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Spatial and temporal changes of prehistoric human land use in the Wei River valley, northern China

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Abstract

Agricultural land use has been established as the dominant prehistoric human activity in early cultural centers for thousands of years. However, because of lack of data, there is still considerable debate about the amount and spatial distribution of prehistoric land use across the world. Quantitative reconstruction of it on the basis of human activity records, for example, archaeological data, is the key to resolving the issue. Here, we focus on one of the most representative regions for prehistoric human activity in northern China, the Wei River valley. Based on archaeological and environmental data, a recently developed quantitative prehistoric land use model (PLUM) is applied to reconstruct spatial and temporal changes of land use between 8 and 4 ka BP. The results reveal that in line with increases in the total number of archaeological sites (from 24 to 3222) and population (from 4000 to 1,550,000), the land area of the valley used by humans increased from 0.2% to 12% during the study interval, expanding from the gentle slopes along the lower reaches of the river to the middle and upper reaches. Meanwhile, the average population for an individual site increased from 160 to 481, but the average land use area per site decreased from 12.84 to 4.68 km^2. Since 6 ka BP, the significant land use increase occurred synchronously in the Wei River valley and other key regions of agricultural origin across the world, which highlights the important role of agriculture activity in transforming the nature of global land cover during the prehistoric period.

Keywords

agricultural development, archaeological sites, environmental conditions, Holocene, land use, prehistoric human activity

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Introduction

Land use (including cultivation, pasture, and construction/living areas) is one of the most important expressions of human activity during the Holocene, and has affected many aspects of the earth system from the regional hydrological cycle to the global climate through biophysical and biochemical processes (Foley et al., 2003, 2005). It has altered more than half of the earth's surface (Hooke et al., 2012) and been the first source of carbon emission and global warming induced by human activity, well in advance of emissions from fuel combustion from ca. AD 1800 onwards (Houghton, 2003).

However, it is difficult to evaluate the contribution of land use to environmental change during the preindustrial period because of the lack of observations or documentary evidence (especially for the prehistoric period). Current dates for the beginning of the Anthropocene are debated, ranging from the Pleistocene/Holocene boundary (Smith and Zeder, 2013), to the mid-Holocene rise of agriculture at approximately 7 ka BP (Ruddiman, 2013), to the industrial revolution, ca. AD 1800 (Steffen et al., 2011), to the Atomic Age (Zalasiewicz et al., 2011). Therefore, quantitative reconstructions of prehistoric land use are key for establishing the extent of human alteration of the earth surface during the Holocene.

Quantitative prehistoric land use reconstructions, from regional to global scale, have mainly used modeling approaches. Hindcasting techniques are usually adopted based on population estimation, establishment of the relationship between land use and population, and the allocation of land use to spatial maps (Kaplan et al., 2011; Klein Goldewijk, 2001; Klein Goldewijk et al., 2011; Lemmen, 2009; Olofsson and Hickler, 2008; Pongratz et al., 2009). An alternative approach to estimating the magnitude of anthropogenic deforestation involves using mechanistic or analogy models based on pollen records. For example, the REVEALS model addresses the non-linear pollen–vegetation relationship in light of pollen production, dispersal, and deposition processes (Sugita, 2007), while the pseudobiomization method (PBM) is a developed biomization method that can potentially reconstruct both natural and cultural land use classes by the transformation of pollen data (Fyfe et al., 2010).

Unfortunately, large discrepancies exist among the current reconstructions achieved using the foregoing methods. For example, the highest estimate of global average land use percentage by the KK10 scenario (Kaplan et al., 2011), growing from 1.50% to

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4.12% during the period 8–4 ka BP, is roughly an order of magnitude greater than that of the HYDE database (Klein Goldewijk et al., 2011), which estimates growth from 0.02% to 0.37% over the same period. Other regional reconstruction results (Fyfe et al., 2015; Lemmen, 2009; Trondman et al., 2015) usually fall within the range of the above two studies, and are more or less close to the estimate of the KK10 scenario. For example, up to 11% of the regional land surface in the Eurasian continent was under cultivation by 4 ka BP, as simulated by the GLUES model (Lemmen, 2009); and about 20% of the land surface had been opened by anthropogenic deforestation in the centers of agricultural development in Europe by around 6 ka BP, revealed by the REVEALS and PBM models (Fyfe et al., 2015; Trondman et al., 2015).

The size of these discrepancies is caused by the uncertainties involved in land use reconstruction. In the case of the hindcasting techniques, because of the limitations of the data on population and land use per capita, the relationship between population and the distributions of environmental variables is always based on records from specific regions or historic periods. When such data are extrapolated to other regions or periods, differences in local human activity are likely to affect the accuracy of land use area estimates. While it is possible to estimate the potential distribution of land use within different regions based on their degree of suitability for human activity, the precision of such estimates is hampered by the lack of direct evidence of prehistoric population distributions which could be used as control points. In addition, in the case of pollen studies, it remains difficult to identify many cereal pollen types to species level and to distinguish anthropogenic biotopes from natural plant communities on the basis of vegetation composition.

Some of these shortcomings could be overcome with the introduction of archaeological sites, direct evidences of prehistoric human occupation, land use reconstruction by bottom-up methods derived from sites containing the information relating to the amount and associated spatial boundaries of local land use during prehistoric periods. Recently, a quantitative prehistoric land use model, PLUM (Yu et al., 2012), has been developed by combining information about human activity from archaeological sites and the relationship between site distributions and environmental conditions.

PLUM has been successfully validated and applied in the Yiluo valley in the middle Yellow River basin of northern China, which is one of the world's four centers for the origin of agriculture (millet) (Yu et al., 2012). The results indicate that about 10% of the regional land areas had been used by humans during the middle to late-Holocene (6–4 ka BP). However, the current reconstructed area of the Yiluo valley comprises less than 3% of the Yellow River basin, which is too small to be representative of the entire agricultural region in northern China.

The present agricultural region in northern China lies mainly in the Yellow River and Liao River basins, southeast of the 400-mm annual isohyet (Gao et al., 2005; Zhang et al., 2008) (Figure 1a), where were also the origin and development centers of primitive agriculture during the prehistoric period (Liu and Fan, 2015). As the largest tributary of the Yellow River, the Wei River valley is highly representative of the agriculture region in northern China, since it forms about 20% of the area of the entire Yellow River basin, and has experienced continuous agriculture development since the early Holocene (8–7 ka BP) (Shen, 2000). Furthermore, the widespread thick loess deposits in the Wei valley are favorable for the preservation of archaeological remains, thus numerous important archaeological sites have been discovered by detailed field surveys, which offers a good opportunity for land use reconstruction using PLUM.

The main objectives of the present research are (1) to reconstruct spatial and temporal changes of prehistoric land use in the Wei River valley, and (2) to reveal changes in the intensity of prehistoric human activity in the core agriculture areas of northern China and the possible drivers of these changes.

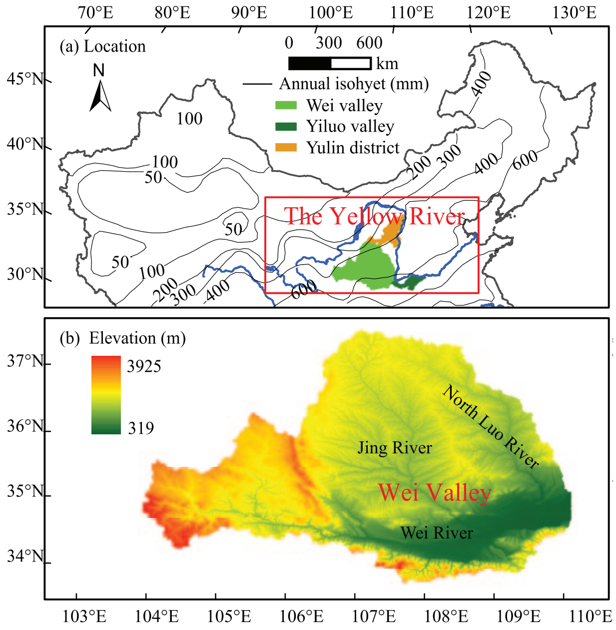

Figure 1. (a) Location of the study regions in northern China (Wei River valley, Yiluo valley, and Yulin district), and isohyets (mm); and (b) elevation and fluvial networks of the Wei River valley.

Materials and methods

Study region and period

The Wei River valley (103.5–110.5°E, 33.5–37.5°N) covers an area of about $13.48 \times 10^4 \mathrm{km}^2$ in the middle reaches of Yellow River basin (Figure 1a), and includes eastern Gansu province, southern Ningxia autonomous region, and central Shaanxi province. It is composed of two tributaries, the Jing and North Luo Rivers, and the main stream of the Wei River (Figure 1b). Landforms in the area include the margin of the Chinese Loess Plateau in the northwestern part, mountains in the west-central part, and alluvial plains (e.g. Guanzhong Basin) in the southeast (Jiang et al., 2013; Zhang et al., 2009). Modern mean seasonal temperatures range from −2.2 to 15.1°C, and the mean annual precipitation decreases from 908 to 335 mm from southeast to northwest across the valley (http://www.geodata.cn; Jiang et al., 2013) (Figure 1a). Natural vegetation reflects the decrease in precipitation, and changes from warm temperate deciduous broad-leaved forest in the east to temperate deciduous broad-leaved forest, temperate forest-steppe, and temperate steppe in the west (Zhou et al., 2015). Currently, about 46% of the valley area is cultivated (http://www.geodata.cn). The soils are mainly developed from loess parent material, and the dominant types are loessial soil (WRB: cambisols), cinnamon soil (WRB: cambisols), brown soil (WRB: luvisols), and dark loessial soil (WRB: cambisols) (Tian et al., 1996b; Zhang et al., 2014).

Different local cultures and cultural subtypes developed inside the valley during the Neolithic Age (National Heritage Board, 1998, 2010, 2011) (Table 1). The first cultural sequence, from 8 to 3 ka BP, developed in the western part of the valley in Gansu Province and Ningxia autonomous region and comprises the Dadiwan, Yangshao, Majiayao, Qijia, and Siwa Cultures. The second sequence, from 8 to 4 ka BP, developed in the eastern part of the valley in southern Shaanxi Province and comprises the Laoguantai, Yangshao, Miaodigou II, and Longshan Cultures. The third, from 7 to 4 ka BP, developed in the eastern part of the valley in northern Shaanxi Province and comprises the Yangshao and the late Neolithic Cultures.

Table 1. Bounding ages and distributions of cultures in the Wei River valley.

Time period (ka BP)	Culture types (subtypes)	Age (a BP)	Distributed area (administrative region)	Source reference
8–7	Laoguantai	8000–7000	Shaanxi	Zhang (1986)
	Beishouling	7150–7020	Shaanxi	Shi (1986a)
	Dadiwan	7850–7400	Gansu	Zheng (1986)
7–6	Yangshao (Banpo)	6800–6300	Gansu, Shaanxi	Shi (1986b)
	Yangshao (Shijia)	6500–6000	Gansu, Shaanxi	Shi (1986b)
6–5	Yangshao (Miaodigou)	6000–5600	Gansu, Shaanxi	Shi (1986b)
	Yangshao (Late Banpo)	5600–5000	Gansu, Shaanxi	Shi (1986b)
	Yangshao (Xiwangcun)	5600–5000	Shaanxi	Shi (1986b)
	Majiayao (Shilingxia)	5600–5300	Gansu, Ningxia	Yan (1986)
	Majiayao (Majiayao)	5300–4900	Gansu, Ningxia	Yan (1986)
5–4	Majiayao (Xiaopingzi)	4900–4650	Gansu, Ningxia	Yan (1986)
	Majiayao (Banshan)	4650–4350	Gansu, Ningxia	Yan (1986)
	Majiayao (Machang)	4350–4050	Gansu, Ningxia	Yan (1986)
	Miaodigou II	4900–4800	Shaanxi	Tong (1986)
	Changshan Lower	5000–4600	Gansu, Ningxia	Shi (1986b)
	Longshan	4600–4000	Shaanxi	Tong (1986)
	Late Neolithic Age	5000–4000	Shaanxi	Pei and An (1986)
	Qijia	Around 4000	Gansu, Ningxia	Xie (1986)
4–3	Siwa	3400–3100	Gansu, Ningxia	Hu (1986)

The study spans the interval from 8 to 4 ka BP, because the earliest agricultural remains found here are from sites dated to around 8 ka BP (Table 1), while few archaeological sites younger than 4 ka BP have been found. This reflects archaeologists pay less attention to the investigations of sites for this later period, as a result of which the detailed historical records increased since the start of the Xia–Shang–Zhou dynasty (about 3600 years ago) (Xia–Shang–Zhou Chronology Project Expert Group, 2000).

Model configuration

PLUM is a quantitative prehistoric land use model which was developed from archaeological site prediction models (Kvamme, 1990; White, 2002) by adding two other sub-models to estimate the amount and spatial distribution of human cultivation and living areas (Supplementary Figure S1, available online).

The archaeological site prediction model is here referred to as the residential area distribution sub-model (Espa et al., 2006; Kvamme, 1990; White, 2002), predicting the potential spatial distribution of human occupation by rank values according to the relationship between environmental conditions and distribution of recorded archaeological sites.

The first, new added ‘land use need sub-model’ provides an estimate of the total population number, and the cultivated and living areas in the region, on the assumption that the food need of humans is totally supplied by local cultivation. Studies have revealed that in the case of settled societies, cultivation became the dominant source of food in the inland regions of China as early as the beginning of the Holocene (Shang, 1992).

The second new added ‘land use allocation sub-model’ distributes the total land use area for an individual archaeological site, as estimated by the land use need sub-model, across the area of suitable locations around the corresponding site, according to the distribution of potential human occupation predicted by the residential area distribution sub-model. The workflows of the above sub-models are outlined below (see Yu et al. (2012) for more detailed information).

In the land use need sub-model, the total population number (P) and human land use area (A_l) in the region are estimated based on economic and social parameters of archaeological sites as follows:

$$P = \frac{A_r}{A_p} \tag{1}$$

The annual average P is equal to the ratio of total residential area (A_r) to area needed by each person (A_p) in the site. A_r is usually inferred by archaeologists according to the total excavation area of each site, while A_p is always obtained by tomb and settlement analysis of the excavated sites (Wang, 2011).

A_l is estimated by the sum of A_r and cultivated (A_c) areas of the sites:

$$A_l = A_r + A_c \tag{2}$$

The number of stone axes found in sites, the rise of charcoal concentrations in sediments around archaeological sites, and the historical documents all indicate the existence of slash and burn agricultural system during the prehistoric period (Huang et al., 2006; Wang, 1997); thus, A_c is further composed of the theoretical area needed to sustain the total population of the site (A_n) together with the area of fallow required by the slash and burn agricultural system, and A_c can be estimated by:

$$A_c = \left[\frac{(T_f + T_c)}{T_c}\right] \times A_n \tag{3}$$

where T_f and T_c are the fallow and tillage periods in a single cultivation cycle, respectively. The equation is based on studies that infer T_f according to the maximum local land carrying capacity of the population (Freachan, 1973; Wang, 1997).

A_n in Eq. 3 is further estimated by P, the food need per person (F_p) and the crop yield per area (Y) based on the assumption of a balance between local food demand and supply:

$$A_n = \frac{(P \times F_p)}{Y} \tag{4}$$

Combining the above equations, the annual average land use area in the sites is calculated as:

$$A_l = A_r + \left\{\frac{\left[(A_r / A_p) \times F_p\right]}{Y}\right\} \times \left[\frac{(T_f + T_c)}{T_c}\right] \tag{5}$$

Currently, most of the sites are only dated based on specific culture types, and the population and land use area under the same culture type are always assumed to be constant. Therefore, the foregoing calculations of population and land use area are assumed to be representative of the intensity of human activity for the entire duration of the culture.

In the residential area distribution sub-model, the weighted overlay method is adopted to predict the potential distribution of human occupation. Two types of weights are calculated and combined in raster layers of environment data. First, the indicative environment variables restricting human activity distribution is selected based on Kolmogorov one sample goodness-of-fit test. Second, the class weights of selected variables are set by comparing the cumulative frequency distributions of the grid values of the above variables for the study region and that of the corresponding values for archaeological sites. Third, the frequency distributions of recorded sites are analyzed for different sub-ranges of selected environmental variables, and the grids of corresponding variable layer are reclassified using the same sub-ranges and assigned spot weights. Finally, the total weight for any given grid cell in a selected variable layer is obtained by multiplying its class weight by spot weight, and the total weighted layers are added up to one layer with a standardized rank of 0–100% to illustrate the potential distribution of human activity from low to high levels.

In the land use allocation sub-model, the cultivated area is always assumed to be located in a suitable environment within a certain distance of the archaeological site. The degree of suitability of each location in the region is assumed to follow the potential distribution of human occupation specified by the residential area sub-model, while the distance radius around the site is determined by the maximum time that humans could realistically spend walking in one day (Zhang, 2003; Zheng et al., 2008). The amount of land needed for each individual site (the output from the land use need sub-model) is matched by the most favorable areas around the corresponding site using the rank values of the environmental grids from the residential area sub-model.

Model inputs

Model inputs are cataloged as spatial and attribute data according to their formats. The former includes layers of environmental variables for the residential area distribution sub-model, while the latter is composed of environmental, economic, and social parameters of the archaeological sites used for all sub-models.

Spatial inputs. The spatial data are derived from digital maps of modern elevation and soil type. This is because the corresponding data for the prehistoric period could not be obtained and the environmental conditions in the valley have not changed significantly during the Holocene (Xiong et al., 2014).

Elevation raster data across the valley are represented by a grid layer with a horizontal resolution of 90 m and a vertical resolution of 1 m from the website of Shuttle Radar Topography Mission (SRTM) (http://srtm.csi.cgiar.org/). Slope, aspect, and river system layers are derived from this elevation dataset using a Geographic Information System (GIS), and the derived river system compares well with the regional topographic map at a scale of 1:50,000 (http://www.ngac.cn/). The layers of river system and elevation are further used to construct grid layers of the horizontal distance to the river system and the relative elevation of the valley. Soil and land use types at a scale of 1:400,000 are taken from the national data sharing infrastructure of earth system science (http://www.geodata.cn; Tian et al., 1996a, 1996b).

Finally, all of these vector and raster layers of environmental variables are resampled to grid data in GIS under the uniform projection of WGS_1984 with a constant resolution of 90 m × 90 m, which produces the combination of high resolution results and acceptable processing speed during modeling.

Attribute inputs. A total of 5022 archaeological sites were collected from the Culture Atlas of Gansu, Shaanxi province and Ningxia autonomous region (National Heritage Board, 1998, 2010, 2011), and Chinese archaeology almanacs (2000–2012) (Chinese Archaeology Society, 2000, 2003, 2005, 2006, 2007, 2008, 2010, 2011, 2012) (Supplementary Table S1, available online). Archaeologists have conducted detailed field investigations in the Wei River valley for 60 years, and systematic information on archaeological sites has been obtained by the Second National Culture Relic Survey, which was led by different archeological teams under the same standard (National Heritage Board, 1998, 2010, 2011). Therefore, the sites that have been discovered are representative of changes of prehistoric human activity and provide lower limits on the actual population and land use amount. However, it should be noted that some sites may have been destroyed by fluvial erosion, human disturbance and other taphonomic factors, or been missed as a result of human omissions during the survey.

Ages of the archaeological sites in the Wei River valley. All of the sites occur within the context of specific culture type or subtype, which are documented in the excavation reports (Chinese Archaeology Society, 2000, 2003, 2005, 2006, 2007, 2008, 2010, 2011, 2012; National Heritage Board, 1998, 2010, 2011). The boundaries for the various cultures are well established by ^{14}C dating (Shi, 1986a, 1986b; Tong, 1986; Xie, 1986; Yan, 1986; Zhang, 1986; Zheng, 1986) and are listed in Table 1. The Laoguantai Culture and Dadiwan Culture (8–7 ka BP) are the earliest ceramic pottery-making culture in northern China; the Yangshao Culture (6.8–5 ka BP) and Majiayao Culture (5.6–4.05 ka BP), including various subtypes, both span intervals of more than 1000 years; the Miaodigou II, Longshan, and Qijia Cultures all belong to the period 5–4 ka BP (Table 1).

In order to compare the intensity of human activity on a common temporal scale, the sites were assigned to four 1000-year intervals from 8 to 4 ka BP according to the duration of their corresponding cultures. In about 39% of cases ($n = 1000$) of the sites of the Yangshao Culture, and 32% ($n = 72$) of the sites of the Majiayao Culture, no information was available regarding their subtypes and therefore they could not be directly assigned to a specific 1000-year interval. In these instances, the subtype of the nearest known sites during the corresponding cultural periods was adopted, assuming similar environmental conditions for prehistoric human activity. This approach is validated by the comparable percentages observed for different subtypes between site groups with known subtypes and groups with values adopted from comparable nearby sites. For example, the values for known groups for the early and late Yangshao Culture are 37% and 63%, respectively; while the equivalent values for adopted groups for the corresponding Cultures are 40% and 60%, respectively. Finally, about 81% of the sites ($n = 4070$) are classified within a single culture type, while the remaining sites ($n = 952$) have developed continuously and span more than one cultural period and therefore are classified into two or more 1000-year intervals.

Socioeconomic parameters of the sites in the Wei River valley. For 98% ($n = 4947$) of the archaeological sites, the residential areas, which are always much larger than the excavated areas, are documented in excavation reports (Chinese Archaeology Society, 2000, 2003, 2005, 2006, 2007, 2008, 2010, 2011, 2012; National Heritage Board, 1998, 2010, 2011). For the remaining 2% ($n = 83$), the areas are estimated from the average of the known residential areas of sites in corresponding cultural periods.

Other socioeconomic parameters for the sites are listed in Table 2. Among the various parameters, it is noteworthy that the average residential area per person decreased during the period of study, as indicated by statistical analysis of the data from 18 typical excavated sites for corresponding periods inside or near the Wei River valley (Wang, 2011).

Table 2. Social and economic parameters used for the application of PLUM to the Wei River valley.

Time period (ka BP)	Average residential land use area[a] (m^2)	Food need per person[b] (kg/yr)	Crop yield[c] (g/m^2)	Length of fallow[d] (year)	Length of tillage[d] (year)	Spatial extent of land use[e] (km)
8–7	580 (177–647)	240	45	42	3	7
7–6	220 (135–297)	240	60	17	3	12
6–5	177 (45–594)	240	60	10	3	15
5–4	137 (32–266)	240	75	5	3	15

PLUM: prehistoric land use model.
[a] From Wang (2011).
[b] From Ning (1997).
[c] From Ning (1997), Wei (1982), Zhao (2002), and Liu (2004).
[d] From Wang (1997).
[e] From Zheng et al. (2008).

The per capita food requirement was estimated from the earliest documented values for the early Han Dynasty (2 ka BP) (Ning, 1997). The values are regarded as a constant in this study since it is logical to assume no significant changes in human physiognomy and physiology (Wu, 1995).

It is difficult to separate quantitatively the impacts of climatic fluctuations and agricultural improvements on crop yield and therefore the yield per unit area for each cultural period was estimated by linear interpolation of data from three sources (Table 2). The initial value at around 8–7 ka BP (45 g/m^2) was averaged from observations of modern slash and burn agriculture (Liu, 2004; Wei, 1982) and reconstructions based on amounts of plant opal found at archaeological sites (Zhao, 2002), which together may be taken to represent the upper and lower limits of agricultural productivity at the time. The final value, at about 3–2 ka BP (105 g/m^2) is based on documentary evidence for the Han Dynasty (Ning, 1997).

Fallow and tillage periods from 8 to 4 ka BP are set according to the estimates of Wang (1997) for the Banpo site (7–5 ka BP), in the Wei River valley, and the Cishan site (8–7 ka BP), also located in the Yellow River basin. Since 7 ka BP, cultivation in the Loess Plateau has changed from long duration forest fallow to bush and short fallow with less than 20 fallow years, as a result of increasing population pressure and the greater time needed for regeneration of the natural vegetation (Wang, 1997).

Finally, the threshold value for definition of the available area for human land use is based on an estimated maximum time (2 h) that humans can reasonably be expected to spend reaching agricultural fields in one day (Zheng et al., 2008).

Internal parameters of PLUM. Five environmental variables pass the Kolmogorov one sample goodness-of-fit test (Habib and Thomas, 1986) in each 1000-year interval (Supplementary Figure S2, available online). The differences between the paired cumulative frequency distributions of these variables for the whole valley and sites can be listed as follows, in decreasing order: relative elevation, distance to the fluvial system, slope, soil type, and aspect; thus, their grid layers obtain corresponding class weights from 6 to 1 here.

The number of archaeological sites decreases with increasing relative elevation, slope, and distance to the fluvial system in each 1000-year interval (Supplementary Figure S3, available online), and the spot weights of specific layers are set according to the percentage of the above sites in different ranges of the corresponding environmental variable, which also varies from 6 to 1.

Results

Spatial and temporal changes of archaeological sites from 8 to 4 ka BP

The values of the total number of archaeological sites found in the Wei River valley for the four 1000-year intervals from 8 to 4 ka BP (from older to younger) were as follows: 24, 628, 2099, 3222 (Figure 2a). With the development of the Yangshao Culture (7–6 ka BP), the greatest relative increase in site number occurred around 7 ka BP, while the most significant absolute increase occurred around 6 ka BP (Figure 2a). The percentages of new recorded sites as a proportion of the total number of sites in the latter three millennia (98%, 94%, and 80%, respectively) were high (Figure 2a), confirming that prehistoric settlements were normally abandoned after a thousand years of development. However, the decreasing trend of the percentages indicates that a settled lifestyle became increasingly significant.

Together with the increase in the total number of archaeological sites in the valley, the total residential area of the sites also increased, with the values for the four 1000-year intervals (from older to younger) as follows: 0.02×10^8, 0.52×10^8, 1.81×10^8, and 2.12×10^8 m^2. However, the average residential area of individual archaeological sites decreased, as follows: 9.24 $(\pm 2.56) \times 10^4$, 8.24 $(\pm 0.68) \times 10^4$, 8.60 $(\pm 0.38) \times 10^4$, and 6.59 $(\pm 0.30) \times 10^4$ m^2 (Figure 2b).

According to the size of residential area, the sites can be further grouped into five size classes, as follows: extremely small (10^0–10^3 m^2), small (10^3–10^4 m^2), middle (10^4–10^5 m^2), large (10^5–10^6 m^2), and super large ($>10^6$ m^2). About 60% of sites are in the middle size, while the percentage of sites in the small size classes increased with time, and the large size classes exhibited the opposite trend (Figure 2b), which reflects the development of the settlement structure.

In a spatial sense, the few sites found from 8 to 7 ka BP were almost exclusively distributed along the main branch of the Wei River in the Guanzhong Basin in the southern part of the valley (Figure 3a). From 7 to 6 ka BP, there was a northward spreading of sites by about 1.5° latitude in the middle and upper reaches of the valley, for example, in the Jing and North Luo sub-branches (Figure 3b). Since 6 ka BP, the sites expanded by some 2° longitude to the west to cover the entire valley (Figure 3c and d).

During the 4000-year study interval, the archaeological sites were mainly located close to the river system, at low relative elevations and with gentle slopes (Supplementary Figure S3, available online). However, there was a clear decline in the percentage of sites (60%, 45%, 30%, and 28% during four millennia) with the following attributes: relative elevation <30 m, slope angle $<2.5°$, and horizontal distance to river <1000 m, indicating progressively greater environmental adaptability of the population.

The distribution of sites further reveals a constant preference for specific aspects and soil types, for example, since 7 ka BP 40% of the sites were located in south-facing locations and about 80% of sites were distributed on loessial soil, old manorial loessial (a type of anthropogenic soil related to the dry farming system in northern China), and dark loessial soils (WRB: cambisols) during the period.

With regard to the spatial distribution of sites with different residential areas (Supplementary Figure S4, available online), the

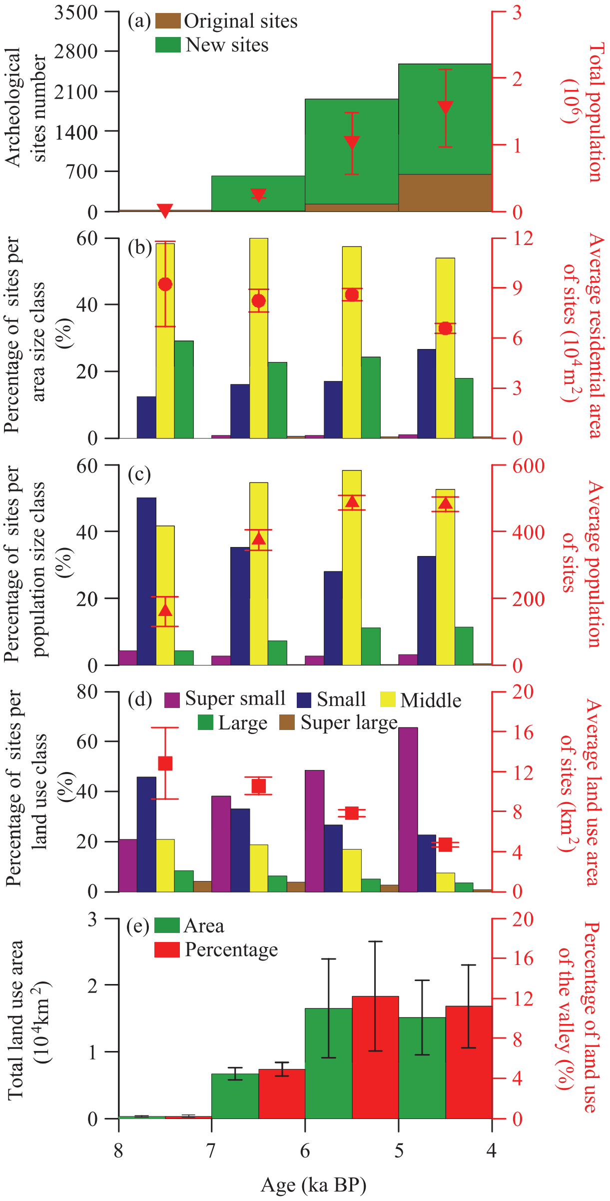

Figure 2. Results of statistical analysis of the changing intensity of human activity in the Wei River valley from 8 to 4 ka BP: (a) total number of archaeological sites and population (the standard error of the population number is indicated); (b) average residential area of the sites and frequency distribution of sites with different residential areas (the standard error of the average residential area is indicated); (c) average population number of the sites and frequency distribution of sites with different population numbers (the standard error of the average population number is indicated); (d) average land use area of the sites and frequency distribution of sites with different land use areas (the standard error of the average land use area is indicated); and (e) amount and percentage of land use areas in the Wei River valley (standard errors are indicated).

larger sites were usually surrounded by smaller ones, and the degree of differentiation of sites increased continuously with time because of the increasing complexity of the social structure. Sites with larger residential areas occurred more frequently through time in the northern and western parts of the valley with the spread of sites from 8 to 4 ka BP.

Spatial and temporal changes of population from 8 to 4 ka BP

From 8 to 4 ka BP, the total population of the Wei River valley increased continuously with values for the four 1000-year intervals as follows (from older to younger): 0.004 (±0.002) × 10^6, 0.24 (±0.03) × 10^6, 1.02 (±0.46) × 10^6, and 1.55 (±0.58) × 10^6 (Figure 2a). The largest increase occurred around 6 ka BP and was in accordance with the absolute change in the total number of sites. The corresponding average population numbers for an individual site were as follows (from older to younger): 160 (±44), 375 (±31), 486 (±22), and 481 (±22) (Figure 2c). The most significant increases occurred from 8 to 6 ka BP and thereafter the values remained constant, reflecting a tendency for the scale of the settlements to become more and more stable with time.

The sites can be grouped into five classes according to the population number at each archaeological site (Figure 2c). Statistical analysis reveals that more than 40% of sites were in the middle class with a population between 100 and 1000. The percentage of sites with population <100 decreased over time, while that of sites with population >1000 increased slightly (Figure 2c), which is contrary to the trend exhibited by sites in the small and large residential area classes mentioned in section "Spatial and temporal changes of archaeological sites from 8 to 4 ka BP" (Figure 2b). This is because the population of each site was calculated by dividing the residential area by the average residential land use area per person in PLUM (Yu et al., 2012), and the decrease of the numerator (Table 2) was more significant than that of the denominator with time because of increasing land use efficiency.

The spatial changes of the sites with different population size classes (Supplementary Figure S5, available online) were similar to that of the sites with different residential area size classes described above (Supplementary Figure S4, available online).

Spatial and temporal changes of land use from 8 to 4 ka BP

During the four 1000-year intervals from 8 to 4 ka BP, the total areas of cultivation and living land use in the Wei River valley were (from older to younger) 0.03 (±0.02) × 10^4 km^2, 0.66 (±0.09) × 10^4 km^2, 1.65 (±0.74) × 10^4 km^2, to 1.51 (±0.56) × 10^4 km^2 (Figure 2e). These data show that the most significant increase in land use area occurred at around 6 ka BP. The additional land use areas for the next three millennia were 0.65 (±0.10) × 10^4 km^2, 1.57 (±0.74) × 10^4 km^2, and 0.92 (±0.36) × 10^4 km^2, respectively, in accordance with the appearance of new archaeological sites (Figure 2a).

Compared with 46% of the area in the valley that has been cultivated and settled in modern times, 0.2 (±0.1)%, 5 (±1)%, 12 (±5)%, and 11 (±4)% of the area was used between 8 and 4 ka BP (Figure 2e), which showed a relatively low intensity of human activity before 6 ka BP. However, about 26% of modern land clearance levels occurred 5000–6000 years ago indicating that humans significantly changed the prehistoric land cover in the valley.

The average land use area of each site decreased from 12.84 (±3.56) to 4.68 (±0.21) km^2 from 8 to 4 ka BP (Figure 2d). The reclassification of sites into five groups according to land use area further reveals that the percentage of sites with smaller land use areas (<3 km^2) increased significantly during the study interval, while the percentage of sites with area of >3 km^2 decreased (Figure 2d). The trends of land use area for individual sites in the small and large classes were similar to that of residential area (Figure 2b), but converged to that of population for individual sites in two classes (Figure 2c), which indicates that increased land use efficiency and population growth occurred simultaneously.

Spatially, prehistoric land use areas were mainly distributed in the areas close to those archaeological sites that were characterized by favorable environmental conditions (Figure 4a–d). As is the case with the archaeological sites, the percentage of land use areas with these favorable characteristics decreased from 8 to 4 ka BP. The largest changes occurred in areas with relative elevation of <30 m, with values for the four 1000-year intervals (from older

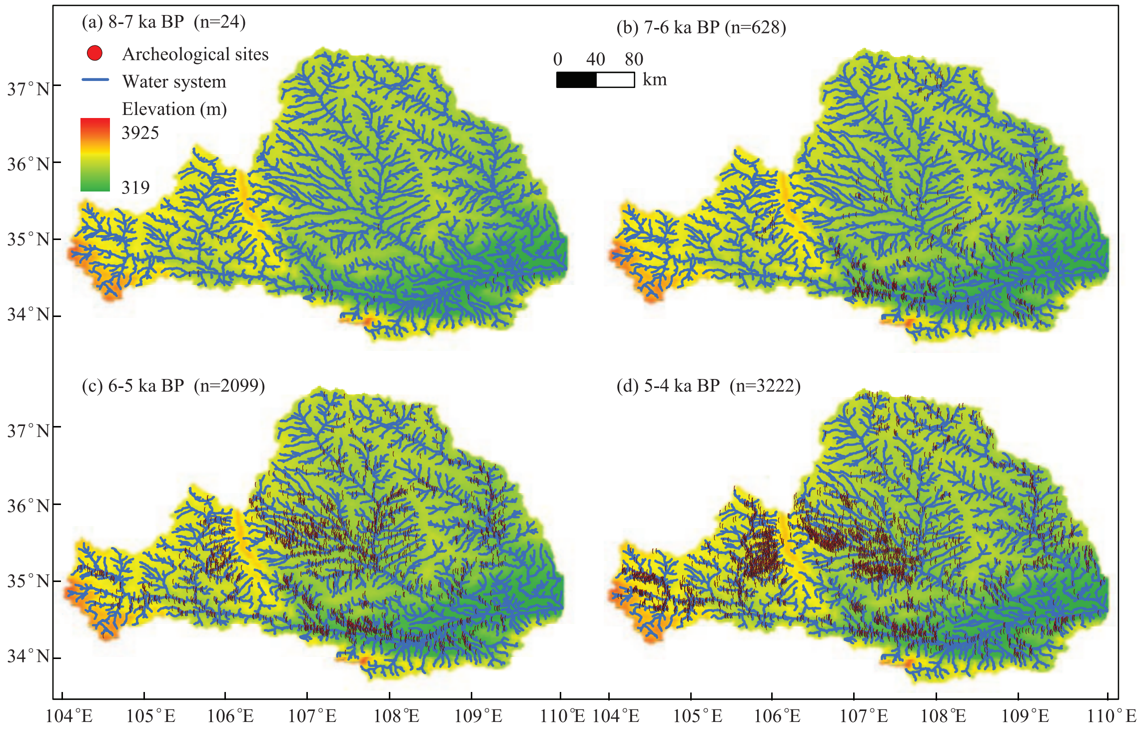

Figure 3. Spatial distribution of archaeological sites in the Wei River valley from 8 to 4 ka BP: (a) 8–7 ka BP, (b) 7–6 ka BP, (c) 6–5 ka BP, and (d) 5–4 ka BP.

to younger) of 90%, 61%, 51%, to 49%; and of areas with slope of <2.5°, with values of 76%, 54%, 35%, and 31%. Because cultivation was mainly dependent on the availability of water resources and sunshine, but conversely affected soil development continuously, the percentage of land use areas with horizontal distance to the fluvial network of <1000 m was always above 73%; and that of areas with south-facing aspect was always higher than others by about 10%. In addition, the soils of about 80% of the land use areas developed into cultivated types (e.g. old manorial loessial soil and dark loessial soil (WRB: cambisols)) based on the occurrence of soils with horizon characteristics indicative of ancient cultivation.

With regard to the geographic spread of land use during the 4000-year interval, three stages can be distinguished in accordance with the distribution of archaeological sites. First, the land use area expanded from the main branch of the Wei River to the middle and upper reaches of the valley after 7 ka BP; second, it spread to the west and to the north to cover the whole valley after 6 ka BP; and finally, after 5 ka BP the spatial distribution pattern of land use changed to a form similar to that of the present day (Figure 4c–e). These changes clearly demonstrate that human activity has significantly altered the land cover over the Wei River valley.

Discussion

Comparison with previous studies of the Wei River valley

Comparison with quantitative land use reconstructions. Quantitative land use reconstructions for the Wei River valley have also been presented in three studies of continental to global scale (Kaplan et al., 2011; Klein Goldewijk et al., 2011; Lemmen, 2009); however, the human land use types reconstructed among them are not exactly same.

The areas of both cropland and pasture are estimated by the HYDE database and the KK10 scenario. But the former study only includes active cropland with a short fallow period (Klein Goldewijk et al., 2011), while all of the deforested areas used for cultivation, including abandoned areas, are estimated in the latter study (Kaplan et al., 2011). In the GLUES and PLUM models, only cropland is reconstructed (Lemmen, 2009). Except for the GLUES simulation, the other reconstructions use grid cells with different resolutions (5′, about 85 km^2 at the equator, for the HYDE database and KK10 scenario; and 0.0081 km^2 for PLUM). In order to make the results comparable, the amounts of land use in grid cells in all reconstructions have been converted to percentage of land use.

The continuous increase of land use cover in the Wei River valley from 8 to 4 ka BP is revealed by all of the reconstructions (Figure 5a). However, the highest values in the KK10 scenario (9.01–34.09%) (Kaplan et al., 2011) are more than 25 times larger than the lowest estimates from the HYDE database (0.04–1.33%) (Klein Goldewijk et al., 2011), while the intermediate values are produced by PLUM (0.2–12%) and GLUES (about 11% around 4 ka BP) models (Lemmen, 2009).

The spatial distribution of land use during 5–4 ka BP is used as an example for comparison, because it exhibits the widest spread of values within the study interval. The HYDE database indicates that the grid cells with high land use percentages only occur in Guanzhong Basin in the lower reaches of the Wei River valley (Klein Goldewijk et al., 2011) (Figure 5b), while in both the KK10 scenario (Kaplan et al., 2011) (Figure 5c) and PLUM output (Figure 4d) the wider distribution of land use also occurs in the middle and upper reaches of the valley. However, spatial differences in land use across the Wei River valley estimated by GLUES are not apparent because the entire valley consists of only two administrative districts (Figure 5a in Lemmen, 2009).

Above all, the land use estimates by PLUM here are more comparable with the KK10 scenario (about 3 times higher) than with the HYDE database (about 10 times lower), because pasture areas are not calculated in PLUM, larger fallow areas are assumed in the KK10 scenario than in PLUM since 7 ka BP, and the archaeological sites used in PLUM represent only the lower limit of prehistoric human land use.

Other contrasts among four studies are because of the different assumptions made during the three steps involved in reconstructions. With regard to the first step of population estimation, the

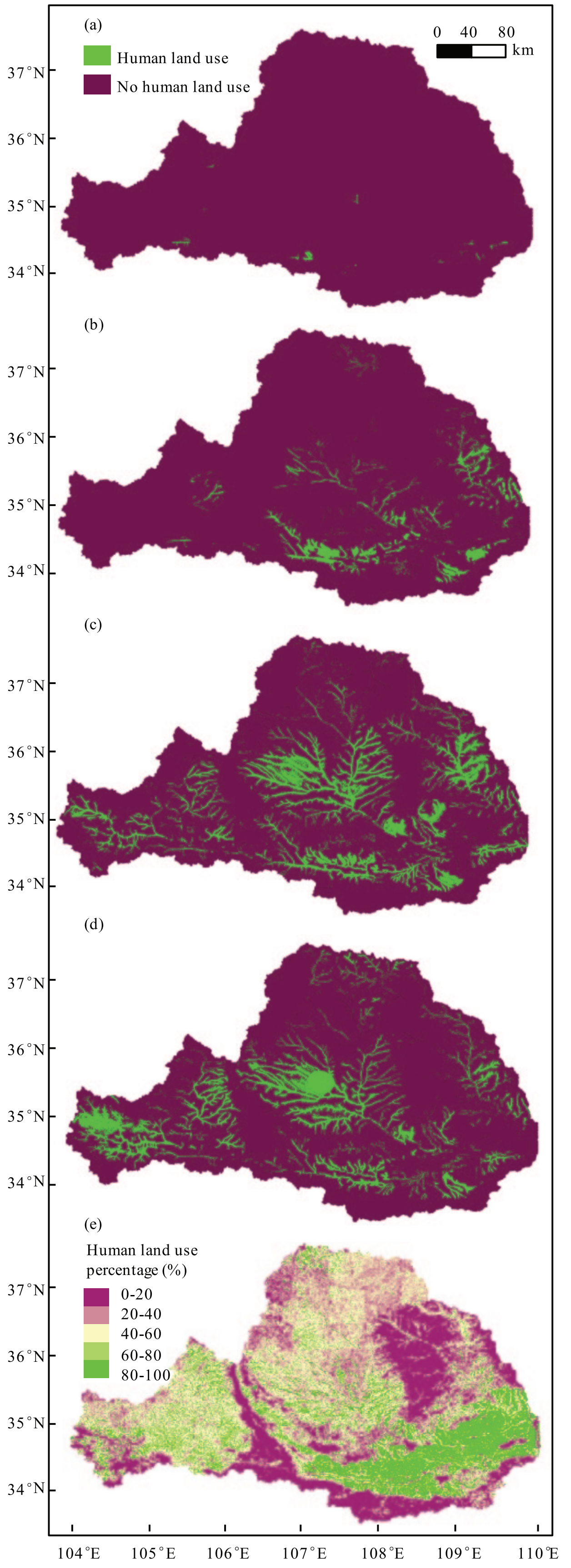

Figure 4. Spatial distribution of land use in the Wei River valley from 8 to 4 ka BP: (a) 8–7 ka BP, (b) 7–6 ka BP, (c) 6–5 ka BP, (d) 5–4 ka BP, and (e) Modern (1980).

slowest increase in population density from 8 to 4 ka BP in the Wei River valley (0.79–3.24 person/km^2) is estimated by the HYDE database, which is based on the extrapolation of historical data from Denevan (1992), Lahmeyer (2004), Livi-Bacci (2007), Maddison (2001), and McEvedy and Jones (1978) (Klein Goldewijk et al., 2011). The KK10 scenario (Kaplan et al., 2011) adopts a higher value of population density (about 6 person/km^2 at 4 ka BP) output by GLUES model, which is simulated based on a theoretical balance between population growth and regional cultural traits (Lemmen, 2009; Wirtz and Lemmen, 2003). The significant rise in population density (0.03, 1.75, 7.57, and 11.49 person/km^2) is estimated by the PLUM model, based on the measured relationship between residential area and population for typical prehistoric sites within or around the Wei River valley. The population growth curves produced by GLUES and PLUM are intermediate between those of the geometric and linear population models (Boyle et al., 2011), and this higher population estimates are also supported by the results of other demographic models (Groube, 1996).

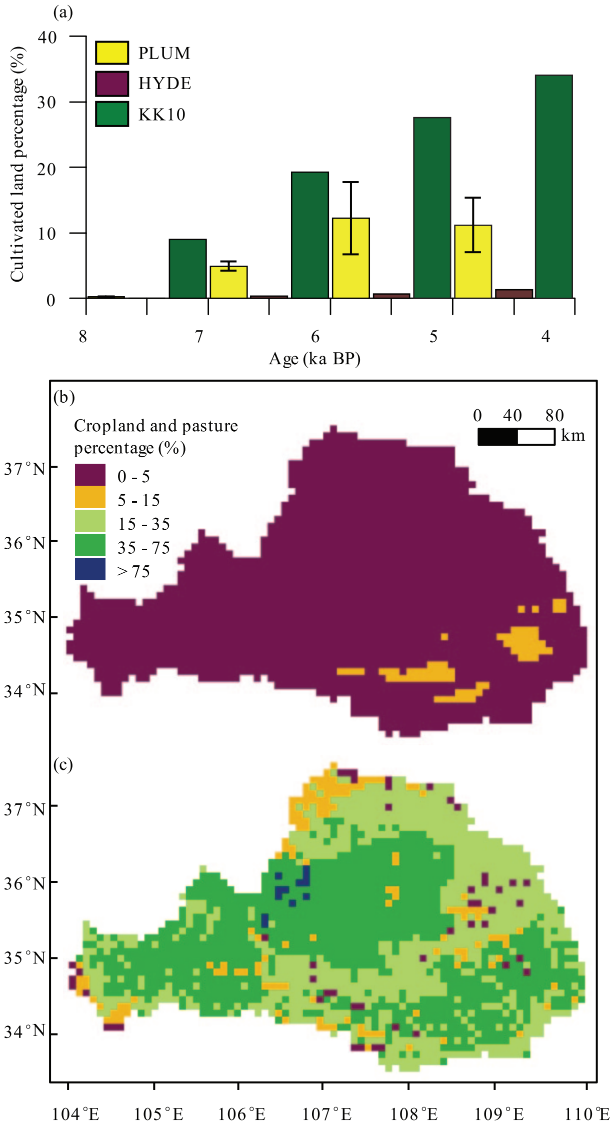

Figure 5. Comparison of land use change in the Wei River valley reconstructed using the HYDE database, KK10 scenario, and PLUM: (a) amount of land use from 8 to 4 ka BP estimated in three different studies (Kaplan et al., 2011; Klein Goldewijk et al., 2011); (b) distribution of land use in the HYDE database during 5–4 ka BP (Klein Goldewijk et al., 2011); and (c) distribution of land use in the KK10 scenario during 5–4 ka BP (Kaplan et al., 2011).

For the second step of land use per capita estimation, low and roughly constant values from 8 to 4 ka BP (0.145–0.146 ha/capita) are used for the Wei River valley in the HYDE database and the GLUES model (Klein Goldewijk et al., 2011; Lemmen, 2009) on the assumption of approximately linear relationship between population and land use area over time. In contrast, high land use per capita values are obtained in the KK10 scenario (about 8 ha/capita in southeast China) and PLUM model (8.0, 2.8, 1.6, and 1.3 ha/capita in the Wei River valley), which assume that humans used land more intensively with increasing population density, scarcity of productive arable land, and technological improvements (Kaplan et al., 2009, 2011). Currently, the changing land use per capita values are widely supported by published evidence and by accepted land use theory (Boserup, 1981; Johnston, 2003; Kaplan et al., 2009; Ruddiman and Ellis, 2009).

In the third step of spatial allocation of land use, the four reconstructions all allocate land use to grid cells or districts according to the spatial suitability maps for human activity, which are weighted by distributions of population density and environmental conditions (Kaplan et al., 2011; Klein Goldewijk et al., 2011; Lemmen, 2009). In the HYDE database, GLUES model, and KK10 scenario, the spatial patterns of prehistoric population density are obtained by scaling the values for current time periods; however, in the PLUM model population density maps are based on distributions of archaeological sites during the contemporaneous prehistoric periods (Yu et al., 2012), and this approach may overcome the problem of the uncertainties caused by the impact of climatic fluctuations on population migration over time.

More reliable land use reconstruction in the Wei River valley are likely to be obtained by PLUM, since it uses the archaeological data from the same region and time periods, while other approaches all use extrapolations of data from other regions or historical periods. The model has significant advantages for regional studies and it could potentially be applied to larger scales based on a larger compilation of archaeological site data, which is meaningful for global land use reconstruction research.

Comparison with the qualitative studies of human activity. The development of land use produced by PLUM for the Wei River valley is also in accordance with temporal and spatial changes in other lines of evidence (pollen, phytolith, carbonized crop seeds, charcoal, and soil property) recorded in the sediments in the valley.

During 8–7 ka BP, the indicators of human activity (large peaks in Poaceae pollen or charcoal concentration, pedological characteristics such as surface crusts and the subsequent breakdown of these soil aggregates, carbonized millet seeds) were only present at several sites in the southern alluvial plain of Wei River valley (He, 1987; Huang et al., 2002, 2006; Institute of Archaeology, Chinese Academy of Social Sciences, 1983; Li et al., 2009; Tan et al., 2011; Wang and Xu, 2003; Zhuang and French, 2012).

Since 7 ka BP, the sites with indicators of human activity not only became more abundant in the southern parts of the valley (Huang et al., 2006; Li et al., 2007, 2009; Liu et al., 2004; Shang et al., 2012; Zhang et al., 2010), but also were discovered in the northwestern part (e.g. Qingyang and Xujianian sites) (Huang et al., 2006; Liu et al., 2004; Zhang and Wang, 2000; Zhou et al., 2011).

Prehistoric land use change in the Yellow River basin and its possible drivers

PLUM has also been applied to reconstruct prehistoric land use change in two other areas of the middle Yellow River basin; Yiluo valley and Yunlin district locate in the southeast and north of the Wei River valley, respectively (Figure 1a) (Lin et al., in preparation; Yu et al., 2012).

In Figure 6a, similar trends of increasing land use from 8 to 4 ka BP occurred within the three areas; however, the total amount and rate of increase in the Yunlin district (2.60% and 0.43%/ka) were much lower than those in the Yiluo valley (8.40% and 2.13%/ka) and Wei River valley (9.91% and 3.24%/ka) during 8–5 ka BP. However, the accelerating increase in the Yulin district since 5 ka BP made the land use percentages in the three areas reach similar levels (Yunlin district: 7.60%, Yiluo valley: 9.48%, and Wei River valley: 11.19%). These asynchronous increases in the three areas indicates an expansion of land use from the southeastern middle Yellow River basin to the entire region between 8 and 4 ka BP, which is also revealed in previous qualitative and semi-quantitative studies (Dong et al., 2007; Huang et al., 2007; Li et al., 2011, 2013; Ren, 2000; Ren and Beug, 2002; Rosen, 2008; Wang et al., 2004, 2011, 2013; Xu et al., 2002; Zhuang and Kidder, 2014; Zhuang et al., 2013).

The land use expansion recorded here could be well explained by the two phases of population increase in northern China during the Holocene (Li et al., 2015; Wagner et al., 2013; Wang et al., 2014a) (Figure 6b). The times of the first (7.8–5.9 cal ka BP) and the second phase (5.9–2.7 cal ka BP) closely correspond to the introduction of agricultural land use during 8–7 ka BP and its significant spread during 6–5 ka BP.

Population fluctuations in the Holocene are further affected by climatic evolution and agricultural development. A consistently warm and humid climate from 8 to 5 ka BP has been recorded by multi-proxy data from northern China (Li et al., 2014; Lv et al., 2007; Peterse et al., 2011; Shi and Song, 2003; Wang et al., 2014b; Xu et al., 2003; Zhao et al., 2009; Zheng et al., 1998) (Figure 6c), and this may have promoted the increase in population; while the cooler and drier climate after 5 ka BP (Figure 6c) did not appear to affect the trend of increasing population, which may indicate that agricultural development influenced the population dynamics at that time.

Agricultural production as well as its structure and technology in northern China continuously developed during 9–4 ka BP (Shen, 2000). The most significant increases in both production and technology occurred between 6 and 4 ka BP, for which there is evidence from sites with crop remains, the density of crop seeds, the caves for crop storage, and the agricultural tools per site (An, 1988; Fuller et al., 2009; Gong et al., 2007; Jin, 2007; Lee et al., 2007; Pang and Gao, 2006; Ruddiman et al., 2008; Su, 2008; Yu, 2010) (Figure 6d and e). The agricultural structure also became more diversified between 6 and 4 ka BP by the development of millet cultivation in northern China (Li et al., 2015; Lv et al., 2009; Zhao, 2014), the spread of rice cultivation from southern China (Zhang et al., 2010, 2012), and the introduction of wheat from western Asia (Li et al., 2007). These processes could well explain the second phase of population increase.

The global significance of prehistoric land use change in northern China

Current quantitative land use estimates for different global centers of early agriculture are compared in Figure 6f. Based on population hindcasting techniques, the highest (25.59–34.09%) and lowest (0.41–3.40%) percentages of land use in the Levant area of western Asia, northern China, and southern Mexico between 8 and 4 ka BP are provided by the KK10 scenario and HYDE database. This is likely to be the result of different assumptions used as described in section “Comparison with quantitative land use reconstructions.” Although the two reconstructions are significantly different, the estimated land use in the centers of early agriculture are comparable in each reconstruction itself and are much higher than in other regions of the world. Similar intermediate levels of human activity from 7 to 4 ka BP (4.5–15%) in western Asia and northern China have been reconstructed by the GLUES and PLUM models (Lemmen, 2009; Yu et al., 2012), and are more comparable with the KK10 scenario considering the different estimated land use types among them.

Based on pollen data, the application of the REVEALS model indicates that a significant increase (>20%) occurred in the

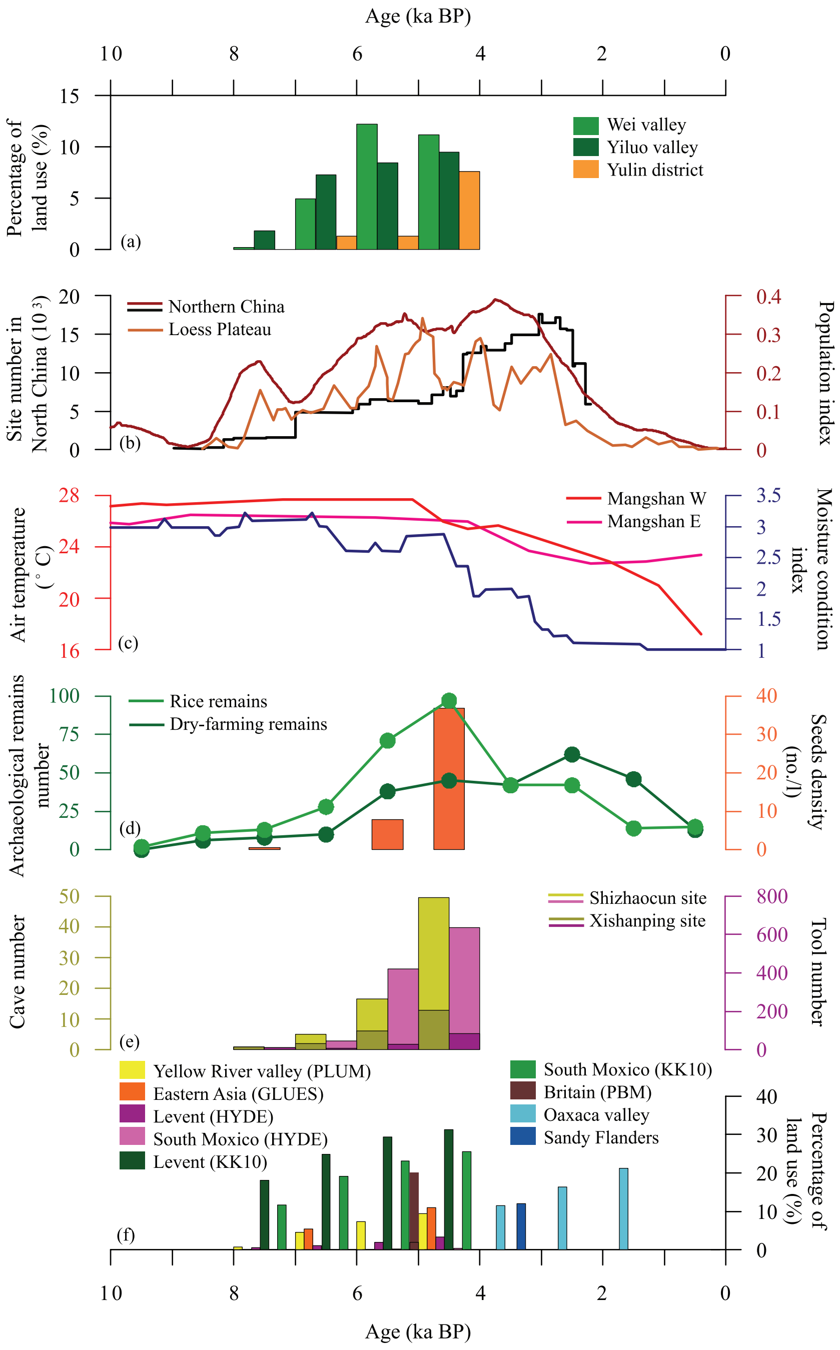

Figure 6. Comparison of records of early human activity, climatic conditions, and agricultural development in northern China with records from other regions: (a) amount of land use in the Yiluo valley (Yu et al., 2012), Wei River valley (this study), and the Yulin district (Lin et al., in preparation) from 8 to 4 ka BP; (b) change in population numbers in the Chinese Loess Plateau (Li et al., 2015) and northern China (Wagner et al., 2013; Wang et al., 2014a) during the Holocene; (c) temperature (Peterse et al., 2011) and moisture conditions (Zhao et al., 2009) in northern China during the Holocene; (d) change in numbers of archaeological records of agricultural seeds across China during the Holocene (Ruddiman et al., 2008; Yu, 2010) and the crop seed intensity at a typical site in northern China from 8 to 4 ka BP (Lee et al., 2007); (e) change of the numbers of crop caves and tool numbers found at typical sites in northern China from 8 to 4 ka BP (Su, 2008); and (f) Holocene land use reconstructions in centers of early agriculture (Kaplan et al., 2011; Kirkby, 1973; Klein Goldewijk et al., 2011; Lemmen, 2009; Lin et al., in preparation; Woodbridge et al., 2014b; Yu et al., 2012; Zwertvaegher, 2012).

amount of open land and grassland between 6 and 3 ka BP in temperate and northern Europe (Trondman et al., 2015), while the use of PBM approach reveals that human activity progressively affected the forest composition after 6 ka BP on a pan-European scale, with about a 20% decline in the area of woodland occurring in Britain from 6 to 5.4 ka BP (Fyfe et al., 2010, 2015; Woodbridge et al., 2014a, 2014b). These results are also closer to the reconstructions of the KK10 scenarios; however, the overestimation may be made because of the difficulty of assigning pollen taxa indicative of both natural and anthropogenic biotopes to an individual open land cover class.

The studies for the period after 4 ka BP can be used to infer land use trends in earlier periods. According to the relationships between crop production, properties, population, and livestock composition, the percentages of past cultivated areas have been estimated in the Oaxaca valley of southern Mexico (Kirkby, 1973) and Sandy Flanders of northwest Belgium (Zwertvaegher, 2012). The results show that about 12% of the area was used in both regions 3000 years ago, and the value can be regarded as a threshold of land use for the prehistoric period in these regions.

In sum, the impact of human activity on land cover just occurred in the centers of early agriculture at local scale before 6 ka BP, while the spatial scale of intensified land use and its effects on vegetation cover increased after 6 ka BP, as also indicated by fossil pollen data.

Conclusion

We have used an improved quantitative land use reconstruction model (PLUM) to reveal changes in the intensity of prehistoric human activity in the Wei River valley during the period 8 to 4 ka BP. During this interval, the number of archaeological sites increased from 24 to 3222, while the estimated population and area of human land use increased from 0.004 (±0.002) $\times 10^6$ to 1.55 (±0.58) $\times 10^6$ and from 0.03 (±0.02) $\times 10^4$ to 1.51 (±0.56) $\times 10^4$ km^2, respectively. In terms of spatial patterns, prehistoric land use spread from the southeastern part of the valley, which had the most favorable environmental conditions, to the entire valley during this 4000-year interval.

Based on quantitative comparisons of land use changes within the Yiluo valley, the Wei River valley, and the Yulin district, the expansion of human activity from the southeastern parts of the middle Yellow River basin to the entire region during the Holocene has been revealed. This expansion can be attributed to the occurrence of suitable climatic conditions and the process of continuous agricultural development.

In general, a higher land use intensity (KK10 scenarios) during the prehistoric period is supported by regional reconstructions by PLUM, based on archaeological data, and by REVEALS and PBM models, based on pollen data. As a consequence, the anthropogenic land cover change likely made an important contribution to increasing atmospheric CO_2 concentration after 6 ka BP (Kaplan et al., 2011; Ruddiman, 2013).

The archaeological data used in PLUM give prehistoric human activity information for corresponding time periods; thus, the model significantly improves the accuracy of land use reconstructions. With the extrapolation of model to larger scales, more realistic spatiotemporal patterns of land use can potentially be obtained. Overall, these efforts may improve our evaluation of the role of human activity in local, regional, and global environmental change during the Holocene.

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