Simulating Loess with Underlying Bedrock Paleotopographic strata for Landscape Evolution in the Loess Plateau Based on Digital Elevation Models

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Abstract—**the evolution processes of loess landforms are greatly controlled by the pre-quaternary underlying bedrock terrain, which is one of the most important aspects to explain the formation mechanism of loess landforms. In this research, on the basis of multiple data sources, 1729 outcropping points of underlying terrain are detected to construct a simulated digital elevation model of the pre-quaternary underlying paleotopography in a severe soil erosion area of Loess Plateau. The results show that obvious differences could be found between the underlying terrain and modern terrain; the topographic complexity of the underlying terrain appears simpler than that of the modern terrain. In addition, the modern surface has a gentler topographic relief than the topographic relief of the underlying terrain, as well as shows a significant landform inheritance characteristic of loess deposition. All these results deepen the understanding of the formation and evolution of loess landform.**

INTRODUCTION

The Loess Plateau is a positive geomorphic unit formed following the transportation and accumulation process of loess deposits on the basis of inheritance of underlying bedrock terrain during the Quaternary period (Liu, 1985). This unique formation mechanism directly determines the current complex and diverse landscapes, which attract world attention with their deep background of global change, thick loess sediments, varied loess landscape types, serious soil erosion and interaction between natural and human activities. Hence, a study of the paleotopography beneath the loess and its controlling impact on the current loess landform is of critical significance in understanding the formation mechanism and the landscape evolution process of the Loess Plateau and loess landforms.

Previous studies have developed many landscape evolution models to numerically represent landscapes and their evolution process over time, like SIBERIA (Willgoose et al., 1991); GOLEM (Tucker and Slingerland, 1994); CASCADE (Braun and Sambridge, 1997); CAESAR (Coulthard et al., 2000); CHILD (Tucker et al., 2000); ULTIMA THULE (Kaufmann and Romanov, 2012); PECUBE (Braun et al., 2012); CASQUS (Maniatis et al., 2009); parallel method (Braun and Willett, 2013); TIN-based method (Refice et al., 2012); phenomenological method (Dymond and Rose, 2011) and global flow path search method (Park, 2012). At the same time, different landscape evolution models have been used in different landforms to test the capability of the model (Ravazzi et al., 2013; Lehmkuhl et al., 2012; Berthling and Etzelmüller, 2011; Ciampalini et al., 2012; Fujioka and Chappell, 2011; Egholm et al., 2012; Bowman et al., 2010; Temme et al., 2011; Perron et al., 2009). Despite the success of these methods and applications in modeling various aspects of landscape evolution, the original underlying surface before landscape evolution process is usually been ignored. Especially for loess landform in the Loess Plateau of China, it is a typical fluvial landform with stable tectonic activity in Ordos platform during Quaternary period (Liu, 1985; Liu et al., 2001). The morphology and distribution of the underlying paleotopography are greatly affecting the process of the landscape formation and evolution. Since the 1950s, much work has been done for loess landforms through geological and geomorphological views. Liu (1985) investigated several intact and complete loess deposit profiles located in the three typical loess landforms, i.e. loess hilly, loess ridge and loess tableland in the Loess Plateau, and found that the sedimentary environment of loess deposit strata including the underlying bedrock paleotopography, closely relate to the climate change, which achieve a deep descriptive understanding of loess deposition and evolution during the Quaternary period. Other scholars also adopted qualitative and semi-quantitative method to describe the regional variance of soil erosion and geomorphological developmental stage of loess landforms (Cheng et al., 2007; Chen et al., 2010; Liu and Liu, 2010; Chen et al., 2008; Zhu, 2012; Zheng et al., 2008; Xu et al., 2004; Stolte et al., 2003; Fu et at., 2011; Hughes et al., 2010). All these research achievements laid a solid foundation in the further study of loess landforms and their evolution process. However, as Liu et al. (2001) pointed out: 'loess landscape morphology sequence should strictly correspond to the loess deposition sequence with their geological age', which means that the underlying strata in the loess landforms, including the Ma-lan, Li-shi, Wu-cheng loess strata and the bedrock strata, should be given priority consideration for the landscape evolution process modeling. These existing underlying strata represent different time nodes during the evolution process, which means that, without these underlying strata, all current proposed landscape evolution models may useless in representing loess landform evolution process, at least not correctly. Especially for the underlying bedrock strata, an initial landform surface acted as the erosion base level to control the development and evolution process of loess landform.

In this paper, the paleotopography beneath the loess, i.e. the underlying bedrock strata is prior taken into consideration for its controlling effect to landscape evolution process in loess landform. On the basis of geologic maps, RS images, DEMs and loess thickness drilling points, we construct a DEM of the paleotopographic surface through intensive sampling of outcropping paleotopographic points in a severe soil erosion area of the Loess Plateau.

MATERIALS AND METHODS

Materials

The DEMs (digital elevation models) used in this study come from the Shuttle Radar Topography Mission (SRTM) which is an international research effort that obtained digital elevation models on a near-global scale from 56° S to 60° N (Nikolakopoulos et al., 2006; Farr et al., 2007). The cell size of elevation models derived from the SRTM data is approximately 90 m in the Loess Plateau and can be downloaded freely. Geologic maps, with a scale of 1:200,000 composed by the Institute of Geology and Geophysics (Chinese Academy of Sciences), are used as an information source for bedrock outcropping points detected in the loess area. A remote sensing image is applied for the positional correction of bedrock outcropping points mapping. Liu (1985) used 167 loess thickness drilling points to construct a loess thickness distribution map. These point data have exact loess thickness values for different loess underlying terrains. In this paper, the Tertiary Red Clay and the early paleotopographic region are signed in the geologic map. Hence, the information of loess thickness drilling points could make a further control of the terrain simulation of the Tertiary surface.

Methods

1. Data Preprocessing

The SRTM is globe subdivision elevation data with approximately 90 m cell size, and there exist a systematic deviation on the resolution for each dataset. In order to unify the resolution of DEM data, all of them are resampled, and then, the new DEM data is achieved with the cell size of 100 m and covering the entire study area.

2. Outcropping Bedrock Strata Points Detection

In this experiment, coordinates and elevations for the outcropping bedrock strata points are collected based on the geologic maps, in which definite geologic age and rock type for those points were assigned, such as Tertiary, Cretaceous, Jurassic for geologic age and basalt or limestone for rock type. The method is implemented via the following steps. First, the bedrock outcropping points with the geologic age of Tertiary in channels or valleys are determined based on the geologic maps. Second, image-based positional correction of the bedrock points is done. Finally, an overall outcropping bedrock strata point dataset (Figure 1) is constructed. Because the limited sample points could not provide an overall surface trend for the Tertiary red clay strata, the loess drilling point dataset (Liu, 1985) is used to assist construction of a loess paleotopographic surface model. All sampling points are shown in Figure 1. The main research area is the severe soil erosion zone (Upper and Middle Yellow River Bureau, 2012) on the Loess Plateau, whose north part is a desert area, west part with LIU-PAN Mountains and LONG-XI Basin, east and south are TAI-HANG Mountains and GUAN-ZHONG Basin respectively. The research area is located in the Ordos platform with specific and stable geologic process, where there is a high density of outcropping bedrock strata points.

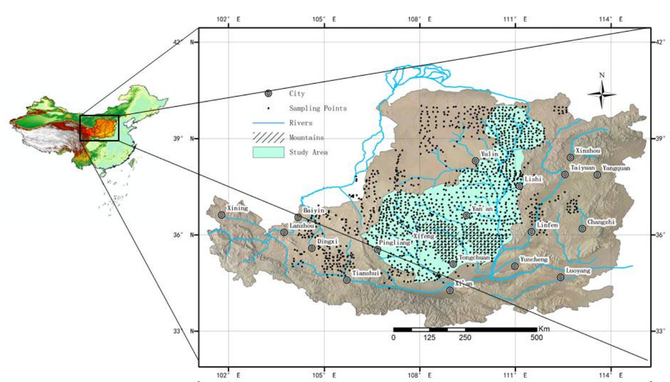


Figure 1. Test area and distribution of sampling points

3. Points Encryption

In the Loess Plateau, there are relatively large mountain ranges (Li and Lu, 2010), such as Ziwu Mountain and Huanglong Mountain etc., it is bedrock strata areas without buried during the Quaternary period and do not need to detect. In this paper, their DEM data are directly added in the elevation modeling of the loess underlying paleotopography.

4. Underlying bedrock strata surface modeling

Based on the outcropping bedrock strata points, the digital elevation model of loess underlying palaeotopography in the experimental area is constructed via interpolation. Through a comparison of all the interpolation methods (Franke, 1982; Mitas and Mitasova, 1988), spline is believed to be the most suitable method in this application for its high accuracy (the RMSE is 36.5 m, relative error is less than 12 percent), as well as relatively low variation. Among all sampling points, 80 percent of the points are prepared for interpolation, the remaining 20 percent ones are for accuracy detection. The simulation result of the loess underlying palaeotopography is shown as the Figure 3b.

The Spline function uses the following formula for the surface interpolation:

$$S(x,y) = T(x,y) + \sum_{j=1}^{N} \lambda_j R(r_j) \tag{1}$$

where: j = 1, 2, ..., N; N is the number of points. λj are coefficients found by the solution of a system of linear equations. rj is the distance from the point (x, y) to the jth point.

T(x, y) and R(r) are:

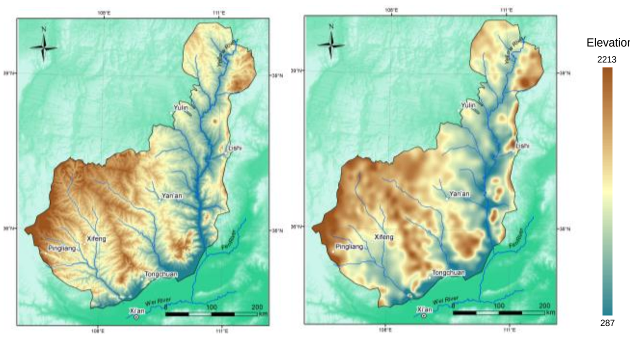
$$T(x, y) = a1 + a2x + a3y \tag{2}$$

$$R(r) = \frac{1}{2\pi}\left\{\frac{r^2}{4}\left[ln\left(\frac{r}{2\tau}\right)+c-1\right]+\tau^2\left[K_o\left(\frac{r}{\tau}\right)+c+\ln\left(\frac{r}{2\pi}\right)\right]\right\} \tag{3}$$

where: τ^2 and ϕ^2 are the parameters entered at the command line; *r* is the distance between the point and the sample, K_O is the modified Bessel function, *c* is a constant equal to 0.577215, a_i are coefficients found by the solution of a system of linear equations.

RESULTS

By using the above method to model the loess underlying paleotopography, the simulation result is shown in Figure 3(b), and Figure 3(a) shows the modern DEM as a contrast. The result shows that great differences could be found in the spatial distribution between the modern DEM surface and the underlying paleotograpphic surface intuitively. At the same time, the basic trend of these two terrains has similarities to some extent. All these differences and similarities reflect the landscape evolution result from the pre-quaternary to now.



(a) (b)

Figure 2. Illustrations of modern DEM and Simulated underlying palaeotopographic DEM

CONCLUSIONS

The Ordos platform in China was once a smoothly bedrock strata terrain in pre-quaternary, while after more than 2 million years of landscape evolution process of the loess deposition, loess accumulation and loess transportation, the morphology of the Ordos platform has been reshaped and thousands of ditches and valleys were formed which result to a more diverse terrain texture features of the platform.

The simulation result of loess palaeotopography can only be a result at macro-level due to the limited sampling methods and density. The development of modern geophysical techniques would provide better condition in the future study of loess landform evolution process investigating and modeling at other spatial scale. The construction of DEMs of Ma-lan, Li-shi and Wu-cheng loess strata should the carried on, which would deepen the understanding of the loess landform genesis and development mechanism.

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REFERENCES

[1] Berthling, I., Etzelmüller, B., 2011. The concept of cryo-conditioning in landscape evolution. Quaternary Research 75, 378-384.

[2] Bowman, D., Svoray, T., Devora, S., Shapira, I., Laronne, J. B., 2010. Extreme rates of channel incision and shape evolution in response to a continuous, rapid base-level fall, the Dead Sea, Israel. Geomorphology 114, 227-237.

[3] Braun, J., Sambridge, M., 1997. Modelling landscape evolution on geological time scales: a new method based on irregular spatial discretization. Basin Research 9, 27–52.

[4] Braun, J., van der Beek, P., Valla, P., Robert, X., Herman, F., Glotzbach, C., Pedersen, V., Perry, C., Simon-Labric, T., Prigent, C., 2012. Quantifying rates of landscape evolution and tectonic processes by thermochronology and numerical modeling of crustal heat transport using PECUBE. Tectonophysics 524–525, 1-28.

[5] Braun, J. Willett, S. D., 2013. A very efficient O(n), implicit and parallel method to solve the stream power equation governing fluvial incision and landscape evolution. Geomorphology 180–181, 170-179.

[6] Chen, H., Shao, M., Li, Y., 2008. The characteristics of soil water cycle and water balance on steep grassland under natural and simulated rainfall conditions in the Loess Plateau of China. Journal of Hydrology 360, 242-251.

[7] Chen, L., Wang, J., Wei, W., Fu, B., Wu, D., 2010. Effects of landscape restoration on soil water storage and water use in the Loess Plateau Region, China. Forest Ecology and Management 259, 1291-1298.

[8] Cheng, H., Zou, X., Wu, Y., Zhang, C., Zheng, Q., Jiang, Z., 2007. Morphology parameters of ephemeral gully in characteristics hillslopes on the Loess Plateau of China. Soil and Tillage Research 94, 4-14.

[9] Ciampalini, R., Follain, S., Le Bissonnais, Y., 2012. LandSoil: A model for analysing the impact of erosion on agricultural landscape evolution. Geomorphology 175–176, 25-37.

[10] Coulthard, T.J., Kirkby, M.J., Macklin, M.J., 2000. Modelling geomorphic response to environmental change in an upland catchment. Hydrological Processes 14, 2031–2045.

[11] Dymond, J. R., Rose, R. D., 2011. Modelling landscape evolution in the Waipaoa catchment, New Zealand — A phenomenalogical approach. Geomorphology 132, 29-34.

[12] Egholm, D. L., Pedersen, V. K., Knudsen, M. F., Larsen, N. K., 2012. Coupling the flow of ice, water, and sediment in a glacial landscape evolution model. Geomorphology 141–142, 47-66.

[13] Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., Alsdorf, D., 2007. The Shuttle Radar Topography Mission. Reviews of Geophysics 45, RG2004.

[14] Franke, R., 1982. Smooth Interpolation of Scattered Data by Local Thin Plate Splines. Comp. & Maths. with Appls, 8:237-281.

[15] Fu, B., Liu, Y., Lü, Y., He, C., Zeng, Y., Wu, B., 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecological Complexity 8, 284-293.

[16] Fujioka, T., Chappell, J., 2011. Desert landscape processes on a timescale of millions of years, probed by cosmogenic nuclides. Aeolian Research 3, 157-164.

[17] Hughes, M. W., Almond, P. C., Roering, J. J., Tonkin, P. J., 2010. Late Quaternary loess landscape evolution on an active tectonic margin, Charwell Basin, South Island, New Zealand. Geomorphology 122, 294-308.

[18] Kaufmann, G., Romanov, D., 2012. Landscape evolution and glaciation of the Rwenzori Mountains, Uganda: Insights from numerical modeling. Geomorphology 138, 263-275.

[19] Lehmkuhl, F., Hülle, D., Knippertz, M., 2012. Holocene geomorphic processes and landscape evolution in the lower reaches of the Orkhon River (northern Mongolia). CATENA 98, 17-28.

[20] Li, L.P., Lu, H.Y., 2010. A preliminarily quantitative estimation of the sedimentation and erosion rates of loess deposits in Chinese Loess Plateau over the past 250 ka. Acta Geographica Sinica, 1:37-52.

[21] Liu, L., Liu, X., 2010. Sensitivity Analysis of Soil Erosion in the Northern Loess Plateau. Procedia Environmental Sciences 2, 134-148.

[22] Liu, T., 1985. Loess and Environment. Beijing: Science Press. 481

[23] Liu, T., Sun, J., Wu, W., 2001. Past, present and future of the Chinese loess research: a discussion on the reality of facts and myth. Quaternary Sciences, 3:185-207.

[24] Maniatis, G., Kurfeß, D., Hampel, A., Heidbach, O., 2009. Slip acceleration on normal faults due to erosion and sedimentation — Results from a new three-dimensional numerical model coupling tectonics and landscape evolution. Earth and Planetary Science Letters 284, 570-582.

[25] Mitas, L., Mitasova, H., 1988. General Variational Approach to the Interpolation Problem. Comput. Math. Applic, 16:983-992.

[26] Nikolakopoulos, K.G., Kamaratakis, E.K., Chrysoulakis, N., 2006. SRTM vs ASTER elevation products. Comparison for two regions in Crete, Greece. International Journal of Remote Sensing 27, 4819-4838.

[27] Paik, K., 2012. Simulation of landscape evolution using a global flow path search method. Environmental Modelling & Software 33, 35-47.

[28] Perron, J. T., Kirchner, J. W., Dietrich, W. E., 2009. Formation of evenly spaced ridges and valleys. Nature 460, 502-505.

[29] Ravazzi, C., Marchetti, M., Zanon, M., Perego, R., Quirino, T., Deaddis, M., De Amicis, M., Margaritora, D., 2013. Lake evolution and landscape history in the lower Mincio River valley, unravelling drainage changes in the central Po Plain (N-Italy) since the Bronze Age. Quaternary International 288, 195-205.

[30] Refice, A., Giachetta, E., Capolongo, D., 2012. SIGNUM: A Matlab, TIN-based landscape evolution model. Computers & Geosciences 45, 293-303.

[31] Stolte, J., Liu, B., Ritsema, C. J., van den Elsen, H. G. M., Hessel, R., 2003. Modelling water flow and sediment processes in a small gully system on the Loess Plateau in China. CATENA 54, 117-130.

[32] Temme, A. J. A. M., Claessens, L., Veldkamp, A., Schoorl, J. M., 2011. Evaluating choices in multi-process landscape evolution models. Geomorphology 125, 271-281.

[33] Tucker, G.E., Lancaster, S.T., Gasparini, N.M., Bras, R.L., Rybarczyk, S.M., 2000. An object-oriented framework for hydrologic and geomorphic modelling using triangulated irregular networks. Computers and Geoscience 27, 959–973.

[34] Tucker, G.E., Slingerland, R.L., 1994. Erosional dynamics, flexural isostasy, and long-lived escarpments: a numerical modelling study. Journal of Geophysical Research 99, 12229–12243.

[35] Willgoose, G., Bras, I., Rodriquez-Iturbe, I., 1991. Results from a new model of river basin evolution. Earth Surface Processes and Landforms 16, 237–254.

[36] Xu, X., Zhang, H., Zhang, O., 2004. Development of check-dam systems in gullies on the Loess Plateau, China. Environmental Science & Policy 7, 79-86.

[37] Zheng, M., Cai, Q., Cheng, Q., 2008. Modelling the runoff-sediment yield relationship using a proportional function in hilly areas of the Loess Plateau, North China. Geomorphology 93, 288-301.

[38] Zhu, T., 2012. Gully and tunnel erosion in the hilly Loess Plateau region, China. Geomorphology 153–154, 144-155.