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

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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 archaeological sites. The PLUM is driven by environmental and social parameters of archaeological 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.

Key words: human activity; prehistoric; land use; 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 and Thomson, 2001; Ruddiman, 2003, 2007;). 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. Indermuhle et al., 1999; Archer et al., 2000; Broecker et al., 2001; Matsumoto et al., 2002; Ridgwell et al., 2003; Joos et al., 2004), 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. (Olofsson and Hickler, 2007; Lemmen, 2009; Pongratz et al., 2009; Kaplan et al., 2009, 2011), 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 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, roughly 21,000 km^2 in area, is located in the southern part of the middle Yellow River area, which has experienced intensive and continuous human occupation throughout the Holocene, evidenced by the large number of archaeological remains discovered (Chen et al., 2003). It also has been the focal 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 (Kvamme, 1990; White, 2002; Espa et al., 2006), 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:

$$A_l=A_r+A_c \qquad (1)$$

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:

$$A_c = R \times A_n \qquad (2)$$

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:

$$R=(T_f+T_c)/T_c \qquad (3)$$

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:

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

In equation 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:

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

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

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 equations 1 to 6 allows the equation for the land use area in each archeological site to be derived:

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

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 (Kvamme, 1990; White, 2002; Espa et al., 2006) 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 archaeological 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):

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

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 3.4).

(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.

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 archaeological 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

3.1 Background of Yiluo valley

The Yiluo Valley 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 average yearly temperature and precipitation of the valley are 12-14℃ and 600-900mm, while Cinnamon soils (WRB: Kastanozems) and deciduous broad-leaved forest are the dominant soil and vegetation type, respectively (Ding and Liang, 2007).

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).

3.2 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 90m and vertical resolution of 1m 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 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 90m×90m, which leads to high resolution results and acceptable processing speed in modeling.

3.3 Attribute input data

The attribute data include environmental, social and economic parameters of archaeological 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 (Wang, 1992; National Heritage Board, 1998; Zhao, 2001; Chen et al., 2003; Xu et al., 2005) (Appendix A in supplementary materials). Usually found archeological sites only represent part of actual human habitation in the past, because some of them vanished due to erosion by rivers, following human disturbance and other taphonomic reasons. In addition, survey density in the field is also important to reveal actual number of archeological sites. in the main part of Yiluo valley has been under detailed dragnet investigation in the field (Zhao, 2001; Chen et al., 2003), furthermore, study (Zhang et al., 2007) also shows that the environmental condition has not changed significantly during the Holocene in the valley. Therefore we conclude that these found sites well represent actual intensity of prehistoric human activity.

3.3.1 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 (Wang, 1992; National Heritage Board, 1991, 1998; Zhao, 2001; Chen et al., 2003; Xu et al., 2005). 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 (Wang, 1992; National Heritage Board, 1991, 1998; Zhao, 2001; Chen et al., 2003; Xu et al., 2005). 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 1,000 years. Thus all the sites can be reclassified into 1,000-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 1,000-year intervals.

3.3.2 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 (Wang, 1992; National Heritage Board, 1991, 1998; Zhao, 2001; Chen et al., 2003; Xu et al., 2005). 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 1,000-year intervals from 8 to 4 ka B.P. are listed in Table 3. Among them, residential area per person in archaeological sites has decreased during the period, which is deduced by statistical analysis of 6 typical excavated archaeological 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 2). The starting value around 8-7 ka B.P. (45 g m^{-2}) is averaged from observation of modern slashing and burning agriculture (Wei, 1982; Liu, 2004) and reconstructions from plant opal amounts found in archeological sites (Zhao, 2002), while the end value about 3-2 ka 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 hour) for humans in one day (Zheng et al., 2008).

3.4 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 1,000-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 (normal distribution) in each 1,000-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-b).

Statistical analysis shows that the number of archeological sites decreases with increasing elevation, slope and distance to river system in each 1,000-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-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 archaeological sites in Yiluo valley, respectively.

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%). This indicates a good prediction capability of the sub-model. The difference between simulated and archaeological data, that is 7-17% found sites distributed in middle potential areas, is closely related to the weights set in residential area distribution sub-model. Firstly, the importance of these weights is affected by spatial variation of corresponding environmental conditions in the valley. For example, in the upper part of valley, these areas would receive lower total weight in the model due to their higher elevation, but in reality some archaeological sites could exist here because of other local favorable conditions (e.g. distance to river, slope) for human activity. Secondly, only five main environmental parameters have been selected in the model, while other local conditions (e.g. social factors, presence of springs, and buried conditions), which also

Opmerking [PF1]: Unclear. Are the sites buried under recent sediments?

could affect the distribution of archaeological sites, were not considered due to the complexity.

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 1,000-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 on land use

PLUM deduces land use areas based on the relationship between population and land use as previous methods do (Olofsson and Hickler, 2007; Lemmen, 2009; Kaplan et al., 2009, 2011). 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 (Lemmen, 2009; Kaplan et al., 2009, 2011). Therefore, the PLUM provides a more realistic spatial distribution of land use.

Land use change in the Yiluo valley 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 (Wang et al., 2004; Sun and Xia, 2005). 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 archaeological 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.

5.2 Comparison with previous studies on archaeological data

The temporal and spatial changes of archaeological site distributions from 8-4 ka B.P. in a much larger region of China (the Yellow River and Yangtze River valley) have been analyzed by Li et al. (2009). The increase pattern of sites in the above region (Li et al., 2009) was different from our study in a small river valley during the same time period. Firstly, the growth rate of total sites number between 5-4 and 8-7 ka B.P. was much faster in the Yellow River and Yangtze River valley than that of Yiluo valley. Secondly, an especially rapid increase in total sites number occurred from 5-4 ka B.P. in Li et al. (2009), which was, however, not shown by our data.

The differences could be explained by an unbalance of development of human activity among various regions in China, because the above two aspects of discrepancy would become insignificant, if the comparison is made at the same spatial scale. The very rapid growth in sites from 5-4 ka B.P. in Li et al. (2009) was mainly attributed to the increase of sites in upper Yellow River Valley, middle and lower Yangtze River Valley, which was shown in Fig 2 in Li et al. (2009). These areas are outside the current study area. These increases may be driven by the spread of dry agriculture to upper Yellow River valley from its middle and lower parts since 6 ka B.P. (An, 1988; Jin, 2007), the introduction of wheat from Western Asia to north China since 5 ka B.P. (Li et al., 2011), and the expansion of rice agriculture in Yangtze River Valley in south China around 5 ka B.P. (Ruddiman et al., 2008).

The amount of agriculture remains per site also significantly increased around 5 ka B.P. (Zhou et al., 2011), which shows that the yield of crop increased.

The significant differences in increase of archaeological sites between Li et al. (2009) and our study directly affect the growth rates of estimated population. In addition, population was directly inferred based on the numbers, density and size of sites in Li et al. (2009), without considering change of area needed by per person for activity with time, however, the area was varied for population estimation in our study according to statistical analysis of 6 typical excavated archaeological sites of corresponding periods in the valley (Wang, 2005).

Besides population, per-capita land requirement is another important parameter for land use reconstruction in Holocene. About 2-fold decrease of land use per-capita occurred from 8-4 ka B.P. in Yiluo valley, while former studies (Buck, 1937; Chao, 1989; Ruddiman et al., 2011) show that it fell almost linearly by a factor of about 4 between AD 5 and the early-middle 1800's as farmers gradually learned to produce more food per hectare of land. The acceleration of decrease since 2 ka B.P. may be related to the development of agriculture tools and technology, which is symbolized by widely application of iron tools, cattle farming, etc (Cao, 1982; Wang, 2004).

5.3 Correlations among land use, agriculture development and climate change

Environmental change and agricultural development are two main drivers of the evolution of land use. Based on combination of corresponding records from northern China (An, 1988; Xu, 1998; Shen, 2000; Yu et al., 2001; Jin, 2007; Ren, 2007; Guiot et al., 2008; Li et al., 2011; Zhou et al., 2011), the correlations among change of land use, climate and agriculture in Yiluo valley can be explained as follows: the continuous increase of land use from 8 to 5 ka B.P. was at first supported by favorable climate conditions (Yu et al., 2001; Ren, 2007; Guiot et al., 2008). Contrastingly, the increasing area of agricultural land use after 5 ka B.P. was not reversed by drier climate conditions (Yu et al., 2001), because this trend was mainly driven by agricultural development (An, 1988; Xu, 1998; Shen, 2000; Jin, 2007; Li et al., 2011; Zhou et al., 2011) and the dependence of human on environmental conditions also became weaker in this period. This is confirmed by the observation that the percentage of archeological sites found in superior environmental conditions (e.g. low elevation, gentle slope and near the river) has decreased with time in Yiluo valley (Fig 3). Furthermore, the increase in land use from 5 to 4 ka B.P. is less than that of the previous 3 millenniums, which was contributed to the increase of yield of crop per area (Zhou et al., 2011).

Although the land use covered 2-9% of the area in Yiluo valley during 8 to 4 ka B.P., it shows a relatively low intensity of human activity in prehistoric periods. However, the distribution pattern of land use since 5 ka B.P. was similar to that in modern times (Fig 4c and Fig 6d), which indicates that land use might have had impact on environmental change.

Some synchronous changes exist between the abnormal Holocene CO_2 rise and human land use in Yiluo valley. Firstly, the beginning of CO_2 rise and the origin of agriculture happened at the same time around 8-7 ka B.P. Secondly, the continuous increase of CO_2 from 8 to 4 ka B.P. was in accordance with the spread of land use. However, it remains difficult to estimate the impact of human land use on the rise of

CO_2 in the Holocene, because the results only represent a significant land use change by human activity in a region in China, and thus can hardly represent the global land use changes. Therefore application of PLUM to larger regions is a possible option for further rational evaluations in the future.

5.4 Uncertainty and future improvements

Although the PLUM has been established and successfully applied to regional prehistoric land use reconstruction, uncertainties still exist and corresponding improvements should be developed to broaden applicable of the model.

Firstly, if more efforts are made on collecting, comparing, selecting and standardizing archeological research and in improving chronology, the precision of input prehistoric social and economic parameters will be highly improved and corresponding output of model could be more realistic.

Secondly, since PLUM is based on assumptions of one single land use type and a closed balance of food need and supply in the region, more kinds of human induced land use types (e.g. hunting, grazing and fishing) should be added to the future versions of PLUM for more accurate reconstruction of land use during the prehistoric period. Furthermore, with the introduction of livestock to China, it also enlarged the need of land use for pasture and fodder production (Fuller et al., 2011), which could be calibrated by increasing land use per-capita in the model.

Since land use reconstruction by PLUM is based on objective evidence of human activity, when it is scaled up to larger regional or global levels by a greater use of archeological data, the impact of human land use on global change may be amenable to study.

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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

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

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

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] (yr)	**Tillage years**[d] (yr)	**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] is from Wang, 2005; [b] is from Ning, 1979; [c] is from Ning 1979; Wei, 1982; Zhao, 2002 and Liu, 2004; [d] is from Wang, 1997; [e] is from Zheng et al., 2008

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

Figure Captions

Fig. 1 Structure of the PLUM model

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., (d) 5-4 ka B.P.

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, (b) 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, (d) Distribution of predicted modern land use

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., (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. (e) 8-4 ka B.P.

Supplementary materials Caption

Appendix A: Information of archeological sites in Yiluo valley and source references