Agriculture, Ecosystems and Environment 156 (2012) 99–107

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Reconstructing prehistoric land use change from archeological data: Validation and application of a new model in Yiluo valley, northern China

Yanyan Yu[a,*], Zhengtang Guo[a], Haibin Wu[a], Peter A. Finke[b]

[a] Institute of Geology and Geophysics, Chinese Academy of Science, 100029 Beijing, China
[b] Department of Geology and Soil Science, University of Ghent, Krijgslaan 281, 9000 Ghent, Belgium

ARTICLE INFO

Article history:
Received 14 February 2012
Received in revised form 11 May 2012
Accepted 14 May 2012

Keywords:
Human activity
Prehistoric
Land use
Holocene

ABSTRACT

Estimation of land use during the Holocene is crucial to understand impacts of human activity on climate change in preindustrial period. Until now it is still a key issue to reconstruct amount and spatial distribution of prehistoric land use due to lack of data. Most reconstructions are simply extrapolations of population, cleared land amount per person and land suitability for agriculture. In this study, a new quantitative prehistoric land use model (PLUM) is developed based on semi-quantitative predictive models of archeological sites. The PLUM is driven by environmental and social parameters of archeological sites, which are objective evidences of prehistoric human activity, and produces realistic patterns of land use. After successful validation of the model with modern observed data, the PLUM was applied to reconstruct land use from 8 to 4 ka B.P. in Yiluo valley, one of the most important agriculture origin centers in northern China. Results reveal that about 2–9% of land area in the valley was used by human activity from 8 to 4 ka B.P., expanding from gentle slopes along the river to hinterlands in middle and lower parts of the valley. The land cover was affected by increasing agricultural land use during the middle Holocene.

1. Introduction

Land use induces land surface property changes, which significantly feed back on climate by modulating exchanges of energy, water vapor and greenhouse gases with the atmosphere. Current research shows that land use has been the second most important source of carbon emission by human activity at timescales of hundreds of years (Houghton, 1999). The assessment of the role of human activity in the abnormal CO_2 rise since 7 ka B.P. is an important issue in the scientific community (Joos et al., 2004; Lüthi et al., 2008).

The hypothesis on the role of early human activity on abnormal CO_2 change during the Holocene is advanced by Ruddiman (2003), based on comparing the CO_2 trends between Holocene and previous early interglacial intervals (Ruddiman, 2003, 2007; Ruddiman and Thomson, 2001). Since these earlier downward trends were unquestionably of natural origin, the upward trend after 7 ka B.P. is anomalous and might be induced by prehistoric human agriculture activity. However, the hypothesis is challenged by other potential carbon sources found in terrestrial ecosystem or the ocean (e.g. Archer et al., 2000; Broecker et al., 2001; Indermühle et al., 1999; Joos et al., 2004; Matsumoto et al., 2002; Ridgwell et al., 2003), thus quantitative reconstruction of Holocene land use by human activity and how it induced carbon changes becomes the key to settle the issue.

Due to lack the incomplete nature of observational data, it is hard to reconstruct land use at timescales comprising thousands of years, and modeling becomes a potential solution. Such attempts have been made in Europe and worldwide on land use change since 6 ka B.P. (Kaplan et al., 2009, 2011; Lemmen, 2009; Olofsson and Hickler, 2007; Pongratz et al., 2009), based on extrapolations of population, per capita crop intensity, cleared land per person and suitability of land for agriculture or pasture in the region.

However, uncertainty still exists in the above reconstructions. Firstly, population, land use per capita data and the relationship between population and land use are always based on evidence in specific regions (Kaplan et al., 2011). When these results are extrapolated to continental and global scale, the different human activities among regions would affect the accuracy of land use area estimates. Secondly, spatial distributions of past land use have low resolution due to lack of spatial data in detail.

Archeological sites, as direct evidence of human activities during the prehistoric period, are records of occupancy patterns and associated intensity at regional scale. Additionally, semi-quantitative archeological site prediction models (Kvamme, 1990; White, 2002) provide an option to reveal at full spatial extent the selectivity of

---

* Corresponding author at: Institute of Geology and Geophysics, Chinese Academy of Sciences, 19th Bei Tu Cheng Xi Road, Chaoyang District, P.O. Box 9825, Beijing 100029, China. Tel.: +86 10 82998382; fax: +86 10 88871410.
E-mail address: yyy@mail.iggcas.ac.cn (Y. Y. Yu).

0167-8809/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agee.2012.05.013

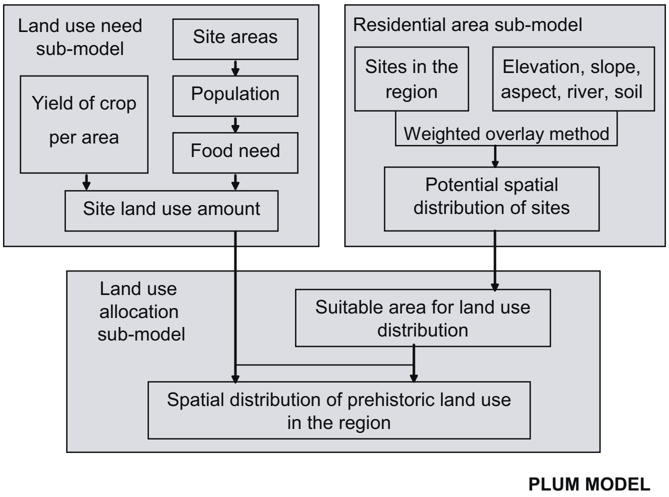

Fig. 1. Structure of the PLUM model.

humans for suitable sites. Such models predict potential archeological sites distribution based on an extrapolation of the relationships between found sites and environmental conditions. Therefore, we propose that these data and methods become the basis of the potential solution to overcome shortcomings in current land use reconstructions at timescale of thousands of years. To this aim a new quantitative prehistoric land use distribution model based on archeological sites is developed.

As one of the agriculture origin centers in northern China, Yiluo valley, ~21,000 km^2 in area, is located in the southern part of the middle Yellow River area. It is a vast fertile alluvial basin bounded by mountains and hills in three directions, and is composed of mountains (52.4%), hills (39.7%) and plains (7.9%). At present, ~44% of the valley areas have been cultivated. Modern mean annual temperature and precipitation of the valley are 12–14 °C and 600–900 mm, Cinnamon soils (WRB: Kastanozems) and deciduous broad-leaved forest are the dominant soil and vegetation type, respectively (Ding and Liang, 2007).

Yiluo valley has experienced intensive and continuous human occupation throughout the Holocene, evidenced by the large number of archaeological remains discovered (Chen et al., 2003), and also has been the key region for detailed archeological studies on prehistoric periods. Therefore, this valley offers a good opportunity for development and application of the prehistoric land use model.

In summary, the major objectives of this paper are: (1) to develop a new prehistoric land use model (PLUM) based on archeological sites prediction models; (2) to apply the PLUM in Yiluo valley to reconstruct spatial and temporal land use change from 8 to 4 ka B.P.

2. Model structure

Fig. 1 shows the structure of PLUM, which is composed by three modules: land use need, residential area distribution and land use allocation sub-model.

The land use need sub-model provides an estimate of the total area needed by human activity in the region. The residential area distribution sub-model, which directly adopts the form of archeological sites prediction models (Espa et al., 2006; Kvamme, 1990; White, 2002), predicts the potential spatial distribution of human activity. The land use allocation sub-model distributes the total land use area, estimated by the land use need sub-model, over the suitable locations around the archeological sites according to the distribution of potential human activity predicted by residential area distribution sub-model. The workflows of above sub-models are described in detail in the following sections.

2.1. Land use need sub-model

Since prehistoric human activity in each archeological site was often isolated from others, communication among sites was rare (Kirkby, 1973). Consequently the food need and supply in each site can be assumed to have been, on balance, local. Agriculture, as the main driver of resident life style in human society (Shang, 1992), gradually became the dominant source of food supply in inland regions at the beginning of the Holocene. Thus prehistoric human land use area (A_l) is mainly composed by residential (A_r) and cultivated (A_c) area in archeological sites and could be calculated by the following equation:

$$A_l = A_r + A_c \tag{1}$$

A_r is usually deduced by archaeologists according to excavation area of the site documented in literature, while A_c could be estimated with the following equation:

$$A_c = R \times A_n \tag{2}$$

A_n is the theoretically area needed to sustain the total population of the region, while R is the ratio of actual cultivated area to A_n, which is induced by the slashing and burning agriculture system in prehistoric period. Since the cultivated area was normally abandoned after some years of cultivation due to their declining productivity (Wang, 1997), the actual cultivated area would be much larger than the needed area, and R could be estimated as follows:

$$R = \frac{T_f + T_c}{T_c} \tag{3}$$

T_f and T_c are estimates for the fallow and tillage period in one cultivation cycle, respectively. The equation is based on studies on slashing and burning agriculture (Freachan, 1973; Wang, 1997), that infer T_f according to the maximum local land carrying capacity of population.

Furthermore, A_n mentioned above is estimated by food need (F) and yield of crop per area (Y) based on the assumption of local food need and supply balance:

$$A_n = \frac{F}{Y} \tag{4}$$

In Eq. (4), F is calculated using the population number (P) and food need per person (F_p), while P is equal to the ratio of total residential area (A_r) to area needed by per person (A_p) in sites:

$$F = P \times F_p \tag{5}$$

$$P = \frac{A_r}{A_p} \tag{6}$$

The parameters T_f, T_c, Y, F_p, A_r and A_p in various prehistoric periods have been intensively studied in regions with a long agriculture history in China and can be reconstructed from the archeological literature.

Combining Eqs. (1)–(6) allows the equation for the land use area in each archeological site to be derived:

$$A_l = A_r + \left\{ \frac{(A_r/A_p) \times F_p}{Y} \right\} \times \left[\frac{T_f + T_c}{T_c} \right] \tag{7}$$

2.2. Residential area distribution sub-model

In order to obtain a spatially creditable distribution of human activity, the principle and method of archeological sites prediction models (Espa et al., 2006; Kvamme, 1990; White, 2002) are directly adopted here. The principle of each such model is that human activity was controlled by surrounding environmental conditions in prehistoric periods (White, 2002).

In the residential area distribution sub-model, the weighted overlay method (Bona, 1994; Espa et al., 2006) was adopted to predict at grid nodes the regional distribution of potential human activity. Here, two types of weights were calculated and combined in raster layers of environmental data:

i. Class weight, which gives the rank of restriction to human activity of different environmental variables; and
ii. Spot weight, which shows the degree of dependency of human activity to various ranges of one specific environmental variable.

Both weights are set by statistical analysis revealing the relationship between locations of found sites and local values of environment variables:

(1) Selection of the indicative environmental variables

To distinguish the environmental variables that have significant influence on human activity from others, the Kolmogorov one sample goodness-of-fit test (Habib and Thomas, 1986) is used. The cumulative frequency distribution of the grid values of each environmental variable of the region serves as a background referent, while the cumulative frequency distribution of corresponding variable values in found archeological sites is compared against the above referent. In order to ascertain whether the above two distributions differ significantly, they are plotted as curves in one graph. The null hypothesis of no difference between the distributions may be rejected if the maximum distance (D_{max}) between two curves exceeds a critical value (D_c), which indicates that archeological sites are non-randomly distributed in the study region and have selectivity for environmental conditions. D_c is usually estimated according to large-sample theory (Habib and Thomas, 1986):

$$D_c = 1.36\sqrt{n} \quad (\alpha = 0.05,\ \text{two-tailed test}) \tag{8}$$

n is the number of archeological sites in the study region.

In the following steps, each selected raster layer of environmental variables would receive a class and a spot weight, respectively.

(2) Setting of class and spot weights for selected layers of variables

The difference between the D_{max} and D_c, mentioned above, shows the rank of significance of different environmental variables to human activity, thus it could be taken as the standard for class weights setting. The highest class weight value is given to the environmental variable layer with the highest value of $|D_{max}| - D_c$, where this weight is set to 0 if $|D_{max}| < D_c$ (e.g. non-significant difference).

The frequency distribution of found archeological sites is also analyzed for different sub-ranges of each specific environmental variable, which results in a sub-range weight D_s. The grids of the corresponding regional environmental variable layer are reclassified using the same sub-ranges and assigned spot weights (see the figure in Section 3.3).

(3) Calculation of total weights

In order to show the total impact of environmental conditions on human activity in each grid of the study region, the total weight value for any given grid cell in a specific environmental variable layer is obtained by multiplying its class weight by its spot weight. The process is then repeated for each layer. Finally, all total weighted layers are added up into one layer with standardized rank of 0–100%, which shows the potential distribution of human activity from low to high level.

Table 1
Information of input and output data in the PLUM.

Data	Name	Type	Sub-model
Inputs	Residential area	A[a]	Land use need
	Average human land use area	A	Land use need
	Food need per person	A	Land use need
	Yield of crop per area	A	Land use need
	Tillage period	A	Land use need
	Fallow period	A	Land use need
	Elevation	S[b]	Residential area
	Water system	S	Residential area
	Soil	S	Residential area
	Land use	S	Residential area
	Archeological sites	A/S	Residential area
	Human activity radius	A/S	Spatial distribution of land use
Outputs	Population	A	Land use need
	Total food need and yield of crop	A	Land use need
	Amount of land use	A	Land use need
	Potential distribution of sites	S	Residential area
	Spatial distribution of land use	S	Spatial distribution of land use

[a] Type A is attribute data.
[b] S is spatial data.

2.3. Land use allocation sub-model

Cultivated area is always assumed to be located within a certain distance around residential areas during the prehistoric period due to the time limit that humans could spend on walking in one day (Wang, 1997; Zhang, 2003; Zheng et al., 2008). Inside this spatial range, people would further select areas with suitable environmental conditions for agriculture. The degree of suitability in each location of the region is assumed to follow the potential distribution of human activity output by the residential area sub-model, under the hypothesis that environmental conditions chosen by humans for cultivated area were similar to those for residential area.

Thus, the total amount of land needed (output from the land use need sub-model) is allocated to the grids around the archeological sites within a certain radius. The needed land is matched by the most favorable areas using the rank values of the environmental grids from the residential area sub-model. This reconstructs the spatial distribution of prehistoric land use in the study region.

All the inputs and outputs of the PLUM model, catalogued as attribute and spatial data according to their format, are listed in Table 1.

3. Model input for Yiluo valley

The study covers a timescale from 8 to 4 ka B.P., because the first agricultural remains found here date from around 8 ka B.P. (Chen et al., 2003). Few investigations of archeological sites are dated after 4 ka B.P. in the valley due to increasingly detailed historical records kept since the start of the Shang dynasty 3600 years ago (Xia-Shang-Zhou Chronology Project Expert Group, 2000).

3.1. Spatial input data

The spatial data includes digital maps of today's elevation, river system, soil and land use, since corresponding data of thousands of years ago could not be obtained and the environmental condition has not changed significantly during the Holocene in the valley (Zhang et al., 2007).

Elevation raster data across the region is represented by a grid layer with a horizontal resolution of 90 m and vertical resolution of 1 m from the website (http://srtm.csi.cgiar.org/) of Shuttle Radar Topography Mission (SRTM). Slope and aspect layers are further derived from this elevation dataset using a

Table 2
Bounding ages of cultures in Yiluo valley and source references.

Culture	Age (year B.P.)	Source
Peiligang	8000–6900	An (1986)
Yangshao	7000–5000	Shi (1986)
Early Yangshao	7000–6000	
Late Yangshao	6000–5000	
Longshan	4900–4000	Tong (1986)

Geographic Information System (GIS). The river system in the valley is digitized from the topographic map in the scale of 1:500,000 (http://nfgis.nsdi.gov.cn/csi/) and used to construct grid layers with horizontal and vertical distances to the river system. Soil and land use types at a scale of 1:100,000 are taken from the national data sharing infrastructure of earth system science (http://www.geodata.cn).

All these vector and raster layers of environmental variables are finally resampled to grid data in GIS under the uniform projection of WGS_1984 with the same resolution of 90 m × 90 m, which leads to high resolution results and acceptable processing speed in modeling.

3.2. *Attribute input data*

The attribute data include environmental, social and economic parameters of archeological sites from 8 to 4 ka B.P. in Yiluo valley. Totally, 516 archeological sites are collected from the culture atlas of Henan province (National Heritage Board, 1991) and other publications (Chen et al., 2003; National Heritage Board, 1998; Wang, 1992; Xu et al., 2005; Zhao, 2001) (Appendix A in supplementary materials). Yiluo valley was one of the key areas where Chinese archaeologists looked for the origins of Chinese civilization (Xu, 1959), more than five archaeological survey projects have been carried out in the valley by dragnet investigation in the field (Chen et al., 2003; Zhao, 2001). Therefore, this region has been under the most detailed investigation, and the archeological sites could well represent change of prehistoric human activity and indicate the lower limit of actual land use amount, although some of sites might be undiscovered due to erosion by rivers, following human disturbance and other taphonomic reasons.

3.2.1. *Age of the sites in Yiluo valley*

All the sites occur within the context of specific culture periods, which are documented in their excavation reports (Chen et al., 2003; National Heritage Board, 1991, 1998; Wang, 1992; Xu et al., 2005; Zhao, 2001). The bounding ^{14}C ages for three corresponding cultures have been exactly dated in China (An, 1986; Shi, 1986; Tong, 1986) and are listed in Table 2. Among them, Peiligang Culture, the earliest pottery civilization in China, covered the period 8–6.9 ka B.P. The Yangshao Culture (7–5 ka B.P.) is subdivided into two parts, since most of sites in the Yangshao culture have been attributed to early (7–6 ka B.P.) or late stages (6–5 ka B.P.) based on the features of pottery and tools found in sites (Chen et al., 2003; National Heritage Board, 1991, 1998; Wang, 1992; Xu et al., 2005; Zhao, 2001). The Longshan Culture (4.9–4 ka B.P.), as the initial stage of the Bronze Age with the development of production technology, has also lasted for about 1000 years. Thus all the sites can be reclassified into 1000-year intervals (Fig. 2) and the intensity of human activity becomes comparable at equal temporal scale.

In addition, about 47% of the archeological sites ($n = 240$) occur under single culture type, while the other 276 sites have continuously developed and transgressed more than one culture period, thus they are classified into two or more 1000-year intervals.

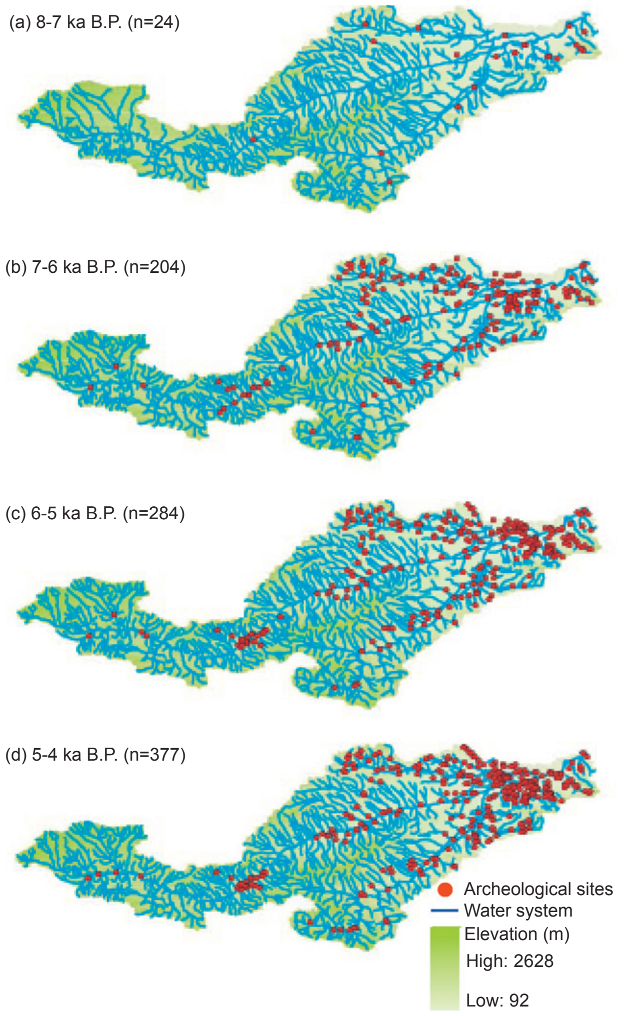

Fig. 2. Distribution of archeological sites in Yiluo valley from 8 to 4 ka B.P. (a) 8–7 ka B.P., (b) 7–6 ka B.P., (c) 6–5 ka B.P. and (d) 5–4 ka B.P.

3.2.2. *Social and economic parameters of the sites in Yiluo valley*

For 93% ($n = 480$) of the above archeological sites, the residential areas are documented in excavation reports (Chen et al., 2003; National Heritage Board, 1991, 1998; Wang, 1992; Xu et al., 2005; Zhao, 2001). For the remaining 7% ($n = 36$), the residential areas are estimated based on average known residential area of sites in corresponding culture periods in the valley.

Other social and economic parameters about human activity at the sites for the 1000-year intervals from 8 to 4 ka B.P. are listed in Table 3. Among them, residential area per person in archeological sites has decreased during the period, which is deduced by statistical analysis of 6 typical excavated archeological sites of corresponding periods in the valley (Wang, 2005).

The food need per person is adopted from the value of early Han Dynasty aged 2 ka B.P. (Ning, 1997), and is taken from the earliest document about this parameter. It is considered a constant in this study because agriculture was always the main source of human food in the valley during the Holocene and the human body has not changed too much (Wu, 1995).

The crop yield per area is linearly interpolated to each culture interval by compiling research results from three sources (Table 3). The starting value around 8–7 ka B.P. (45 g m^{-2}) is averaged from observation of modern slashing and burning agriculture (Liu, 2004; Wei, 1982) and reconstructions from plant opal amounts found in archeological sites (Zhao, 2002), while the end value about 3–2 ka

Table 3
Social and economic parameters in the PLUM for Yiluo valley.

Age (ka B.P.)	Residential average human land use area[a] (m^2)	Food need per person[b] (kg)	Yield of crop[c] (g m^{-2})	Fallow years[d] (year)	Tillage years[d] (year)	Scope of human land use[e] (km)
8–7	412 (177–647)	240	45	42	3	10
7–6	250 (208–297)	240	60	17	3	10
6–5	177 (168–186)	240	60	10	3	15
5–4	151 (116–186)	240	75	5	3	15

[a] From Wang (2005).
[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).

B.P. (105 g m^{-2}) is according to recorded production in Han Dynasty (Ning, 1997).

Fallow and tillage periods from 8 to 4 ka B.P. are set according to the estimates in the Cishan (8–7 ka B.P.) and Banpo (7–5 ka B.P.) archeological sites by Wang (1997), which are also located in the Yellow River basin. The threshold value for the scope of human land use is based on the reasonable walking time (2 h) for humans in one day (Zheng et al., 2008).

3.3. Inner parameters of PLUM

Class and spot weights in the residential area sub-model for environmental variables layers are set based on the analysis of 80% known archeological sites in the valley in each 1000-year interval, which are randomly selected from all sites. The other 20% sites are used as verification samples to test the predictive capability of the model.

The environmental variables, elevation, slope, aspect, distance to river system and soil type all pass the Kolmogorov one sample goodness-of-fit test (positively skewed distribution) in each 1000-year interval. The differences between D_{max} and D_c for these environmental variables show the following sequence in declining order: elevation, slope, soil type, aspect and distance to river system, thus their raster layers obtain corresponding class weights from 5 to 1 (Fig. 3a and b).

Statistical analysis shows that the number of archeological sites decreases with increasing elevation, slope and distance to river system in each 1000-year interval. Additionally, the spot weights of specific layers are set according to the percentage of above sites in different ranges of the corresponding environmental variable (Fig. 3c and d).

4. Results

4.1. Model validation

An essential step before the application of a model is to test its reliability. The PLUM was validated by modern observed land use data and found archeological sites in Yiluo valley, respectively.

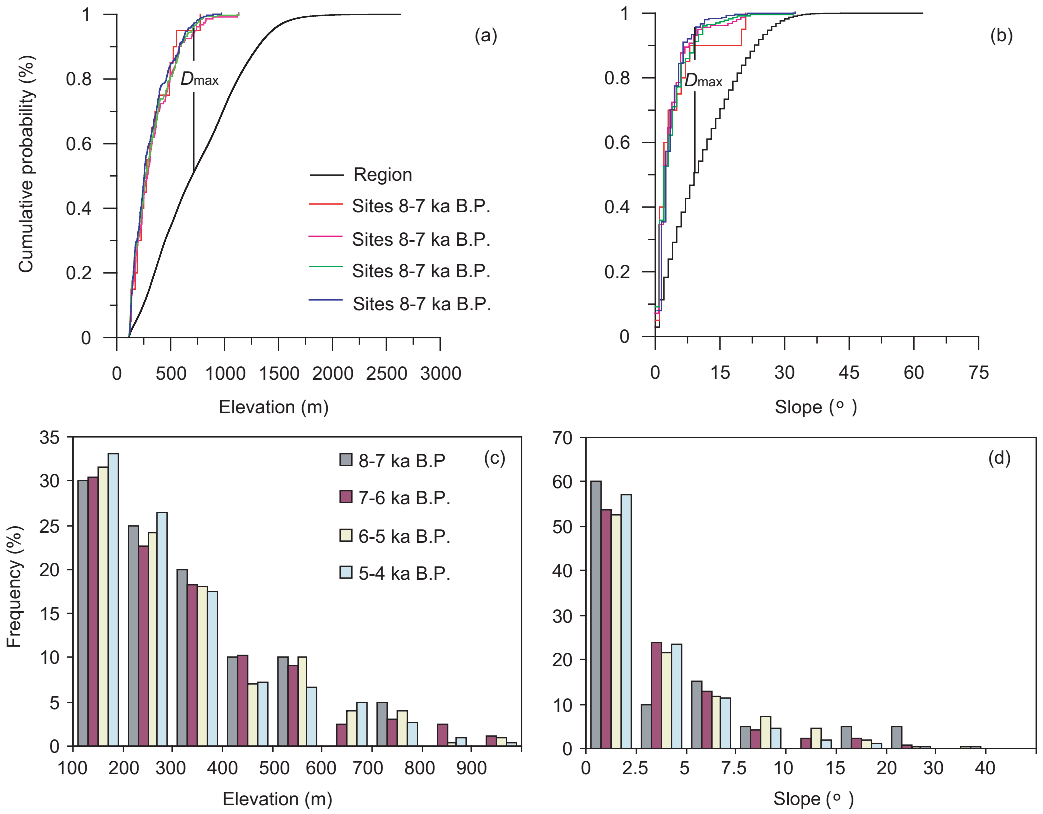

Fig. 3. Class and spot weights setting in PLUM for Yiluo valley from 8 to 4 ka B.P. (taking elevation and slope as examples). (a) Class weights for elevation, (b) class weights for slope, (c) spot weights for elevation and (d) spot weights for slope.

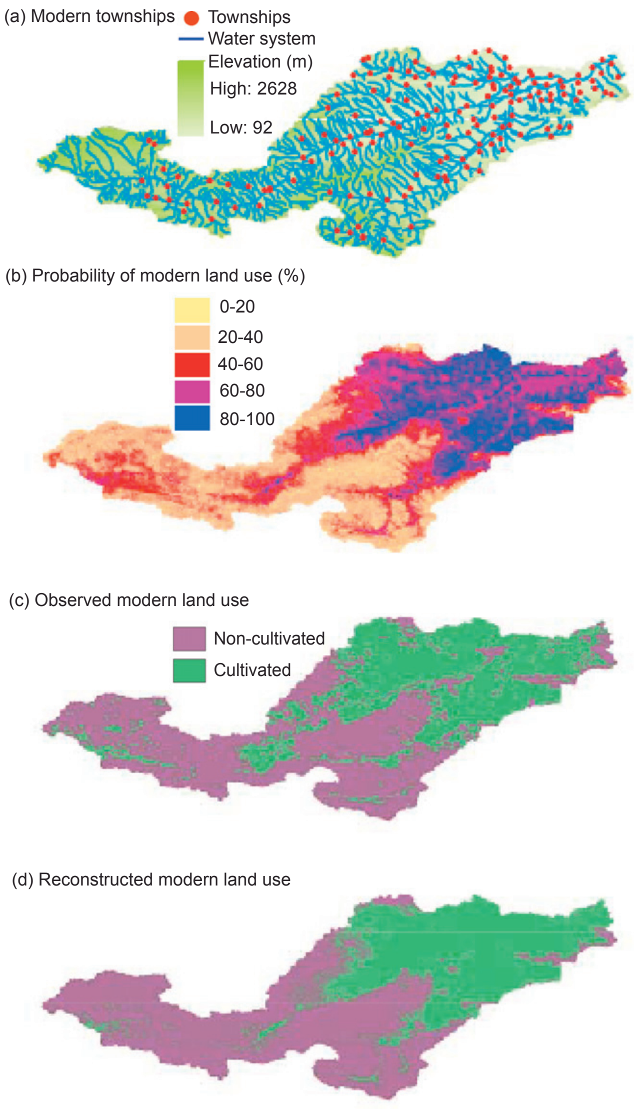

Fig. 4. Distribution of modern land use in Yiluo valley. (a) Distribution of modern townships, (b) distribution of probability of modern land use, (c) distribution of observed modern land use and (d) distribution of predicted modern land use.

Table 4
Distribution of 20% verification samples in three classified potential areas.

Age (ka B.P.)	Low rank (%)	Middle rank (%)	High rank (%)
8–7	0	0	100
7–6	0	18	83
6–5	0	7	93
5–4	0	9	91

Based on the observed amount of land use and distribution of the townships nowadays (Fig. 4a), modern spatial distribution of land use was reconstructed by PLUM in Yiluo valley (Fig. 4b). Comparison between observed (Fig. 4c) and reconstructed land use distribution patterns (Fig. 4d) shows no systematic bias, with a kappa index of 0.67, which falls into the degree of good fit (Monserud and Leemans, 1992).

In total, the spatial distribution of 79.3% cultivated areas and 84.0% non-cultivated areas are correctly simulated, which further indicates that the reconstructed land use is in reasonable agreement with that observed. In particular, the model works well in the lower reaches of the valley, while some disagreements appearing in the upper and middle reach of the valley may be due to the differences between distribution pattern of townships (Fig. 4a) and that of the actual residential areas in these regions. Townships are administrative entities and are always displayed on maps at central locations of the regions they govern. They are not the smallest residential unit in the valley but are the highest resolution data available.

For further validation of the residential area distribution sub-model, it is evaluated whether the percentage of correct predictions exceeds that of the random distribution (Kvamme, 1990). All output raster layers of the sub-model from 8 to 4 ka B.P. are firstly classified into three classes with 33% interval according to the values of grids, which show high, medium and low potential areas for site distributions. Then, the percentages of verification samples (20% of the found sites) occurring in the three potential areas are calculated. Table 4 and Fig. 5 show that at least 83% of verification samples occur in high potential areas from 8 to 4 ka B.P., which is significantly different from that of random distribution (33%) and indicates a good prediction capability of the sub-model. While the remaining 7–17% found sites all distributed in middle potential areas with higher elevation, this relatively small difference between simulated and archeological data may be partly attributed to much lower weights setting of areas in the upper part of valley in the sub-model, and partly to other parameters (e.g. social factors,

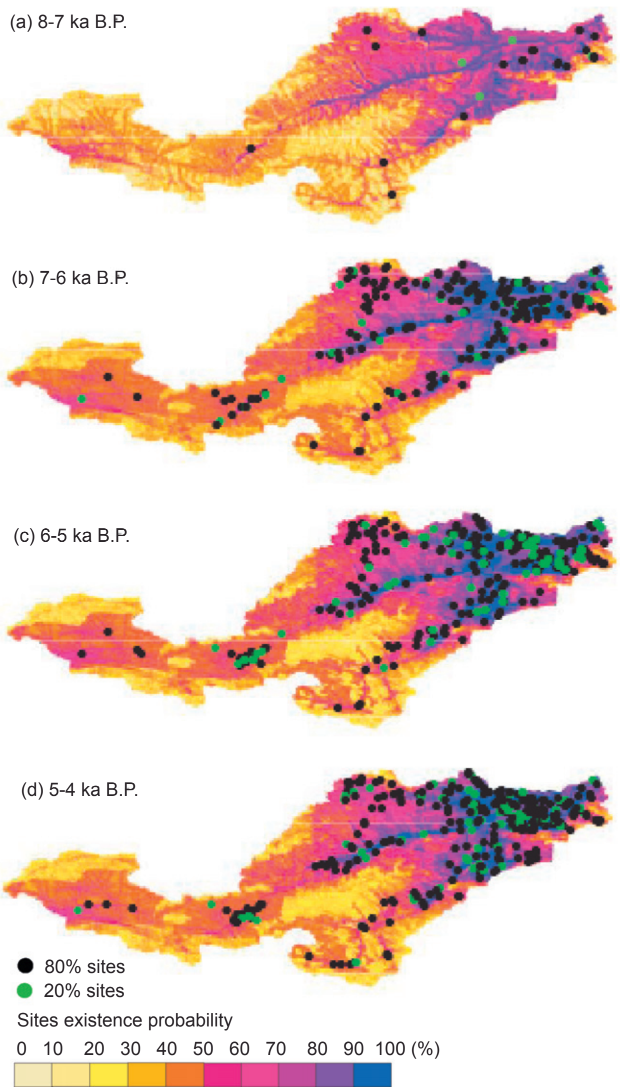

Fig. 5. Distribution of archeological sites and the probability of sites from 8 to 4 ka B.P. (a) 8–7 ka B.P., (b) 7–6 ka B.P., (c) 6–5 ka B.P. and (d) 5–4 ka B.P.

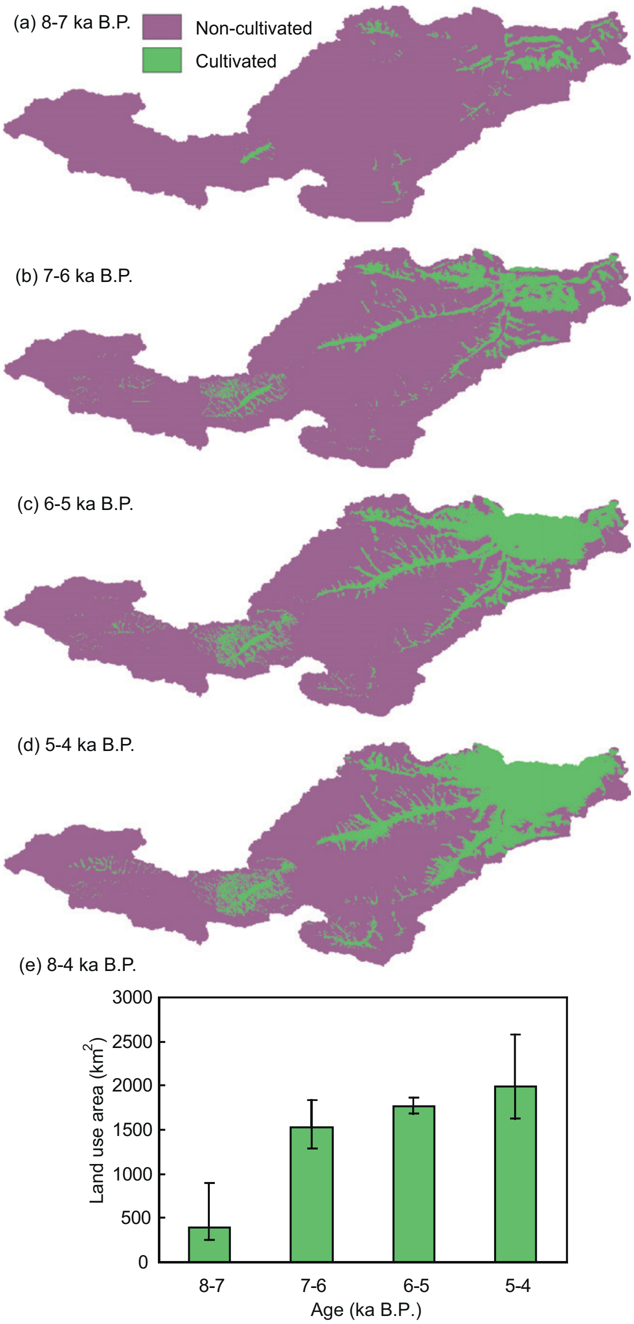

Fig. 6. Amount and distribution of land use in Yiluo valley from 8 to 4 ka B.P. (a) 8–7 ka B.P., (b) 7–6 ka B.P., (c) 6–5 ka B.P., (d) 5–4 ka B.P. and (e) 8–4 ka B.P.

presence of springs and taphonomic conditions) (Chen et al., 2003; Zhao, 2001), which affected the distribution of archeological sites but were not considered in the sub-model.

The validations of the PLUM show that the model has reasonably reconstructed distribution of modern land use and prehistoric archeological sites in Yiluo valley, and thus it can be applied to prehistoric land use reconstruction.

4.2. *Spatial and temporal prehistoric land use in Yiluo valley*

From 8 to 4 ka B.P., the total area of land use in Yiluo valley increased from 387 (247–898) km^2, 1529 (1289–1835) km^2, 1773 (1688–1867) km^2 to 1991 (1622–2582) km^2 for four 1000-year intervals (Fig. 6e), which shows the most significant spread of agriculture happened around 7 ka B.P. New increased cultivated areas in the latter three millennia are 1362 (1148–1634) km^2, 1029 (979–1083) km^2 and 783 (638–1015) km^2, respectively, in accordance with the appearance of 195, 164 and 133 new archeological sites.

Compared with 44% of the area in the valley that has been cultivated in modern times, only 2% (1–4%), 7% (6–9%), 8.4% (8–9%) and 9% (8–12%) of the area was used between 8 and 4 ka B.P., which shows a relatively low intensity of human activity in prehistoric periods.

In a spatial sense, prehistoric land use was mainly distributed close to the river in the lower reach of the valley, which has low elevation and gentle slope (Fig. 6a–d). The land use area further expanded from the lower to the middle reach of the valley from 7 to 4 ka B.P. Finally, the spatial distribution pattern of land use since 5 ka B.P. became similar to that of modern times, which shows that human activity has indeed changed the land cover.

5. Discussion and conclusion

5.1. *Comparison with previous approaches*

PLUM deduces land use areas based on the relationship between population and land use as previous methods do (Kaplan et al., 2009, 2011; Lemmen, 2009; Olofsson and Hickler, 2007). This is due to lack of sufficient observed data on prehistoric land use. However, significant progress has been made by development of the PLUM model. The key innovative point is that archeological sites, as direct evidence of human activity, are used for land use reconstruction. Firstly, a bottom-up method to calculate regional population is introduced in PLUM relying on objective information from archeological sites in corresponding periods, while previous studies often estimate total regional prehistoric population by (non)linear-extrapolation in time. Secondly, the distribution of archeological sites in PLUM suggests limits in spatial boundaries of human land use, while previous studies allocate land use in space according to the degree of suitability for agriculture of the whole region (Kaplan et al., 2009, 2011; Lemmen, 2009). Therefore, the PLUM provides a more realistic spatial distribution of land use.

Archeological sites and land use per-capita are the most important input data for PLUM and affect the precision of land use reconstruction. The increase rate of archeological sites since 7 ka B.P. in our study (about 32–39% for one thousand years) was much lower than that in Li et al. (2009) (above 140%), because their study region was much wider than ours and their rapid growth during 5–4 ka B.P. was mainly attributed to the abrupt increase of sites in upper Yellow River Valley, middle and lower Yangtze River Valley which are outside of Yiluo valley. Our increase pattern further indicated a slow population growth in Yiluo valley, which followed the geometric population model whereby growth rate is assumed to be proportional to the population (Boyle et al., 2011), and was also comparable with the estimate of global population by McEvedy and Jones (1978).

For the land use per-capita, our study shows that about 2-fold decrease occurred from 8 to 4 ka B.P. in Yiluo valley based on estimate from excavated archeological sites (Liu, 2004; Wei, 1982; Zhao, 2002). This change is about half of decrease between AD 5 and the early-middle 1800s (Buck, 1937; Chao, 1986; Ruddiman et al., 2011). The acceleration of the decrease since 2 ka B.P. may be related to the development of agriculture tools and technology (e.g. widely application of iron tools and cattle farming), which could significantly improve the yield of crop per area (Cao, 1982; Wang, 2004). Furthermore, the above studies for China all did not considered other human-induced land uses (e.g. pasture and cultivated areas for feeding livestock), thus the estimated land use per-capita would be lower than the actual situation (Fuller et al., 2011).

Land use change in the Yiluo valley output by PLUM suggests that human activity has indeed changed the land cover in middle Holocene. This result is further supported by other archeological records (e.g. agricultural tools, sites areas, archaeobotanical evidence) from Yiluo valley and other parts of China (Fang et al., 1998). In a temporal sense, the number of agricultural tools and the size of residential areas all have increased from 8 to 4 ka B.P., which suggests population increase and the intensification of human activity (Shen, 2000). In a spatial sense, compilations of found crop remains (e.g. seeds of millet, rice and wheat etc.) (An, 1988; Gong et al., 2007; Jin, 2007; Ruddiman et al., 2008) also show that a significant spread of agriculture happened around 6 ka B.P. The process is reflected by the expansion of the dry agriculture systems from the middle Yellow River in northern China to other areas (An, 1988; Jin, 2007), and that of rice agriculture from the Yangtze River in southern China to the north (Gong et al., 2007; Ruddiman et al., 2008). Finally, the blended zone of crop agriculture in central China formed at that time (Wang and Xu, 2003).

In addition, the development of land use in the Yiluo valley is also in accordance with change of other evidences (pollen, charcoal and soil property) recorded in soil profiles in the valley (Sun and Xia, 2005; Wang et al., 2004). The emergence of peak concentrations of charcoal in soil profiles near the archeological sites (Wang et al., 2004) indicates that human land use was continuous since 7 ka B.P. Furthermore, soil fertility was reduced as evidenced by lower nitrogen amounts in these soil profiles (Wang et al., 2004). The pollen records, show different vegetation change patterns depending on distance from archeological sites. Records show that deciduous broad-leaved forest has developed in the region around 6 ka B.P. (Sun and Xia, 2005), while low arboreal percentages are found in latter record since 7 ka B.P. (Wang et al., 2004), which might be induced by human land clearing.

Land use reconstruction in the Yiluo valley is helpful for evaluating the role of human activity played in global environmental and greenhouse gas changes, due to a new quantitatively method is advanced. However, it remains difficult to estimate the impact of human land use on the abnormal rise of CO_2 in the Holocene, because the area of Yiluo valley is too small to represent the global land use changes. Therefore application of PLUM to larger regions is a possible option for further rational evaluations in the future.

5.2. *Uncertainty and future improvements*

PLUM is one of the first attempts to quantitatively reconstruct change of prehistoric land use based on environmental and social parameters of archeological sites, and it has been successfully applied to regional prehistoric land use reconstruction. With improvements in model input parameters and structures in future version, the accuracy of spatial and temporal land use reconstruction is expected to be improved.

Firstly, a more systematic database of input parameters for the model simulation should be developed. Together with improving precision of current environmental (e.g. elevation, slope, aspect, distance to river and soil type) and social (e.g. land use need per person, yield of crop and fallow period) input parameters in PLUM, other parameters related to land use (e.g. taphonomic condition, crop types) also need to be considered in the future.

Secondly, since PLUM is based on the assumptions of one single land use type and a closed balance of food need and supply in the region at present, a more accurate land use per-capita will be obtained by improvement of the structure of PLUM by adding other human activities (e.g. hunting, grazing and feeding livestock) related to land use (Fuller et al., 2011) in next version of the model.

With the scaling up of PLUM to larger regional or global levels by a greater use of archeological data, the impact of human land use on global change can be studied more accurately.

Acknowledgments

This work was supported by National Basic Research Program of China (973 Program) (No: 2010CB950204), the National Natural Science Foundation of China (No: 41102222) and the Bairen Programs of the Chinese Academy of Sciences. Thanks are extended to two anonymous reviewers for their constructive suggestions and improvements of English. Ann Zwertvaegher is also thanked for helpful discussion and suggestions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2012.05.013.

References

An, Z.M., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology. Encyclopedia of China Publishing House, Beijing, pp. 592–595 (in Chinese).

An, Z.M., 1988. Chinese prehistoric agriculture. Acta Archaeol. Sin. 4, 369–381 (in Chinese).

Archer, D., Winguth, A., Lea, D., Natalie, M., 2000. What caused the glacial/interglacial atmospheric pCO_2 cycles? Rev. Geophys. 38 (2), 159–189.

Bona, L.D., 1994. Cultural heritage resource predictive modeling project final report (volume 3): methodological considerations. In: Centre for Archaeological Resource Prediction (Ed.), Report to Ontario Ministry of Natural Resources. Lakehead University, Ontario, pp. 12–14.

Boyle, J.F., Gaillard, M-J., Kaplan, J.O., Dearing, J.A., 2011. Modeling prehistoric land use and carbon budgets: a critical review. Holocene 21 (5), 715–722.

Broecker, W.S., Lynch-Stieglitz, J., Clark, E., Hajdas, I., Bonani, G., 2001. What caused the atmosphere's CO_2 content to rise during the last 8000 years? Geochem. Geophys. Geosyst. 2, http://dx.doi.org/10.1029/2001GC000177.

Buck, J.L., 1937. Land Utilization in China. Commercial Press, Shanghai, 494 pp. (in Chinese).

Cao, Y.Y., 1982. The origin and development of cattle farming in China. Agric. Archaeol. 2, 96–101 (in Chinese).

Chao, K., 1986. Man and Land in Chinese History: An Economic Analysis. Stanford University Press, Stanford, 268 pp.

Chen, X.C., Liu, L., Li, R.Q., Wright, H.T., Rosen, A.M., 2003. Development of social complexity in the central China: research into the settlement pattern in the Yiluo river valley. Acta Archaeol. Sin. 2, 161–218 (in Chinese).

Ding, S.Y., Liang, G.F., 2007. Analysis of geographic environmental factors on forest landscape dynamics of Yiluo River basin. Geogr. Res. 26 (5), 906–914 (in Chinese).

Espa, G., Benedetti, R., De Meo, A., Ricci, U., Espa, S., 2006. GIS based models and estimation methods for the probability of archaeological sites location. J. Cult. Herit. 7, 147–155.

Fang, X.Q., Zhang, W.B., Zhang, L.S., 1998. The land use arrangement of China in the Holocene Megathermal period and its significance. J. Nat. Resour. 13 (1), 16–22 (in Chinese).

Freachan, R.G.A., 1973. A clarification of carrying-capacity formula. Aust. Geogr. Stud. 11 (2), 234–236.

Fuller, D.Q., Etten, J.V., Manning, K., Castillo, C., Kingwell-Banham, E., Weisskopf, A., Qin, L., Sato, Y-I., Hijmans, R.J., 2011. The contribution of rice agriculture and livestock pastoralism to prehistoric methane levels: an archaeological assessment. Holocene 21 (5), 743–759.

Gong, Z.T., Chen, H.Z., Yuan, D.G., Zhao, Y.G., Wu, Y.J., Zhang, G.L., 2007. The temporal and spatial distribution of early rice in China and its significances. Chin. Sci. Bull. 52 (5), 562–567 (in Chinese).

Habib, M.G., Thomas, D.R., 1986. Chi-square goodness-if-fit tests for randomly censored data. Ann. Stat. 14 (2), 759–765.

Houghton, R.A., 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850∼1990. Tellus 51B, 298–313.

Indermühle, A., Stocker, T.F., Joos, F., Fischer, H., Smith, H.J., Wahlen, M., Deck, B., Mastroianni, D., Tschumi, J., Blunier, T., Meyer, R., Stauffer, B., 1999. Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica. Nature 398, 121–126.

Jin, G.Y., 2007. Early Chinese archaeological discoveries and research of wheat. Agric. Archaeol. 4, 11–20 (in Chinese).

Joos, F., Gerber, S., Prentice, I.C., Otto-Bliesner, B.L., Valdes, P.J., 2004. Transient simulations of Holocene atmospheric carbon dioxide and terrestrial carbon since the Last Glacial Maximum. Global Biogeochem. Cycl. 18, GB2002, http://dx.doi.org/10.1029/2003GB002156.

Kaplan, J.O., Krumhardt, K.M., Ellis, E.C., Ruddiman, W.F., Lemmen, C., Goldewijk, K.K., 2011. Holocene carbon emissions as a result of anthropogenic land cover change. Holocene 21 (5), 775–791.

Kaplan, J.O., Krumhardt, K.M., Zimmermann, N., 2009. The prehistoric and preindustrial deforestation of Europe. Quat. Sci. Rev. 28, 3015–3034.

Kirkby, A.V.T., 1973. The use land and water resources in the past and present, Valley of Oaxaca, Mexico. In: Blanton, R.E. (Ed.), Prehistory and Human Ecology of the Valley of Oaxaca. Museum of Anthropology, University of Michigan, Ann Arbor, pp. 171–174.

Kvamme, K.L., 1990. One-sample tests in regional archaeological analysis: new possibilities through computer technology. Am. Antiq. 55 (2), 367–381.

Lemmen, C., 2009. World distribution of land cover changes during pre- and protohistoric times and estimation of induced carbon releases. Géomorphol.: Relief Process. Environ. 4, 303–312.

Li, X.Q., Dodson, J., Zhou, J., Zhou, X.Y., 2009. Increases of population and expansion of rice agriculture in Asia, and anthropogenic methane emissions since 5000 BP. Quat. Int. 202, 41–50.

Liu, F.J., 2004. On the Wa-Benglong-speaking nationality and their primitive farming. J. Yunnan Natl. Univ. 21 (5), 91–94 (in Chinese).

Lüthi, D., Floch, M.L., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., Stocker, T.F., 2008. High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature 453, 379–382.

Matsumoto, K., Sarmiento, J.L., Brzezinski, M.A., 2002. Silicic acid leakage from the Southern Ocean: a possible explanation for glacial atmospheric pCO_2. Global Biogeochem. Cycl. 16 (3), 1031, http://dx.doi.org/10.1029/2001GB001442.

McEvedy, C., Jones, R., 1978. Atlas of World Population History. Penguin Books Ltd., London.

Monserud, R.A., Leemans, R., 1992. Comparing global vegetation maps with kappa statistic. Ecol. Model. 62, 275–293.

National Heritage Board, 1991. Cultural Atlas—Henan Branch. Sinomaps Press, Beijing, pp. 1–375 (in Chinese).

National Heritage Board, 1998. Cultural Atlas—Shaanxi Branch. Xi'an Map Press, Xi'an, pp. 490–616 (in Chinese).

Ning, K., 1997. Discussion about agricultural production in Han Dynasty. Guangming Daily, 10th April (in Chinese).

Olofsson, J., Hickler, T., 2007. Effects of human land-use on the global carbon cycle during the last 6,000 years. Veg. Hist. Archaeobot. 17 (5), http://dx.doi.org/10.1007/s00334-007-0126-6.

Pongratz, J., Reick, C.H., Raddatz, T., 2009. Effects of anthropogenic land cover change on the carbon cycle of the last millennium. Global Biogeochem. Cycl. 23, GB4001, http://dx.doi.org/10.1029/2009GB003488.

Ridgwell, A.J., Watson, A.J., Maslin, M.A., Kaplan, J.O., 2003. Implications of coral reef buildup for the controls on atmospheric CO_2 since the last glacial maximum. Paleoceanography 18 (4), 1083, http://dx.doi.org/10.1029/2003PA000893.

Ruddiman, W.F., 2003. The anthropogenic greenhouse era began thousands of years ago. Clim. Change 61 (3), 261–293.

Ruddiman, W.F., 2007. The early anthropogenic hypothesis: challenges and responses. Rev. Geophys. 45, RG4001, http://dx.doi.org/10.1029/2006RG000207.

Ruddiman, W.F., Thomson, J.S., 2001. The case for human causes of increased atmospheric CH_4 over the last 5000 years. Quat. Sci. Rev. 20, 1769–1777.

Ruddiman, W.F., Guo, Z.T., Zhou, X., Wu, H.B., Yu, Y.Y., 2008. Early rice farming and anomalous methane trends. Quat. Sci. Rev. 27, 1291–1295.

Ruddiman, W.F., Kutzbach, J.E., Vavrus, S.J., 2011. Can natural or anthropogenic explanations of late-Holocene CO_2 and CH_4 increases be falsified? Holocene 21 (5), 865–879.

Shang, M.J., 1992. Initial exploration of early primitive agriculture. Agric. Archaeol. 3, 69–74 (in Chinese).

Shen, Z.Z., 2000. Developmental stages of primitive agriculture in China. Agric. Hist. China 19 (2), 3–9, 24 (in Chinese).

Shi, X., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology. Encyclopedia of China Publishing House, Beijing, pp. 595–602 (in Chinese).

Sun, H.W., Xia, Z.K., 2005. Paleoenvironment changes since mid-Holocene revealed by a palynological sequence from Sihenan profile in Luoyang, Henan province. Univ. Peking (Acta Sci. Nat.) 41 (2), 289–294 (in Chinese).

Tong, Z., 1986. In: Xia, N. (Ed.), Encyclopedia of China: Archaeology. Encyclopedia of China Publishing House, Beijing, p. 290 (in Chinese).

Wang, B.Q., 2004. Iron farm tools: their emergence, development, and influences. J. Nanjing Agric. Univ. (Soc. Sci. Ed.) 4 (3), 83–93 (in Chinese).

Wang, B.R., 1992. Investigation of archeological sites of Yangshao culture in Wuluo river, Gongyi. Cult. Reli. Cent. China (4), 12–35 (in Chinese).

Wang, J.G., 1997. Population, ecology and evolution of China's slash and burn areas. Agric. Archaeol. 1, 91–95, 152 (in Chinese).

Wang, J.H., 2005. Study on the prehistoric population in the middle and lower reach of the Yellow River. Ph.D. Thesis. Shandong University, Jinan, pp. 18–131 (in Chinese).

Wang, X.G., Xu, X., 2003. A discussion on the rice-millet blended zone in the neolithic age. Agric. Hist. China 22 (3), 3–9 (in Chinese).

Wang, X.L., He, Y., Jia, T.F., Li, R.Q., 2004. Living environment of ancient man since 7000 a B.P. at Xishan relic site of Zhengzhou in Henan Province. J. Palaeogeogr. 6 (2), 234–240 (in Chinese).

Wei, S., 1982. Discussion about the origin of cattle farming. Agric. Archaeol. 2, 102–106 (in Chinese).

White, A.M., 2002. Archaeological predictive modeling of site location through time: an example from the Tucson Basin, Arizona. MA Thesis. University of Calgary, Calgary, pp. 21–36.

Wu, R.K., 1995. Thoughts on the whole course of human evolution. Acta Anthropol. Sin. 14 (4), 285–296 (in Chinese).

Xia-Shang-Zhou Chronology Project Expert Group, 2000. Report on the Xia-Shang-Zhou Chronology Project, 1996–2000 (simplified edition). World Publishing Co. Ltd., Beijing, 118 pp. (in Chinese).

Xu, H., Chen, G.L., Zhao, H.T., Wang, H.Z., Wang, F.C., Wang, C.M., Guo, S.N., Zhao, J.Y., 2005. Archeological survey from 2001 to 2003 in Luoyang Basin, Henan. Archeology 5, 18–37 (in Chinese).

Xu, X., 1959. Preliminary report of the surveys in the Ruins of Xia in 1959. Archaeology 11, 592–600 (in Chinese).

Zhang, B.J., Chen, C.Y., Wang, J.Y., 2007. Evolution of landforms in the plain of Luoyang Basins in Holocene. J. Xinyang Norm. Univ. (Nat. Sci. Ed.) 20 (3), 381–384 (in Chinese).

Zhang, H.Y., 2003. Introduction to Prehistoric Archaeology China. Higher Education Press, Beijing, pp. 24–29 (in Chinese).

Zhao, C.Q., 2001. Evolution of Neolithic Settlements in Zheng Luo Region. Peking University Press, Beijing, pp. 214–280 (in Chinese).

Zhao, X.B., 2002. Discussion about the form of agriculture in Hemudu site. Agric. Archaeol. 1, 53–57 (in Chinese).

Zheng, C.G., Zhu, C., Zhong, Y.S., Yin, P.L., Bai, J.J., Sun, Z.B., 2008. The temporal and spatial distribution of archeological sites and natural environment from Paleolithic Age to Tang and Song Dynasties in reservoir region of Chongqing. Chin. Sci. Bull. 53 (Suppl. I), 93–111 (in Chinese).