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Loess Thickness Variations Across the Loess Plateau of China

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Abstract The soil thickness is very important for investigating and modeling soil-water processes, especially on the Loess Plateau of China with its deep loess deposit and limited water resources. A digital elevation map (DEM) of the Loess Plateau and neighborhood analysis in ArcGIS software were used to generate a map of loess thickness, which was then validated by 162 observations across the plateau. The generated loess thickness map has a high resolution of 100 m × 100 m. The map indicates that loess is thick in the central part of the plateau and becomes gradually shallower in the southeast and northwest directions. The areas near mountains and river basins have the shallowest loess deposit. The mean loess thickness is the deepest in the zones with 400–600-mm precipitation and decreases gradually as precipitation varies beyond this range. Our validation indicates that the map just slightly overestimates loess thickness and is reliable. The loess thickness is mostly between 0 and 350 m in the Loess Plateau region. The calculated mean loess thickness is 105.7 m, with the calibrated value being 92.2 m over the plateau exclusive of the mountain areas. Our findings provide very basic data of loess thickness and demonstrate great progress in mapping the loess thickness distribution for the plateau, which are valuable for a better study of soil-water processes and for more accurate estimations of soil water, carbon, and solute reservoirs in the Loess Plateau of China.

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Keywords Soil thickness · Loess · Digital elevation map (DEM) · Neighborhood analysis · The Loess Plateau

1 Introduction

Soil thickness is very basic data in soil science, hydrology, and ecology but is hard to estimate (Power et al. 1980; Follain et al. 2006; Pelletier and Rasmussen 2009; Catani et al. 2010; Segoni et al. 2012). Determining soil thickness can give a boundary of soil-water processes, which is crucial for landslide prediction, water and solute transport and exchange modeling, together with estimations of soil water, carbon, and nitrogen reservoirs (Power et al. 1980; van Wesemael et al. 2000; Ho et al. 2012). Loess soils cover 10% of the Earth's surface lands, which nurture developed agriculture and industry and large populations (Liu 1985; Pécsi 1990). China has the largest and deepest loess deposit, the Loess Plateau (6.4×10^5 km^2) (Liu 1985). Loess is a medium with a high infiltration capacity (Xu et al. 2000; Fei et al. 2011; Wang et al. 2013). Water and solute can move fast and deeply in the loess profile and, meanwhile, plant roots can grow into deep soil layers (Liu et al. 2011; Wang et al. 2015; Zhang et al. 2017). In addition, the Loess Plateau is located in arid and semiarid regions and is characterized by the shortage of water resources, severe soil erosion, and large-scale revegetation, shaping fragile ecological and hydrological systems (Feng et al. 2016; Fu et al. 2017). Achieving sustainability of the ecosystems and reasonable use of soil and water resources must be based on comprehensive understanding of the processes of water and solute in the loess profile. Clearly, related investigations and modeling are very dependent on the involved boundary, i.e., the loess thickness.

Soil thickness is highly variable because of its vulnerability to terrain, bedrock, soil genesis, vegetation, soil erosion, and human activities. Usually, soil is relatively shallow in mountain areas and relatively thick in plains, e.g., the Loess Plateau of China. The Loess Plateau originates from aeolian dust deposit since 2.6 million years ago (Ding et al. 1999, 2002). Due to the differences in deposit and erosion rates, bedrock morphology, and distance to source zone of the dust, soil thickness changes largely across the plateau (Gan 1982; Zhang and Ma 1998). Richthofen (1877) first recorded a thick loess deposit when he explored geomorphology in Central and East Asia during 1868–1872 and considered that the loess thickness may reach up to 460 m. Liang (1946) investigated the loess thickness near Lanzhou and suggested that the thickness reached up to 270 m. Gan (1982) deduced the loess thickness based on geomorphologic development of the plateau and pointed out that the deepest loess was present in the middle reaches of the Luo and Jing Rivers; the loess thickness in the north central part of the plateau (Ji Yuan (tableland) in Dingbian County) could reach up to 300 m. Zhang and An (1994) reported that the loess was deep in the tableland regions and was shallow in mountain areas. Xiong et al. (2014) used outcropping data of underlying terrain to distinguish paleotopography and modern topography and then calculated loess thickness. In related studies, soil (or loess) thickness estimation is experimental and qualitative and the methods involved are often based on field survey and observations or on other data like terrain. Actually, determining soil thickness is always a challenge. Indirect methods are often based on terrain analysis (Moore et al. 1992; Pelletier and Rasmussen 2009), and direct methods include soil sampling or drilling. The latter is too expensive and time-consuming to be applied on a large scale. Terrain analysis is rarely applied in the Loess Plateau, and most studies describe loess thickness based on geomorphic features of the plateau (Gan 1982; Jing and Chen 1983; Zhang and Ma 1998) except for the investigation by Xiong et al. (2014).

Furthermore, few maps of loess thickness are presented in previous studies of the Loess Plateau. The maps of Zhang (1993) and Wang et al. (2010) are, to some extent, still qualitative. Xiong et al. (2014) gave a quantitative map of loess thickness for the plateau. However, their map is for only a part of the plateau and loess thickness data are absent to the west and east of the plateau. In addition, geophysical techniques like ground penetrating radar (GPR) and soil electric resistivity meter cannot retrieve loess thickness in the plateau because of limited measurement range and deep loess deposit. Hence, pursuing a proper and effective method to determine loess thickness is urgently needed not only to provide important and basic data but also to promote investigations related to soil-water processes in this region.

In this study, we used the digital elevation map (DEM) of the Loess Plateau and neighborhood analysis to derive a loess thickness map and then validated the map by field observation data of loess thickness. This study aimed to (1) show the procedure of loess thickness estimation, (2) map and analyze the distribution pattern of loess thickness across the plateau, and (3) validate the map and compare it with other information.

2 Materials and Methods

2.1 Study Area

The Loess Plateau is in a region to the south of which lie the Qinling Mountains, to the north the Yinshan Mountains, to the east the Taihang Mountains, and to the west the Riyue Mountains (34°–40°N, 102°–114°E, Fig. 1a). Its area is 6.4×10^5 km^2, and its elevation is in the range 800–2000 m on average. The plateau has a warm temperate continental monsoon climate. Its average temperature and precipitation are 8–14 °C and 200–700 mm, respectively; 65% of the precipitation falls between July and September. Loess is a loamy soil and silt accounts for a majority of the total, which makes it loose and have a good infiltration capacity and, meanwhile, be easily eroded. Soil erosion modulus is around 4000 t km^{-2} yr^{-1} (mass of the eroded sediments (ton) per square km per year) on average, and gully density is 2.3–10.9 km km^{-2} (total length of the gullies per square km). The

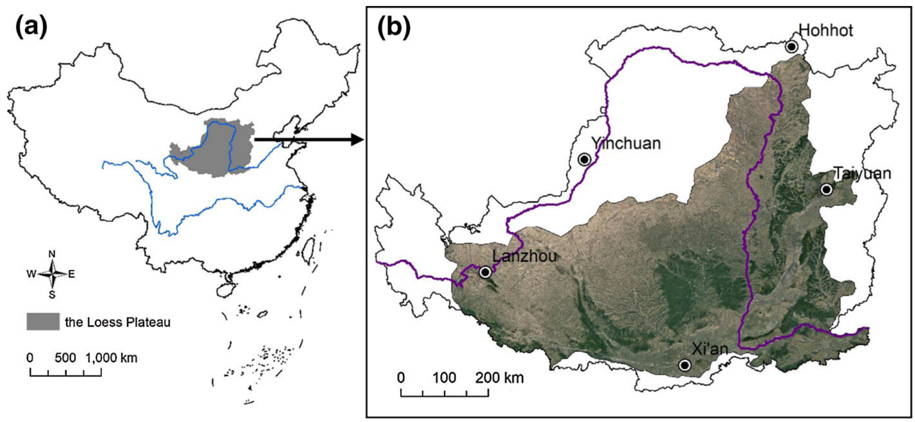

Fig. 1 Location of the Loess Plateau of China (**a**) and the region considered for loess thickness determination (**b**)

plateau is not completely covered by loess because of the effects of soil genesis and landform. As mentioned above, there are four large mountains surrounding the plateau. There are also some mountains (e.g., Liupan, Lvliang, Hengshan, and Zhongtiao Mountains) located inside the plateau. In these mountain areas, it is difficult for loess to accumulate because of steep slopes and forest vegetation. In addition, the northwest region of the plateau is covered by aeolian sandy soil due to its short distance from the source zone of the dust and rare precipitation. And the westernmost part of the plateau is mainly desert soil. Hence, there is deep and continuous loess deposit only in the middle reaches of the Yellow River, i.e., the core region of the plateau (Liu 1985) except for the mountains inside this region and aeolian sandy soil area. Therefore, the region considered for loess thickness determination is from the core region of the plateau with an area of 3.6×10^5 km^2 (Fig. 1b).

2.2 Loess Thickness Determination

Loess is vulnerable to erosion, resulting in rivers cut through deep loess profiles to form thousands of gullies in the plateau (Jing and Chen 1983; Zhang and Ma 1998). In most areas, river beds are exposed bedrock downstream. In this case, the vertical distance between a local point on the ground surface and the river bed is approximately equal to the loess thickness. Based on this assumption, we can use ArcGIS neighborhood analysis (NA) to calculate the loess thickness. Supposing that matrix A is a DEM raster data for a given area, we first find the minimum value (the lowest point, at the river surface in the downstream direction) of A by NA (Fig. 2). After that, we establish a matrix Amin, which is composed of only the minimum value, i.e., the bedrock elevation. Matrix B = A − Amin is then the loess thickness for the given area.

We used the DEM of the region of interest (Shuttle Radar Topography Mission [SRTM] Worldwide Elevation Data with 3-arc-second resolution) to generate the loess thickness map. We set 45×45 pixels as a basic areal unit (matrix A) for NA. The side length of

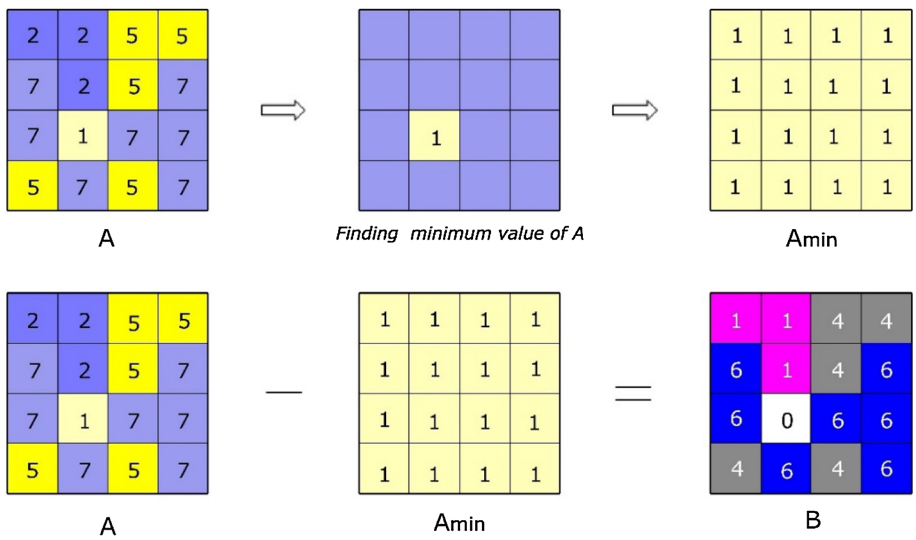

Fig. 2 Procedure of neighborhood analysis for determining loess thickness

each unit is 3420 m (=45 × 76 m; 76 m is the size of a single pixel). Each basic areal unit is around 11 km^2, which is approximately equal to the area of a basic geomorphologic unit (small catchment area) in the region. Within this basic areal unit, the river surface in the downstream direction (often the lowest point) is mostly at the position of the bedrock. If the area is too large, for example A3 in Fig. 3, the lowest point for this area is point B3. The result of NA cannot reflect bedrock geomorphology (changing trend over the region), resulting in an overestimation of the loess thickness (real thickness + h2). If the area is too small, for example A1 in Fig. 3, the lowest point for this area is point B1. Point B1 is higher than point B2 (bedrock position). In this case, point B1 is above the bedrock, resulting in an underestimation of the thickness (real thickness—h1).

After deriving the preliminary thickness map, we needed to remove mountain areas because these areas have very shallow loess deposits (< 1 m). Clearly, the topographic elevation in the mountain areas is high, and, to a large extent, greater than the maximum thickness. In the Loess Plateau, loess thickness is rarely more than 350 m according to previous records. Hence, if the thickness values calculated by NA are greater than 350 m, we appoint them as 0 (representing the mountain areas). By this method, we calculated the areas of the mountains inside the region, which is 3.5×10^4 km^2 (accounting for 9.9% of the total area). The mountain areas determined by this method match the real distribution of the main mountains (Liupan, West Qinling, Lvliang, Hengshan, and Zhongtiao) in the plateau well. The output resolution of the map is set as 100 m × 100 m.

2.3 Loess Thickness Observation

In order to obtain observed thickness data, a grid sampling method is applied to divide the region of interest into uniform grids. The size of each grid is 45 km × 45 km. Only one site is selected in each grid, and the principles of site selection are: (1) relatively flat landform, (2) easy accessibility, and (3) far from human disturbance. Within each grid, we first determined the position of bedrock in the downstream and recorded its elevation (the first point) by a portable GPS receiver (Stonex-S3II, Stonex Co., Ltd, resolution in elevation and horizon < 20 mm). Then, we moved to a relatively flat place which was at least 200 m away from the gully and recorded its elevation (the second point, representing the site). The elevation difference between these two points was approximately equal to the loess thickness at this site, and the geographic coordinates of this site were recorded. In this way, we obtained the observed values of loess thickness at 162 sites across the region (Fig. 4).

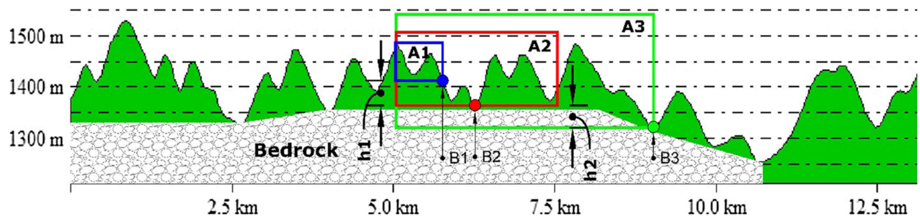

Fig. 3 Side view of landform for a given area and the estimated thicknesses by different basic areal units (A1, A2, and A3)

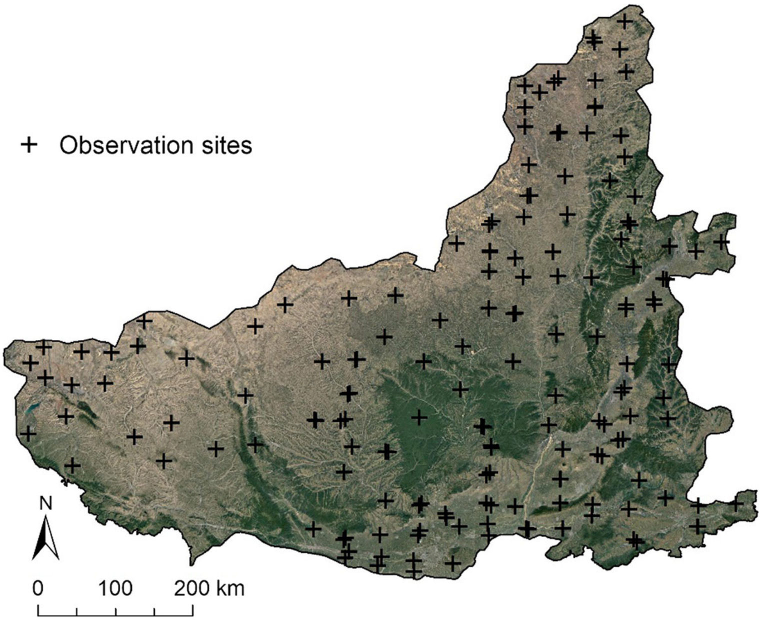

Fig. 4 Observation sites for loess thickness across the region

3 Results

3.1 Loess Thickness Distribution

Figure 5 shows the distribution map of loess thickness across the Loess Plateau region. The white color in the map represents the mountain areas. Loess is thick in the central belt zone (two sides along the blue dotted line) from northeast to southwest and then becomes gradually shallower in the northwest and southeast directions from the blue dotted line. There are, generally, three regions with the deepest loess: Ji Yuan (red circle, north of Qingyang), an adjacent area of Dongzhi Yuan, Xunyi and west of Ziwu Mountains (green circle), and north of Dingxi (blue circle). In these areas, the loess thickness is often more than 200 m on average and even up to 300 m or more in some parts of the areas. The areas near the mountains and river basins such as two sides of the Weihe and Fenhe Rivers have shallow loess deposits. In addition, there is a relatively deep loess deposit in areas to the southeast of the Fenhe River.

Figure 6a is the histogram of loess thickness (thickness versus area) in the region. The calculated thickness is 105.7 m on average over an area of 3.2×10^5 km^2 (not including the mountain areas) or 95.4 m on average over the entire region (3.6×10^5 km^2). The area with the thickness > 300 m is very small (blue ball in Fig. 6a), indicating that it is adequate to state that the maximum thickness is 350 m because this has negligible effects on the loess thickness estimation. Mean loess thicknesses in the different rainfall zones were also calculated (Fig. 6b). The zones receiving 400–600-mm precipitation have the deepest loess (mean thickness > 100 m). And the mean loess thickness becomes gradually shallower where the precipitation is outside the range of 400–600 mm.

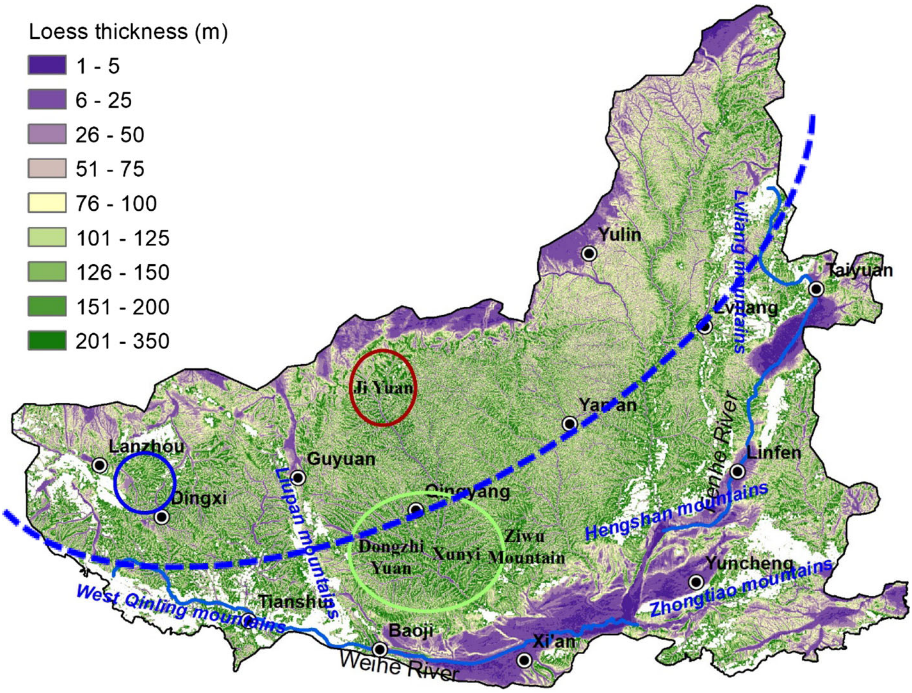

Fig. 5 Map of loess thickness distribution across the region

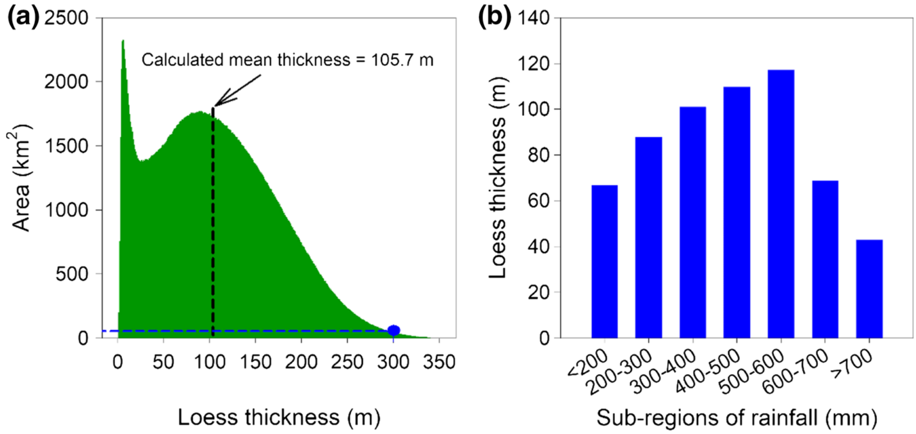

Fig. 6 Histogram of loess thickness (**a**) and mean loess thicknesses in different subregions of rainfall (**b**)

3.2 Validation of Loess Thickness

We used observed loess thickness values to validate the calculated values. The observed thickness values had been obtained at the 162 sites across the region (see Sect. 2.3). We calculated loess thickness values at the same sites for the validation. Thus, we input the geographic coordinates of these 162 sites and extracted their thickness values from the loess thickness map presented in Fig. 5 by ArcGIS extraction tool. The extracted values, i.e., the calculated values, were compared with the observed values in Fig. 7. They are distributed basically along the 1:1 line. The linear regression relationship between the calculated and the observed values could be expressed as:

$$\mathrm{ST}_c = 1.147 \times \mathrm{ST}_o \quad (1)$$

where ST_c and ST_o are the calculated and observed thickness (m), respectively.

The squared correlation coefficient of the regression (R^2) is 0.76 ($P < 0.01$), and the root mean square error (RMSE) of the predicted values using Eq. (1) is 5.7 m. All of these indicate that the thickness determined by our method is, to a large extent, reliable and accurate and can reflect the loess thickness distribution across the region. In addition, this equation could also be used to calibrate the calculated thickness value. The calibration equation should be the inverse of Eq. (1) as:

$$\mathrm{CST} = \mathrm{ST}_c/1.147 \quad (2)$$

where CST is the calibrated thickness (m).

3.3 Comparison of Loess Thickness Maps

Many methods were previously used to estimate the loess thickness in the Loess Plateau. Here, we compare the results obtained by these methods. The map of loess thickness determined by the NA in this study is basically in accordance with the other results (Fig. 8). There are four areas (blue circles) with thick loess in our map (Fig. 8a), which could be found in the same areas in the other two maps published by Wang et al. (2010) and Zhang (1993) (Fig. 8b, c). We also compared our result with the calculated mean loess thickness over part of the Loess Plateau obtained by Xiong et al. (2014) in Fig. 8d, e. It can be seen that our map is very similar to theirs, especially in the dotted line circle regions. The mean loess thickness found by their method in their study area is 104.6 m and is slightly overestimated to 117.4 m by our method over the same area. However, the calibrated mean thickness using Eq. (2) is 102.4 m (=117.4 m/1.147), which is very close to 104.6 m obtained by Xiong et al. (2014).

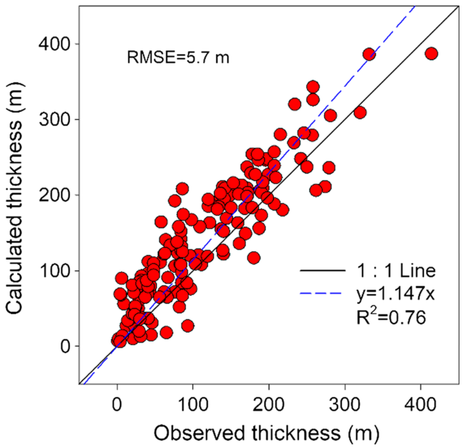

Fig. 7 Loess thickness validation

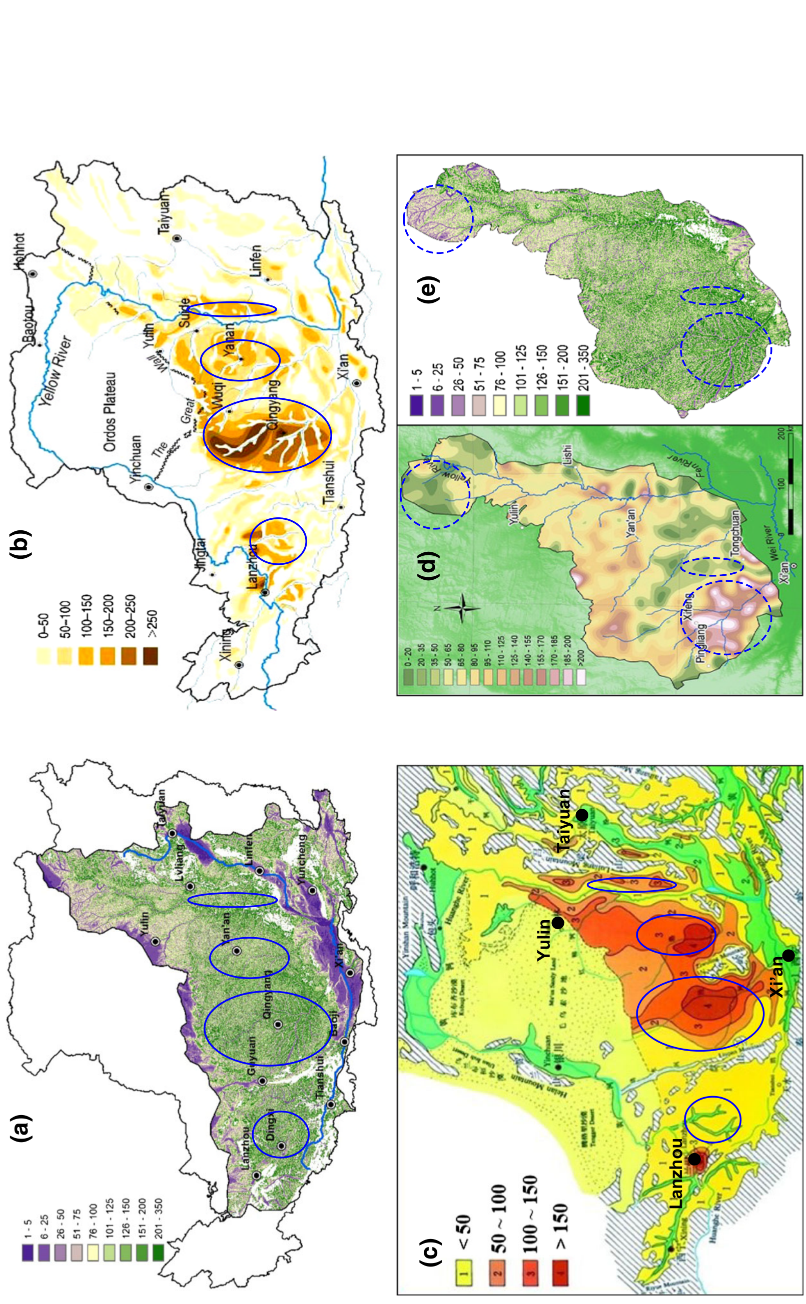

Fig. 8 Comparison of the loess thickness map in this study (**a**) with those by Wang et al. (2010) (**b**), by Zhang (1993) (**c**), and the loess thickness maps over the same area by Xiong et al. (2014) (**d**) and by this study (**e**)

4 Discussion

Estimating soil thickness is always a challenge because of the lack of a proper method and technique and various soil types and landforms. Among all methods, terrain analysis is a powerful tool for determining soil thickness. However, this method must satisfy several prerequisites: (1) significant differences in the materials comprising soil and bedrock, (2) relatively thick soil layer and flat landform (without severe fluctuation of bedrock geomorphology), and (3) bedrock exposure and soil above bedrock. Otherwise, the thickness determined by this method is less reliable. It is clear that the Loess Plateau is a good region for applying this method because (1) loess is relatively homogeneous and deep, (2) landform is relatively flat over the majority of the plateau, (3) loess is significantly different from bedrock in its constituent matter, and (4) bedrock exposures due to intensive soil erosion and thousands of gullies across the plateau. The last feature is particularly important because we can divide the plateau into small basic units and determine loess thickness in each unit and then combine each one into a whole map of loess thickness. In this way, we can suppress the effect of bedrock geomorphology at a larger scale because there is a general trend of bedrock elevation decreasing from northwest to southeast across the whole region (Fig. 9). Furthermore, loess, as a deposit matter of aeolian dust, is particular deep in the Loess Plateau, coupled with the shortage of water resources, resulting in a deep unsaturated zone in which water, soil, and plant (roots system) interact with each other. Hence, loess thickness data are, undoubtedly, valuable, and necessary for investigating soil-water processes such as water and solute transport and exchange and reservoirs of soil water, carbon, and nitrogen for the Loess Plateau of China.

In this study, we use terrain analysis to determine loess thickness. A key step is selecting a proper basic areal unit to perform the neighborhood analysis. As mentioned in Sect. 2.2 (Loess Thickness Determination), if this basic areal unit is too large or too small, the thickness would be over- or underestimated (see Fig. 3). We take the length of 45 single pixels of the DEM as the size of this basic areal unit (with an area of around 11 km^2) because its area is the closest to the area of a small watershed on the plateau. In a small watershed, there are several landforms including relatively flat highland, gullies, and a main stream channel. Here, we show the change of bedrock elevation derived by neighborhood analysis and draw a transect (blue line) from northwest to southeast to demonstrate why selecting this basic areal unit is reasonable (Fig. 9). It is clear that the landforms of the Loess Plateau could be generally divided into two terraces. The first terrace is a plateau with an elevation difference of 657 m over a 313-km transect. The second terrace is the Weihe river basin. The latter is relatively flat, and the selection of the basic areal unit has only a minor effect on the thickness determination. Thus, we mainly discuss the case of the former. For the first terrace, we calculate that the bedrock elevation declines at a rate of 2.1 m km^{-1} (=657 m/313 km) in around 45° direction (the angle of the blue line) on average. Obviously, the bedrock elevation difference increases with the area of the basic areal unit. In this study, the side length of the basic areal unit is 3420 m, the length of the diagonal line is 4.836 km (=3420 m $\times \sqrt{2}$), and consequently, the maximum bedrock elevation difference at the central point of the basic areal unit should be 5.1 m (=(4.836 km $\times$ 2.1 m km^{-1})/2), which is lower than the value of RMSE (5.7 m) in the thickness validation. Hence, selecting this basic areal unit is reasonable. A smaller areal unit can reduce the effect of bedrock geomorphology, but it may result in the lowest point above the bedrock, i.e., there is no bedrock exposure within the basic areal unit (Fig. 3).

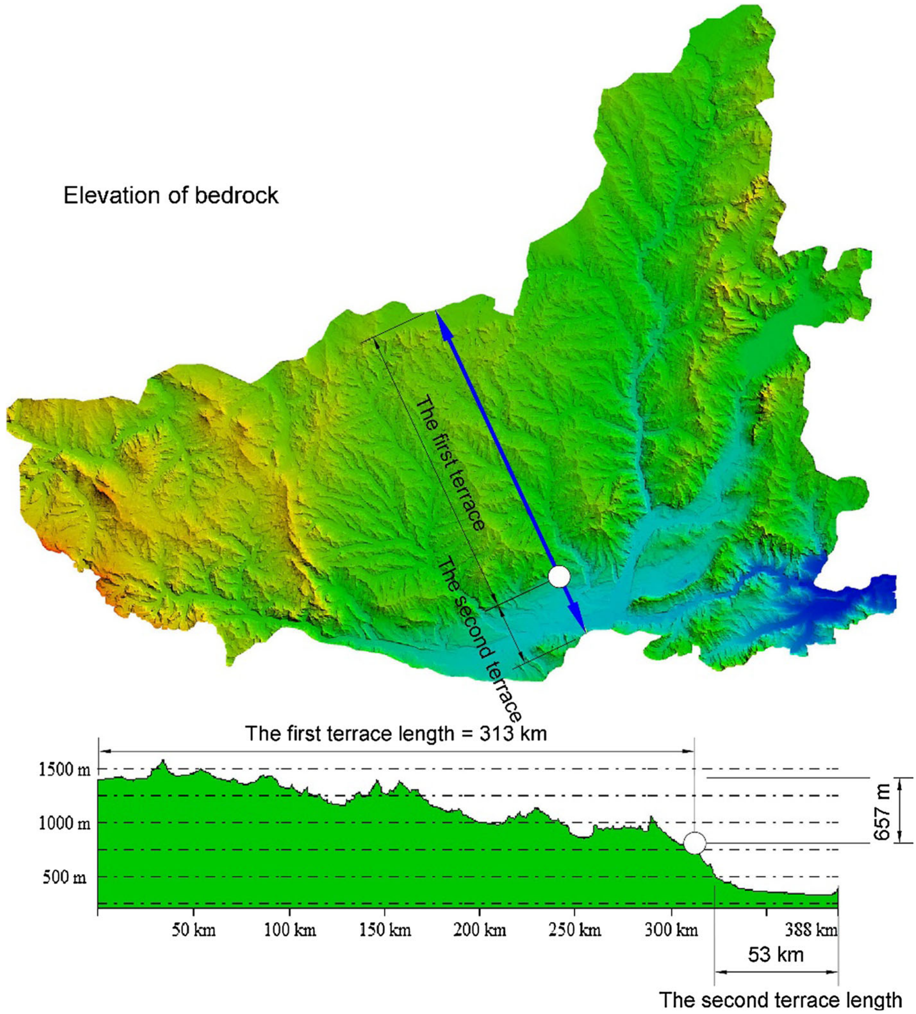

Fig. 9 A northwest–southeast transect across the plateau and bedrock elevation change along the transect

This is the first time that a detailed map of loess thickness with a resolution of 100 m × 100 m for the Loess Plateau of China has been presented. The loess thickness distribution in our map is basically in accordance with the other maps (Zhang 1993; Wang et al. 2010). Our map indicates that the central part of the plateau has the deepest loess deposit and loess becomes gradually shallower in the southeast and northwest directions, which strengthens the principle of aeolian deposit, i.e., the central zone of dust deposit has the deepest dust and the zone near or far away to the source area of dust has shallower dust deposits, which could be mainly attributed to a particle filtering mechanism during the processes of wind blowing and aeolian deposit. We draw an arched dotted line based on the distribution map of loess thickness (Fig. 5). This line could be, to some extent, used to calculate the source area of the dust, given knowledge of the dust particle composition and atmospheric circulation mode. Furthermore, we find that the loess thickness is slightly overestimated by our method because the regression coefficient between the observed and the calculated is 1.147 (a little higher than 1). The reason for this overestimation could be attributed to the river cutting the loess profile to the position beneath the bedrock. In this case, part of the bedrock depth is regarded as loess thickness. On the other hand, this coefficient could be used to calibrate the loess thickness determined by the method. Hence, the calculated thickness is recommended to be calibrated by Eq. (2) for a higher accuracy. In this sense, the calibrated mean loess thickness should be 92.2 m (=105.7 m/1.147) over the region exclusive of the mountain areas. This value is also among the range of loess thickness of 50–200 m on average reported in most studies.

5 Conclusions

A detailed loess thickness map with a resolution of 100 m $\times$ 100 m was generated from the DEM of the Loess Plateau using neighborhood analysis. The distribution map of loess thickness suggests that the loess is thick in the central part of the region and becomes gradually shallower to the southeast and northwest. The areas near the mountains and river basins have a shallower loess deposit. The mean loess thickness is the deepest in the zones receiving 400–600-mm precipitation and decreases gradually as precipitation varies beyond this range. Our method produces a slightly overestimate of loess thickness but an accurate distribution map of loess thickness across the plateau. Loess thickness is mostly up to 350 m. The calculated mean loess thickness is 105.7 m and the calibrated value is 92.2 m over the plateau exclusive of the mountainous areas.

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