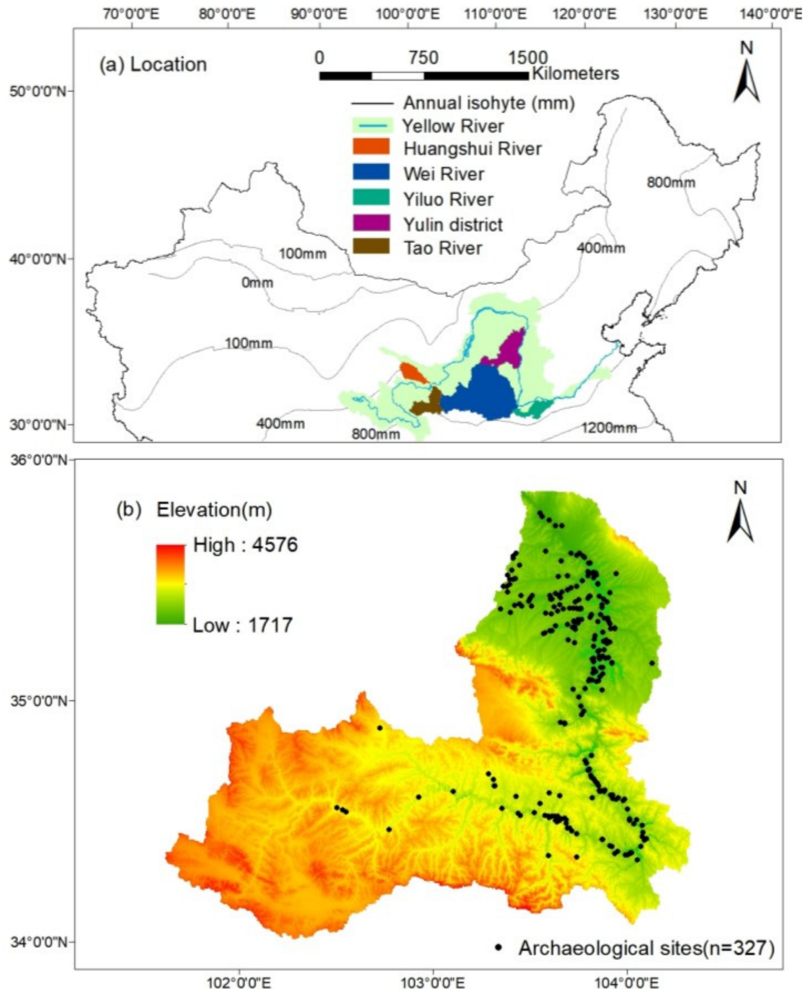

Figure 1. Locations of the river valleys in this study (**a**) and distribution of archaeological sites in the Tao River valley (**b**).

Table 1. The chronological framework and major cultures in the Tao River Valley (redrawn from [22,23]).

Period	Ka/cal. BP	Upper Yellow River	Middle Yellow River
	3	Siba	
Bronze Age			Erlitou
		Qijia	
	4		Longshan
Late Neolithic Age			Miaodigou II
	5	Majiayao	
Middle Neolithic Age			Yangshao
	6		
Early Neolithic Age	7	Dadiwan	Peiligang/Cishan
	8		

The geographical scope of the Tao River valley is between 101°36′ E–104°20′ E and 34°06′ N–36°01′ N (Figure 1), covering an area of 25,527 km^2 [34]. The Gannan and Longxi Loess Plateaus are two key parts of the Tao River valley, which is mainly composed of these plateaus and mountains. A high, cold, humid climate prevails in the upper reach of the valley, which is covered by grassland and shrubs. The middle reach is a transitional zone from a temperate, semi-humid climate to a high, cold, humid climate with large areas of forest. Both a temperate, humid climate and a temperate, semi-arid climate occur in the lower reach of the Tao River valley, which is the main area of modern cultivation land distribution [35]. The annual mean temperature and precipitation are 0–9 °C and 600–300 mm from the upper to lower reaches of the Tao River valley, and black felt soil, gray-brown soil, black hemp soil, chestnut calcium soil, and gray calcium soil are the main soil types in the valley [36].

During the Neolithic and Bronze Ages, the Tao River valley belonged to the Ganqing Cultural region [7], which has played an important role in the cultural exchange between central China and other areas in Eurasia. The Majiayao (including the Shilingxia, Majiayao, Banshan, and Machang sub-types) and Qijia cultures developed sequentially between 6 and 3 ka BP in the Tao River valley (Table 1). In order to make the reconstructed human land uses comparable at equal temporal scales, all the archaeological data used here were reclassified into 1000-year intervals according to their culture types or sub-types. The early stages of the Majiayao culture (the Shilingxia and Majiayao sub-types) were attributed to 6–5 ka BP, the late stages of the Majiayao culture (the Banshan and Machang sub-types) were attributed to 5–4 ka BP, and the following Qijia culture was attributed to 4–3 ka BP. Such attributions are reasonable, as the ^{14}C ages of the above culture types (sub-types) fall into the ranges of different 1000-year intervals. For example, the Shilingxia sub-type covers the period from 5.7 ka BP to 5.4 ka BP [37]; the Majiayao, Banshan, and Machang sub-types correspond to 5.3–4.9 ka BP, 4.7–4.3 ka BP, and 4.3–4.1 ka BP, respectively [37]; and the Qijia Culture corresponds to 4.2–3.5 ka BP [38].

2.2. PLUM

The principle of the PLUM is using archaeological data regarding the intensity and spatial distribution of human activity to quantitatively reconstruct the areas and distributions of prehistoric human land use (detailed model descriptions can be found in Yu et al. (2012, 2016) [3,4]).

Three sub-models are included in the PLUM (Supplemental Figure S1, available online). The land use requirement sub-model estimates the total living and cultivated area in the study region. The residential area distribution sub-model predicts the potential distribution of human occupation based on the relationship between the distributions of different environmental variables and archaeological sites. The land use allocation sub-model allocates the total land use area of the archaeological sites to the appropriate grids around the sites within a threshold radius.

First, the total living and cultivated area in the land use requirement sub-model is estimated according to the assumption that cultivated plants were the population's only food source. This is because, using current archaeological records, it is hard to quantitatively distinguish the contributions of both natural plant and animal resources to the prehistoric human diet. The size of the population (P) in archaeological sites is first estimated by using the sites' total residential (A_r) and the average residential areas per person (A_p); then, the land use areas (A_l) are further calculated based on the balance between food needs and cultivation yield using parameters such as food needs per person (F_p), yield per unit area (Y), and fallow (T_f) and tillage (T_c) intervals in one cultivation cycle. The corresponding equation is as follows:

$$A_l = A_r + \left\{ \frac{\left[\left(\frac{A_r}{A_p} \right) \right] \times F_p}{Y} \right\} \times \left[\frac{\left(T_f + T_c \right)}{T_c} \right]$$

Second, the weighted overlay method is used to predict the potential spatial distributions of human occupation in the residential area distribution sub-model, and two kinds of weights are adopted here. The class weight gives the rank of restriction of the land use based on different environmental variables. The cumulative frequency distribution of the grid values of each environmental variable of the study region serves as a background referent, while the distribution of the values of the corresponding variable for archaeological sites is compared against the above referent. The difference between the two cumulative frequency distributions is taken as the standard for setting the class weight. The values of the class weight show the preference and dependency levels of archaeological sites on different environmental variables. The spot weight shows the degree of land use dependency to various ranges of a specific environmental variable. The frequency distribution of archaeological sites is analyzed for different sub-ranges of each specific environmental variable, which results in a sub-range weight. The grids of the corresponding regional environmental variable layer are reclassified using the same sub-ranges and assigned spot weights. The total weight values of a specific environmental variable in the grid of the study region are multiplied by the above two types of weight layers; all of the total weighted layers are then summed and standardized to one layer (expressing by rank values 0–100%), indicating the potential distribution of land use from low to high across the study region.

Last, the principle of allocating land use to suitable areas is that humans firstly selected the grids around a particular archaeological site with higher rank values, predicted by the residential area distribution sub-model; then, the selection process is continued until the selected suitable human land use areas are equal to the total land use area of a particular archaeological site, calculated by the land use requirement sub-model. Considering the daily walking distance limit of prehistoric humans, allocation happens within a certain distance around the archaeological site.

2.3. Archaeological Data

In total, 327 archaeological sites in the Tao River valley were collected from the Gansu and Qinghai provinces; these were systematically investigated using the second national cultural survey (Supplemental Table S1). Reliable information regarding the archaeological sites was provided in the published atlases [39,40], including the names, locations, areas, cultural types, cultural depths, and archaeological remains of the sites.

The ages of the archaeological sites were assigned, according to their cultural types and sub-types, into three 1000-year time windows during 6–3 ka BP (Table 1). Only 4 archaeological sites under the Majiayao culture in the Tao River valley had no clear culture sub-type information, so we assumed that they continuously existed from 6 to 4 ka BP. Such an assumption could not influence the results of the land use reconstruction, as about 99% of the archaeological sites (n = 323) could be clearly assigned to particular 1000-year intervals.

As for the parameters used for the land use area reconstructions in the PLUM mentioned in Section 2.2, the residential area values for over 90% of the archaeological sites were documented in the atlases; we used the median value of these known sites for other unknown sites with the same cultural type. As some of these known sites covered more than one cultural type (sub-types), but they only had one residential area value. Therefore, the documented residential area value cannot well show the fluctuation of the site population over time, these sites were not used during the area calculation for unknown sites, and only known sites covering a single cultural type were adopted as references. The documented residential areas of the archaeological sites in the study were all deduced by archaeologists according to the scope of the culture remains found (e.g., potteries, houses, and tools) during the field investigations. Based on the archaeological studies [41], the culture remains within the settlement areas were obvious to find, but the culture remains outside the settlement areas were difficult to preserve and find. Therefore, the documented areas of the archaeological sites were taken as the residential areas, which basically include the houses and common spaces for human social activity, but rarely include agriculture fields.

Other socioeconomic parameters for each 1000-year time window were collected from the published literature and are listed in Table 2.

Table 2. Cultural parameters used for the Tao River Valley in the PLUM.

Age (ka BP)	Residential Area Per Person (m^2)	Food Need Per Person (kg/yr)	Yield Per Unit Area (g/m^2)	Fallow Interval (yr)	Tillage Interval (yr)
6–5	186	240	60	10	3
5–4	186	240	60	10	3
4–3	137	240	75	5	3

According to a statistical analysis of data from typical excavated archaeological sites during corresponding periods in the Yellow River valley [42], the average residential area per person in the Tao River valley decreased between the Majiayao Culture and the Qijia Culture during 6–3 ka BP. The average per capita food requirement in the valley was estimated based on the earliest documented values for the early Han Dynasty (around 2 ka BP) [43]. The values were taken as a constant here, as the study showed that no significant changes occurred in human physiognomy and physiology during the Holocene [44]. The yields per unit area for different cultures were estimated based on a linear interpolation of data from different sources (modern observation, historical documents, and archaeological records) [43,45–47]. Fallow and tillage periods were set according to Wang's estimates (1997) [48].

In addition, as 2 h was the estimated maximum time that humans could be expected to spend in reaching agricultural fields in one day [49], this value was used to calculate the threshold value for the available human land use area from 6 to 3 ka BP in the PLUM.

2.4. Environmental Data

Elevation data from across the Tao River valley were obtained from the Shuttle Radar Topography Mission (SRTM) website (http://srtm.csi.cgiar.org/, accessed on 20 February 2024); these are DEM grid data with a horizontal resolution of 90 m and a vertical resolution of 1 m. The soil type data (a grid layer with a scale of 1:1,000,000) were obtained from the Institute of Soil Science, Chinese Academy of Sciences website (http://www.issas.ac.cn/, accessed on 20 February 2024).

The grid and vector layers of the slope, aspect, and river system across the valley were calculated from the elevation data by Geographic Information System (GIS) software (ArcGIS 10.2). The grid layer of the horizontal distance to the river system was derived from the river system layer and the center positions of the elevation grid data in GIS. Therefore, the horizontal resolutions of these data were also 90 m.

The same resolution (90 m $\times$ 90 m) and projection (WGS_1984) of the above environment grid data ensured consistency in extracting environmental information for the archaeological sites, providing a basis for setting reasonable class and spot weights in the PLUM. The modern grid data of the above environment variables were adopted in the land use reconstructions for the different 1000-year time intervals, as the corresponding data from thousands of years ago could not be obtained and environmental conditions did not change significantly during the Holocene.

3. Results

3.1. Changes in Archaeological Sites in the Tao River Valley

The number of archaeological sites increased from 57, 86 to 268 during 6–3 ka BP. The site number increase during 4–3 ka BP was most significant with the development of the Qijia Culture. The percentages of newly recorded archaeological sites as a proportion of the total site numbers in the latter two millennia were high (98% and 69%), representing the high mobility of prehistoric human activity (Figure 2).

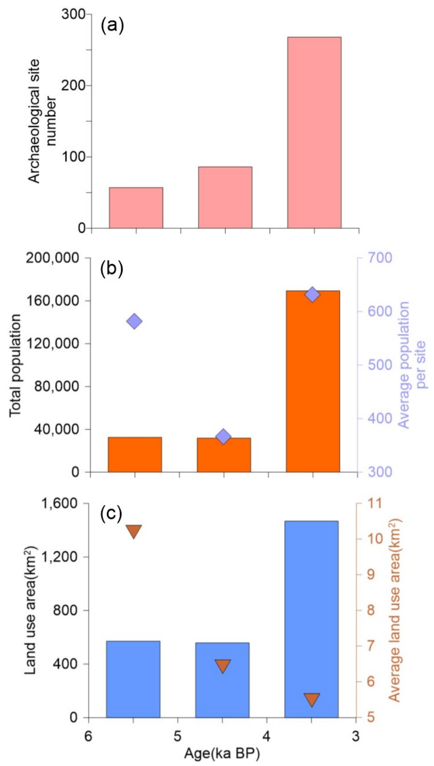

Figure 2. Temporal changes in human activity in the Tao River Valley: (**a**) archaeological site number; (**b**) total population in the valley and average population per site estimated by PLUM; and (**c**) total land use area in the valley and average land use area per site estimated by PLUM.

In a spatial sense, the lower-altitude areas in the northern part of the Tao River valley were covered with a consistently higher density of human occupation from 6 ka BP to 3 ka BP. Prior to 5 ka BP, the archaeological sites were mainly distributed along the main branch of the Tao River. From 5 to 4 ka BP, the sites in the valley spread northwestwards. Since 4 ka BP, these archaeological sites have also expanded to the western part of valley; thus, the number of sites has increased significantly along the upper and middle reaches of the river (Figure 3).

During 6–3 ka BP, the archaeological sites were always located at areas close to the river system, with low elevations and gentle slopes. About 90%, 65%, and 67% of the sites distributed in the areas had elevations between 1700 and 2400 m, a slope angle of <5°, and a horizontal distance to the river system of <1500 m. This distribution of sites further revealed a preference for particular soil types, e.g., from 6 ka BP to 3 ka BP, about 79% of the sites were distributed on black loam soil, loess soil, and gray meadow soil.

3.2. Changes in Prehistoric Population and Land Use Reconstructed by PLUM in the Tao River Valley

From 6 ka BP to 3 ka BP, the numbers of reconstructed populations in the Tao River valley were 3.3×10^4, 3.2×10^4, and 16.9×10^4 during each millennium, while the reconstructed land use areas were 571 km^2, 559 km^2, and 1468 km^2, respectively. The population size and land use remained stable during the former two millennia; however, significant increases in the total population and land use occurred in the latter two millennia, as indicated by the over 4-fold increase in the total population size and the 1.6-fold increase in the total land use area (Figure 2).

The average reconstructed population and land use per archaeological site showed the changes in settlement size between 6 ka BP and 3 ka BP (Figure 2). About 70% and 64% of the archaeological sites had a population size of <500 persons and a land use area of $<500 \times 10^4$ km^2 during each millennium, while only <10% and <12% of sites had a population size of >1500 persons and a land use area of >1000 × 10^4 km^2. These large-size settlements were usually distributed in the conjunction areas of rivers, while archaeological sites with smaller areas were often distributed around larger ones.

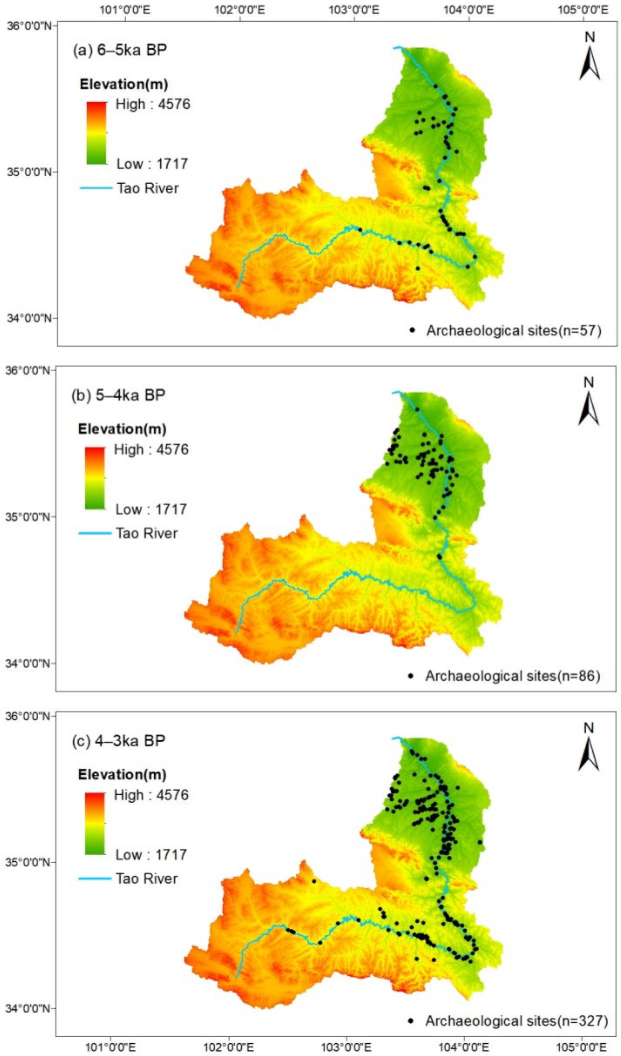

Figure 3. Spatial changes in archaeological sites in the Tao River valley from 6 to 3 ka BP: (**a**) 6–5 ka BP; (**b**) 5–4 ka BP; and (**c**) 4–3 ka BP.

As for the geographic spread of the reconstructed population and land use during the 3000-year interval, the process can be divided into three stages, in accordance with the changes in archaeological site distribution. First, during 6–5 ka BP, the population and land use were mainly distributed along the main branch of the Tao River valley. Second, they expanded into the northwestern part of the valley during 5–4 ka BP, but a decrease also appeared in some areas of the southern part of the valley. Finally, the significant population and land use growth during 4–3 ka BP induced an expansion to the upper and middle reaches of the Tao River valley (Figure 4).

Compared with today, where the human land use reconstructed by PLUM in the Tao River valley is at 14%, from 6 ka BP to 3 ka BP, only 2–6% of land use showed a low human activity intensity during the prehistoric periods. However, due to the impact of fluvial erosion, human disturbance, or other taphonomic factors on archaeological conservation, the archaeological sites found only show the lower limits of the actual prehistoric populations and land use.

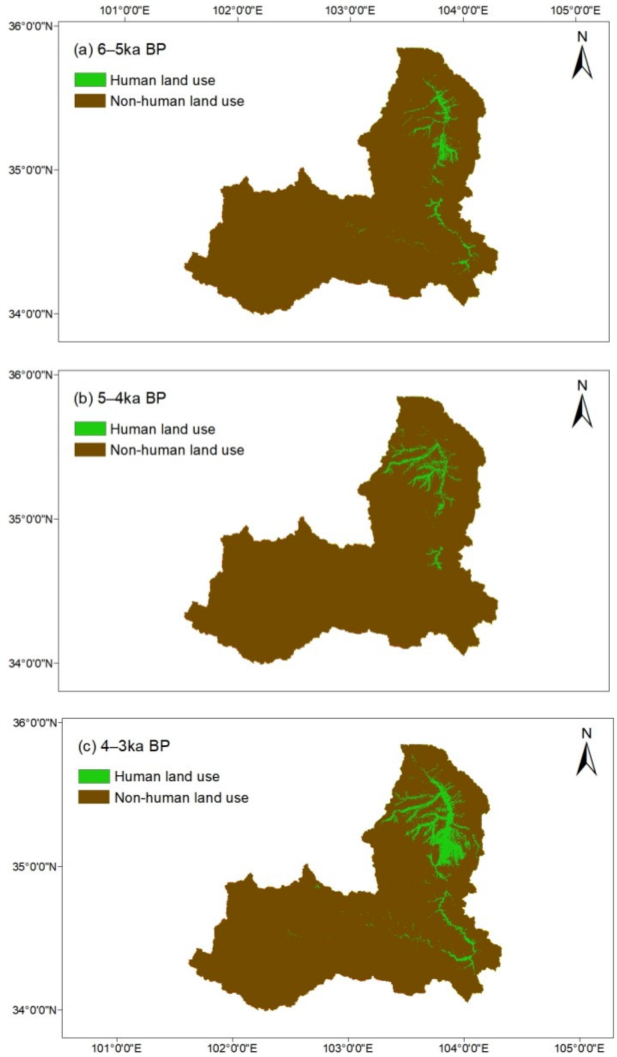

Figure 4. Spatial changes in human land use reconstructed by PLUM in the Tao River valley from 6 to 3 ka BP: (**a**) 6–5 ka BP; (**b**) 5–4 ka BP; and (**c**) 4–3 ka BP.

4. Discussion

4.1. Spatial Variation in Land Use in the Upper and Middle Reaches of the Yellow River Valley

With the addition of the Tao River valley, prehistoric human land use changes were quantitatively reconstructed in the five areas inside the upper and middle reaches of the Yellow River valley [3,4,6,30]. Among these, the Huangshui and Tao River valleys are distributed in the upper reach of the Yellow River valley, while the Yulin district and Wei and Yiluo River valleys are located in the middle reach.

Within the above five areas, different trends of increasing land use from 8 ka BP to 3 ka BP occurred; these could be further divided into two groups. The first group (the Wei River and Yiluo River valleys) saw characteristic rapid, significant growth before 5 ka BP, while the second group (the Huangshui River and Tao River valleys and the Yunlin district) saw a much slower and less significant increase before 5 ka BP and a more significant increase thereafter. The accelerating increase in the Yulin district during 5–4 ka BP even made its land use percentage (7.6%) reach similar levels to those in the Wei River (11.20%) and Yiluo River valleys (9.48%); however, the significant land use increase in the Tao River valley occurred even later (during 4–3 ka BP) (Figure 5a). Additionally, the growth in land use in the Huangshui River valley was relatively small and slow throughout the period. The asynchronous increases in these areas indicate the expansion of land use from the southeastern middle Yellow River valley to the entire upper and middle reaches between 8 ka BP and 3 ka BP.

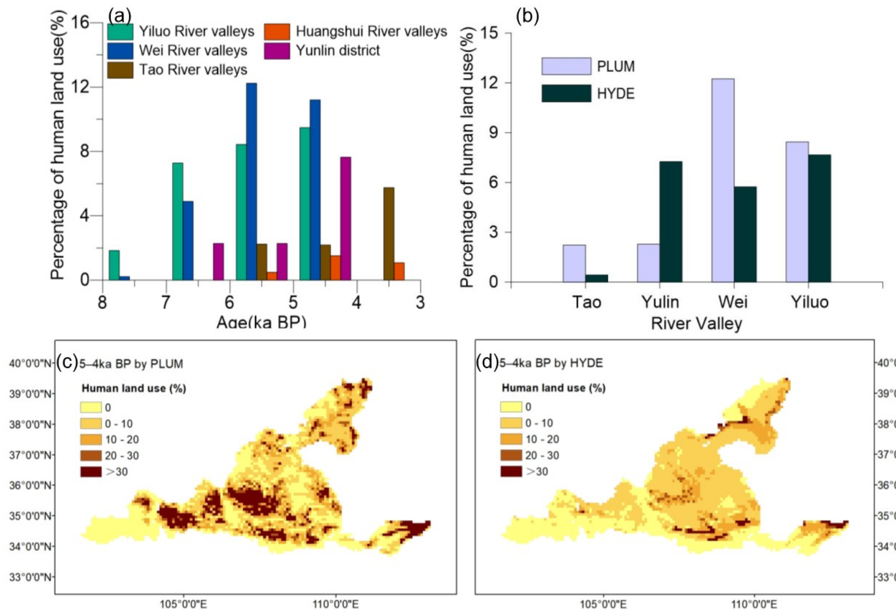

Figure 5. Comparison of land use changes across the upper and middle reaches of the Yellow River valley: (**a**) land use reconstructions from 8 to 3 ka BP in the five areas by PLUM and Hou et al. (2013) [6]; (**b**) land use reconstructions during 5–4 ka BP by PLUM and HYDE [14]; (**c**) spatial distribution of reconstructed land use during 5–4 ka BP by PLUM; and (**d**) spatial distribution of reconstructed land use during 5–4 ka BP by HYDE.

However, the spatial expansion characteristics and distribution preferences of land use within the five areas remained similar during 8–3 ka BP. High land use intensity usually first appeared in the flat areas with a low altitude in the lower reaches of each river valley; with an increasing land use size, there was geographical expansion to the middle and upper reaches of each valley. In the process of land use expansion, areas closer to the river system were usually prioritized for selection by humans.

4.2. Comparison with Previous Land Use Reconstructions

Currently, the HYDE3.2 database is a widely used resource resulting from Holocene land use reconstruction [25]. The size of prehistoric land use in the HYDE was estimated based on extrapolations of historic population data and land use per capita, while the distribution of past land use was reconstructed according to modern distribution patterns of population and environmental variables. Here, using the HYDE and PLUM, the reconstructed results in the four areas (the Yulin district and the Tao, Wei, and Yiluo River valleys) across the upper and middle reaches of the Yellow River valley during 5–4 ka BP were compared by converting them into the same spatial resolution (9 km).

In a temporal sense, the reconstruction using the HYDE revealed that the percentages of land use in the upper reach were significantly lower than those in the middle reach; the values of land use percentage during 5–4 ka BP in the middle reach were similar (all about 6–7%). However, the reconstruction using the PLUM indicated that the percentages of land use in the surrounding areas of the middle reach (the Yulin district) were also as low as those of the upper reach (the Tao River valley), and the human activity intensities in the core agriculture development areas of the middle reach (the Wei and Yiluo River valleys) were much higher (Figure 5b). In a spatial sense, the variations in the reconstructed land use distributions in the upper and middle reaches of the Yellow River valley, according to the PLUM, were more significant than those with the HYDE (Figure 5c,d).

Overall, the accuracy of the PLUM's prehistoric land use reconstruction was improved by the introduction of direct evidence of human activity (archaeological sites). Compared to using historical population data for extrapolation in the HYDE3.2, in the PLUM, the numbers and sizes of the archaeological sites were combined to estimate population changes; this may better reflect local differences in population sizes and their temporal fluctuations. The decreasing land use per capita adopted in the PLUM was estimated directly from the archaeological records of typical sites [42] and supported by previous studies [50–52]; meanwhile, the increasing values of land use per capita used in the HYDE3.2 [25] could not well represent the increasing land use efficiency over time. For land use distribution, compared to the spatial distribution based on the modern population density in HYDE3.2, the direct evidence of prehistoric human activity used in the PLUM reduced the uncertainty caused by the population's spatial migration over time.

According to the PLUM, the reconstructed prehistoric human land use changes across the upper and middle reaches of the Yellow River valley are further supported by previous qualitative or semi-quantitative studies of human activity based on different geological records [53–60]. Abundant evidence of human activity appeared during 6–4 ka BP within the core agriculture development areas of the middle reach of the Yellow River valley mentioned above, but corresponding evidence was rare in the surrounding areas of the upper and middle reaches of the valley, for example, the decline in forest cover revealed by pollen records [56,61] and the high-frequency fire activity history from charcoal records [62,63]. At the same time, the elevated nitrogen isotope values of cereal grains relative to the local vegetation indicate that manuring practices possibly prevailed in the middle Yellow River area during the late Yangshao period, reflecting a higher regional land use intensity [64].

Above all, the application of the PLUM significantly improved the reliability of the quantitative land use reconstruction results from both temporal and spatial perspectives. These reconstructed results will be important foundational data for further climate and land cover change feedback simulations, which cannot be achieved by the previous qualitative studies.

It is worth mentioning that archaeological site excavation bias affected the PLUM's reconstruction results, as currently found archaeological sites only show the lower limits of prehistoric human activity and, during different cultural periods, their probability was impacted by their burial depth. The precision of other environmental and social inputs (e.g., elevation, distance to river system, and yield and fallow periods) also needs to be improved. Furthermore, the current PLUM is based on the assumptions of one single land use type and a closed balance of food needs and supply in the region, and a more accurate land use per capita would be obtained by considering other types of human food resources in a new version of the model.

4.3. Potential Drivers of Regional Land Use Change

Agriculture development has always been considered as the direct driver of human land use expansion during the Holocene, which was further affected by regional climate change. Leipe et al. (2019) [13] revealed the spread of millet agriculture in eastern Asia based on a dataset of radiocarbon dates derived from domesticated millet grains; the results indicated that agricultural spread from the middle to the upper Yellow River during 6–5 ka BP accelerated the significant population growth, thus supporting our reconstructed macro pattern of land use expansion.

He et al. (2022) [21] further explored the spatiotemporal evolutions of the main crop types (millet, rice, and wheat) in different cultural regions of north China based on a comprehensive dataset of archaeobotanical macro-remains. The five areas with quantitative land use reconstruction were distributed inside these different cultural regions (the Yiluo River valley–Central Plains culture region, the Wei River valley–Guanzhong culture region, the Yulin district–Yanbei culture region, and the Tao and Huangshui River valleys–Ganqing culture region); therefore, a comparison of land use percentages, the total number of archaeobotanical macro-remains, and their floating results can further reveal the impact of agricultural development on land use (Figure 6a–d).

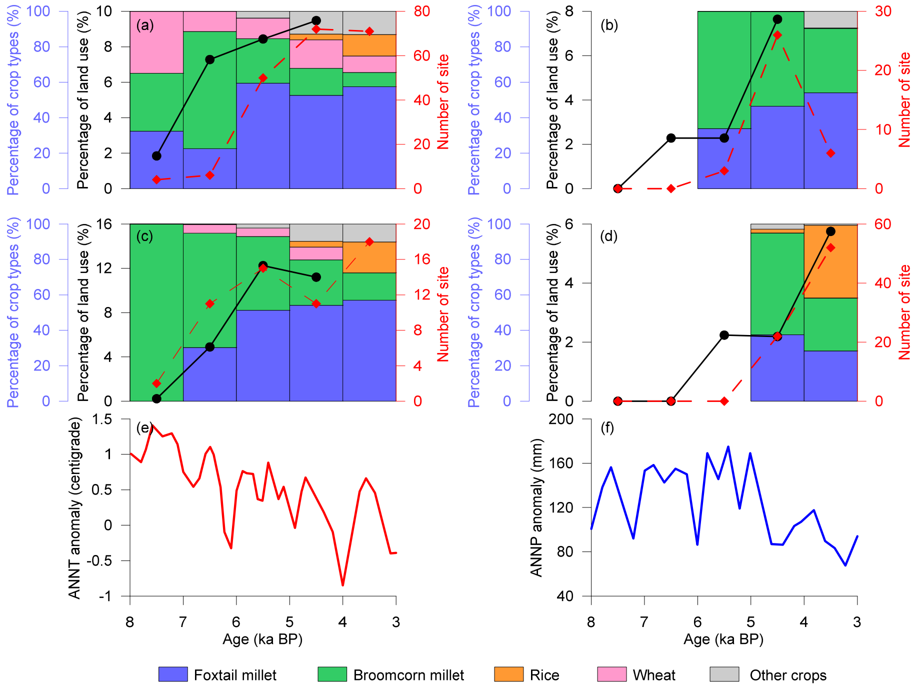

Figure 6. Comparison of changes in land use, archaeobotanical macro-remains, and climate among five areas in the upper and middle reaches of the Yellow River valley: (**a**) Yiluo River valley; (**b**) Yulin District; (**c**) Wei River valley; (**d**) Tao River valley; (**e**) ANNT (annual mean temperature) anomaly in China; and (**f**) ANNP (annual mean precipitation) anomaly in north China. The reconstructed land use area from this study. The archaeobotanical data are from [21]. The reconstructed anomalies of ANNT and ANNP are from studies by [65,66].

Overall, the increases in land use area and the number of archaeobotanical macro-remains from 8 ka BP to 3 ka BP were synchronous within different cultural regions, confirming their close relationship. The crop structure evolution in different cultural regions showed further diverse characteristics. In the Central Plain and Guanzhong cultural regions, more than one crop type (including foxtail millet, broomcorn millet, and rice) has been found since 7 ka BP, and cropping structures became more diversified with the introduction of wheat around 5 ka BP. This ensured rapid population and land use growth in the core agricultural development areas, such as the Yiluo and Wei River valleys (Figure 6a,c). Among the surrounding areas of agricultural development (e.g., the Yulin district), only one crop type (millet) was cultivated in the Yanbei cultural region (Figure 6b); however, wheat's contribution to the total cultivation significantly increased in the Ganqing cultural region after 4 ka BP, thus explaining the abnormal land use growth in the Tao River valley during the corresponding period (Figure 6d).

The period around 6 ka BP was a key time in the dispersal and transition of millet agriculture, and this coincided with the Holocene Optimum and Late Yangshao Culture (Figure 6e,f) [21,65,66]. Besides the significant westward and northward spread of agriculture from the core development region to the surrounding areas, a significant transition from broomcorn millet (low-yield) to foxtail millet (high-yield) also occurred across the upper and middle reaches of the Yellow River valley. Therefore, the combined impact of favorable climate conditions, the pressures of rapid population growth, and improved field management potentially promoted the intensification, dispersal, and transition of millet agriculture and corresponding land use during 6–4 ka BP [21]. In the upper and middle reaches of the Yellow River valley, climate conditions played an overall positive role in regional agricultural development and land use expansion from 6 to 4 ka BP. For the core agricultural development areas of the valley, the explosive growth of the regional population, enhanced by the warm and wet climate, led to improvements in land use efficiency and outward land use expansion into the surrounding areas in order to alleviate regional resource pressure. For the surrounding areas of the valley, climate change provided a good opportunity for population and land use expansion, which even further promoted large-scale communication between different cultural regions. Here, the Yulin district was potentially an important channel for population exchange between the middle reaches of the Yellow and Western Liao River valleys, as the enhanced linkage between the peoples of the two valleys from 5 ka BP was revealed by genetic data [67], which corresponded with the significant regional land use expansion during this time (Figure 6b).

5. Conclusions

In this study, prehistoric land use in the Tao River valley, in the upper reach of the Yellow River valley, was first quantitatively reconstructed using archaeological data and the PLUM model; then, the spatiotemporal variations in land use changes across the upper and middle reaches of the Yellow River valley from 8 ka BP to 3 ka BP were further revealed through reconstructions of land use in the five areas (the Tao, Huangshui, Wei, and Yiluo River valleys and the Yulin district) from the current and previous studies. Due to the introduction of archaeological data, the PLUM reconstructions more accurately reflected the spatiotemporal changes in prehistoric human activity intensity.

During 6–4 ka BP, the warm and wet climate conditions provided a favorable environment for agriculture and cultural communication; the pressures of land use changes in the core agricultural development areas were alleviated by improvements in land management and the expansion of land use to the surrounding areas, which further enhanced large-scale culture exchange.

With improvements in the archeological database in the future, the PLUM's quantitative, prehistoric land use reconstruction could be applied to wider regional levels; the corresponding results could not only help us to understand the interactions among human activities, agricultural development, and environmental change, from both spatial and temporal perspectives, but also provide an important base for evaluating the role played by human activity in global changes over long timescales.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land13060784/s1, Figure S1: Structure of PLUM; Table S1: Information for the archaeological sites in the Tao River valley.

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