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GEOMORPHOLOGY

Transitional relationships among typical loess geomorphologic types: Loess Plateau of China

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ABSTRACT

Taking the distribution area of typical loess geomorphologic types in the Loess Plateau of China as the study area, this research aims to explore the transitional relationships among typical loess geomorphologic types based on their constructed digital index systems using the data sources of digital geomorphologic database, Landsat TM/ETM+ images and SRTM1 DEM data. Based on Landsat TM/ETM+ images, the digital geomorphologic database was firstly checked and improved using visual interpretation combined with expert knowledge methods, so as to acquire the precise spatial distribution of the typical loess geomorphologic types. Then, the digital index systems for the typical loess geomorphologic types were constructed, which included topographic indexes, quantitative indexes from topographic profile method and remote sensing indexes. Finally, the transitional relationships among the typical loess geomorphologic types were explored based on the constructed digital index systems and the spatial distribution pattern on the remote sensing images. The research results show that loess tableland may transform to loess ridge or loess knoll, and loess ridge may transform to loess knoll. As to morphologic types, loess tableland may transform to loess residual tableland, and then to loess beam tableland; loess wide acclivitous ridge may transform to loess narrow acclivitous ridge, and then to loess knoll ridge. For the valley shape types of the loess ridge and loess knoll, the shallow and high valley may transform to deep and high valley, and then to shallow and low valley. This research is meaningful in the fields such as digital mapping of loess geomorphology, water and soil loss, soil erosion and digital topographic analysis.

Keywords: transitional relationship; digital index systems; typical loess geomorphologic type; digital geomorphologic database; Landsat TM/ETM+ images; SRTM1 DEM data; Loess Plateau

Relaciones de transición entre tipos geomorfológicos típicos de loess: meseta de loess de China

RESUMEN

Este trabajo toma como objeto de estudio el área de distribución de los tipos geomorfológicos de loess típicos en la Meseta de Loess de China, con el objetivo de explorar las relaciones de transición entre los tipos geomorfológicos de loess típicos en función de sus sistemas de índices digitales a través de bases de datos geomorfológicos digitales, imágenes Landsat TM/ETM+ y datos DEM SRTM1. Con base en las imágenes Landsat TM/ETM+, la base de datos geomorfológica digital fue verificada y mejorada a través de interpretación visual combinada con métodos de expertos para adquirir la distribución espacial precisa de los tipos geomorfológicos típicos de loess. Luego se construyeron los sistemas de indexación digital para esta clase de loess, los cuales incluyen índices topográficos, índices cuantitativos tomados de métodos de perfil topográfico e índices remotos. Finalmente, se exploraron las relaciones transicionales entre los tipos gemorfológicos de loess con base en los sistemas de indexación digital construidos y los patrones de distribución espacial en las imágenes de detección remota. Los resultados de la investigación muestran que los loess tipo meseta pueden transformarse en loess tipo crestas o montículos, y las crestas pueden transformarse en loess tipo montículos. En cuanto a los tipos morfológicos, los loess tipo meseta pueden transformarse en meseta residual y luego en meseta viga; los loess tipo cresta ancha e inclinada pueden transformarse en cresta estrecha e inclinada y luego en cresta de montículo. Para los tipos de forma de valle de la cresta loess y montículo loess, el valle superficial y alto puede transformarse en valle profundo y alto, y luego en valle superficial y bajo. Esta investigación es significativa en campos como el mapeo digital de la geomorfología del loess, la pérdida de agua y suelo, la erosión del suelo y el análisis topográfico digital.

Palabras clave: Relación transicional; sistemas de indexación digital; tipos geomorfológicos de loess; bases de datos geomorfológicas digitales; imágenes Landsat TM/ETM+; información SRTM1 DEM; Meseta de Loess

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1. Introduction

The popularization and advances of Geographic Information System (GIS) and remote sensing technologies have mean that they were widely used in geomorphologic researches (Remondo & Oguchi, 2009). Based on the digital elevation model (DEM), data and digital topographic analysis, spatial distribution of volcanic landforms, complexity and distribution pattern of natural landform, distribution characteristics of Aeolian sand dune and other geomorphologic-related fields have been extensively studied (Werner, 1999; Kocurek & Ewing, 2005; Bishop, 2007a, 2007b, 2009; Bullard et al., 2011). Meanwhile, topographic indexes, such as slope, fluvial knick zone and shape, are extracted from DEM data, whose spatial distribution and characteristics are analyzed specifically (Saito & Oguchi, 2005; Hashimoto et al., 2008; Lin et al., 2009; Hayakawab & Oguchi, 2009). Furthermore, based on DEM data and remote sensing images, geomorphologic objects are classified and identified from geomorphometric characteristics (Székely & Karátson, 2004; Saadat et al., 2008; Hampton & Cole, 2009; Dragut & Eisank, 2011, 2012).

In soil erosion region, geomorphologic research is meaningful in erosion evaluation and in soil and land-use mapping (Remortel et al., 2004; Saadat et al., 2008). Soil erosion and water flow in a basin are modeled based on the topographic variants using DEM datasets (Zhu et al., 1997; Pennock & Corre, 2001). Landform automatic or semi-automatic classification is widely studied based on derived parameters (elevation, slope, curvature and so on) from DEM datasets (Macmillan et al., 2000, 2004; Shary et al., 2002; Ballantine et al., 2005).

Loess Plateau is one of the most famous soil erosion regions in China. Heavy water and soil loss forms typical loess geomorphologic types in the world. Unique morphologic features, abundant natural resources, dense population and serious soil erosion problems make Loess Plateau an important region to conduct geomorphologic research (Tang et al., 2005), and most researches are focused on loess geomorphologic classification and identification based on slope spectrum index, which is a histogram statistics method based on slope variant (Li et al., 2007; Tang et al., 2008; Wang et al., 2008; Zhou et al., 2010).

The adventure of the Chinese Geomorphologic database at 1:1 M scale provides spatial distribution of the geomorphologic types in vast region (Cheng et al., 2011a). Based on the database and Shuttle Radar Topography Mission at 3" spatial resolution (SRTM3 DEM) data, Zhao & Cheng (2014) attempted to build the transitional relationship among typical loess geomorphologic types using slope spectrum index in the whole Loess Plateau, which is helpful in understanding the relationship among the geomorphologic types. However, in the research by Zhao & Cheng (2014), the geomorphologic types are simple and coarse; meanwhile, the spatial distribution of the geomorphologic types is not accurate enough, which is at 1:1M scale; further, the criteria only chooses slope spectrum, so there are many other indexes to improve the achievements.

Choosing a representative distribution area of typical loess geomorphologic types in the Loess Plateau as the study area, this research aims to construct the digital index system based on the improved geomorphologic database, so as to explore the transitional relationships among the typical loess geomorphologic types specifically. This research is meaningful in automatic digital mapping and classification, understanding the loess geomorphology, soil erosion, and water and soil loss and so on.

2. Study area and primary data sources

2.1 Study area

Loess Plateau distributed in the northern and middle part of China, which is the most widespread distribution region of the loess geomorphology (Fig. 1). The typical loess geomorphology types are mainly loess tableland, loess ridge and loess knoll in the Loess Plateau (Zhao et al., 2017). The distribution of the typical loess geomorphology types is shown in Figure 1.

Loess Plateau is a big region with widely distributed typical loess geomorphologic types. It is difficult to conduct deep research in this vast region, so we choose a test area which is representative in typical loess geomorphologic type distribution. The test area is the region in the black rectangle in Figure 1. The topographic characteristic of the test area is shown in Figure 2:

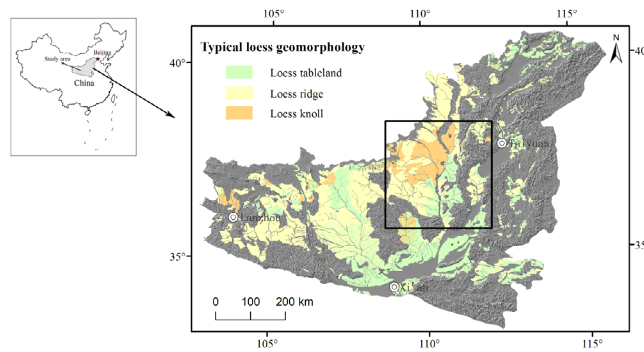

Figure 1. Location and the typical loess geomorphology distribution in the loess plateau of China.

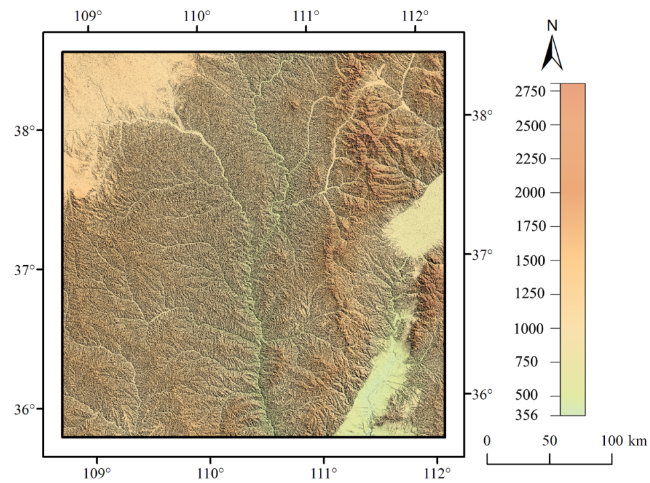

Figure 2. Relief shader map in the test area.

Based on the SRTM1 DEM data, the relief shader map is produced using DEM data in Global Mapper software. Figure. 2 shows that the typical loess geomorphologic types mainly distribute in the fragmental areas with abundant incised valleys, and the elevation mainly ranges from about 500 m to 2000 m. the fragmental topography is due to soil erosion and water and soil loss, which also result in fragile ecology and environment. The soil erosion and water and soil loss are the main causes to form the typical topography and loess geomorphologic types, so there are many researches about topography and geomorphology in this region using digital topographic analysis methods (Tang et al., 2005, 2008; Zhao & Cheng, 2014). Hence, it is meaningful to acquire the digital index system for the typical loess geomorphologic types in this area.

2.2 Primary data sources

The primary data sources in this research are digital geomorphologic database, Landsat TM/ETM+ images and SRTM1 DEM data.

2.2.1 Digital geomorphologic database

Digital geomorphologic database means Chinese 1:1,000,000 geomorphologic database, which is used to provide the spatial distribution of the typical geomorphologic types in the study area. The database is acquired using visual interpretation method at about 1:250,000 scales. The main data sources are Landsat TM/ETM+ images, SRTM3 DEM data, geologic data, published geomorphologic maps and so on (Cheng et al., 2011a). The classification method adopted morpho-genetic types, which can be divided into seven layers, they are, basic morphology and altitude, genesis, sub-genesis, morphology, micro-morphology, slope and aspect, material and lithology (Cheng et al., 2011b).

The digital database is seamless with consistent classification system, so it can be clipped for any regions with the same quality. In this research, the fundamental data for typical loess geomorphologic type distribution is acquired from this database.

2.2.2 Landsat TM/ETM+ images

Remote sensing images are used to revise and improve the digital geomorphologic database data; meanwhile, the remote sensing characteristics for the typical loess geomorphologic types are acquired based on the remote sensing images; finally, the transitional relationship among the typical loess geomorphologic types can be explored by referencing the spatial distribution pattern of them in the remote sensing images.

The main remote sensing images select the Landsat TM/ETM + images, which are global false colour composite images and downloaded from Chinese Scientific Data Base. The acquisition periods of the Landsat TM images are mainly about 1990; as to the Landsat ETM + images, about 2000. They are also the data sources in remote sensing visual interpretation process of the Chinese 1:1,000,000 geomorphologic database data. The composited bands of the remote sensing images are 7, 4 and 2. The combined effect of the images is similar to natural colour, which provides convenience for the visual interpretation and revision of the typical loess geomorphologic types.

2.2.3 SRTM1 DEM data

SRTM1 DEM data is downloaded from the Earth Explorer of the USGS, USA. It has spatial resolution of 1" and continuous surface. Through downloading, merging, projection and clipping, the SRTM1 DEM data in the study area is shown in Figure 2.

The SRTM1 DEM data not only provides topographic characteristics for the study area, but the elevation index and other indexes computed based on the DEM data. It is an important data sources in constructing the index system for the typical loess geomorphologic types.

3. Methodology

The quality and scale of the digital geomorphologic database are improved through different methods. Based on the improved digital geomorphologic database, the spatial distribution of the typical loess geomorphology is acquired and illustrated accordingly.

3.1 Improvement methods to the digital geomorphologic database

The digital geomorphologic database adopted in this research is interpreted at about 1:250,000 scales. The spatial resolution of the images is about 30m, which provides feasibility to improve the database at higher scales. So the database is revised using the Landsat TM/ETM + images at about 1:50,000 scales.

The improvement methods to the digital geomorphologic database include improving the boundary of the units, revising the mis-classifying units and choosing the typical units for the typical loess geomorphologic types.

3.1.1 Improvement to the boundary

At higher scale, the original boundary shows coarse and low quality. All the boundaries of the typical loess geomorphologic types are checked, and the boundary improvement is conducted especially for loess tableland. The change of the boundary can be shown in Figure 3:

Figure 3 shows through boundary improvement, the boundary of the loess tableland becomes more accurate than before. The boundary represents the spatial distribution of the typical loess geomorphology, whose quality affects the construction of the digital index system.

(a)

(b)

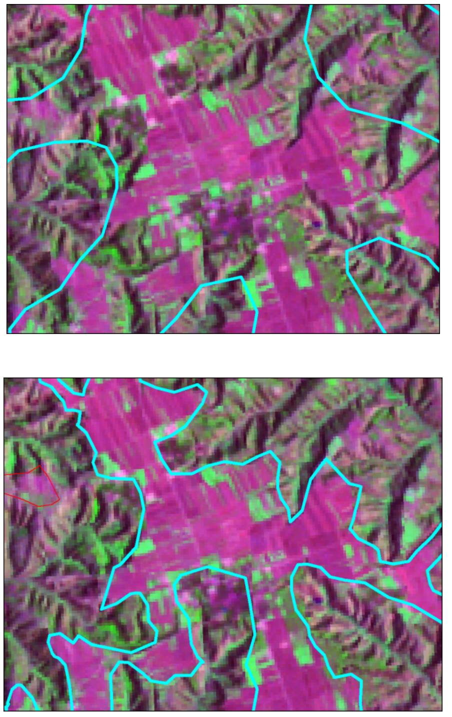

Figure 3. Boundary improvement to the units (a. before improvement; b. after improvement).

3.1.2 Revising the mis-classifying units

The digital geomorphologic database covers the whole China territory. It is not easy to guarantee the attributes of all the units are correct. So the attribute of every unit is checked carefully to guarantee the quality of the data.

To the mis-classifying units, their attributed would be changed to right if the correct attributes can be determined; otherwise would be deleted on the occasion that the proper attributes are not clear or difficult to determine. The distribution of the typical loess geomorphologic types needs not to cover the entire study area.

3.1.3 Choosing the typical units

The revised digital geomorphologic database is checked firstly and the typical loess geomorphologic types are distilled. Then, all the units for every loess geomorphologic type are compared and judged. The typical units are chosen to represent the spatial distribution of the typical loess geomorphologic types, which can guarantee the quality of the constructed digital index system.

3.2 Spatial distribution of the typical loess geomorphology

Through improvement, the spatial distribution of the typical loess geomorphologic types acquired (Figure 4).

The classification method and distribution status for the typical loess geomorphologic types in the study area presented in Table 1, which also gives the codes for the typical loess geomorphologic types. The meanings of the codes are consistent and will be omitted in the following text.

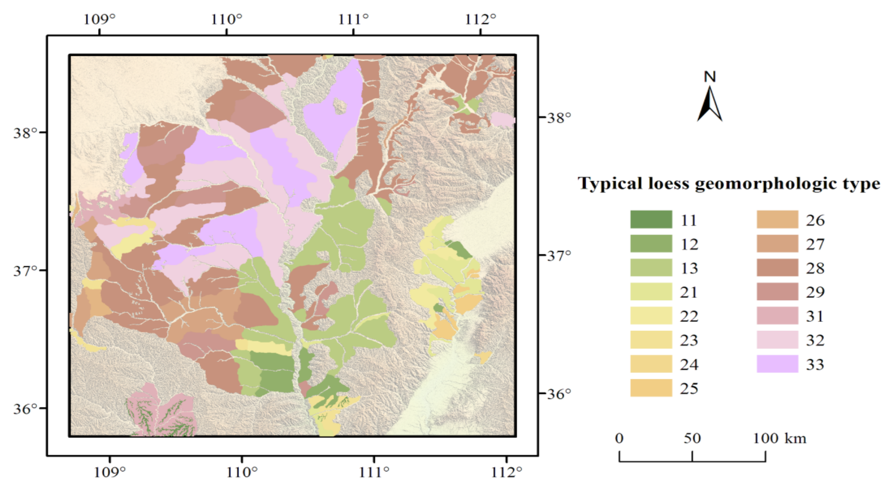

Figure 4. Typical loess geomorphologic distribution type in the test area.

Table 1 Classification and distribution for the typical loess geomorphologic types

Typical loess geomorphology	Morphology	Valley shape		Type	Code	Patch number	Area(km²)
		Depth	Height				
Loess tableland				Loess tableland	11	29	254.9
	Residual			Loess residual tableland	12	8	1504.9
	Beam			Loess beam tableland	13	25	6172.0
Loess type	Narrow acclivitous	Shallow	Low	Loess narrow acclivitous ridge with shallow and low valley	21	13	1408.0
	Narrow acclivitous	Shallow	High	Loess narrow acclivitous ridge with shallow and high valley	22	7	1303.0
	Narrow acclivitous	Deep	High	Loess narrow acclivitous ridge with deep and high valley	23	7	838.7
	Wide acclivitous	Shallow	Low	Loess wide acclivitous ridge with shallow and low valley	24	2	62.6
	Wide acclivitous	Shallow	High	Loess wide acclivitous ridge with shallow and high valley	25	6	537.3
	Wide acclivitous	Deep	High	Loess wide acclivitous ridge with deep and high valley	26	3	298.1
	Knoll type	Shallow	Low	Loess knoll ridge with shallow and low valley	27	12	2262.3
	Knoll type	Shallow	High	Loess knoll ridge with shallow and high valley	28	47	11872.3
	Knoll type	Deep	High	Loess knoll ridge with deep and high valley	29	8	3093.3
Loess knoll		Shallow	Low	loess knoll with shallow and low valley	31	10	1751.3
		Shallow	High	loess knoll with shallow and high valley	32	18	7176.9
		Deep	High	loess knoll with deep and high valley	33	7	5314.6

Figure 4 and Table 1 show that the loess tableland mainly distributes in middle and southern parts; the loess knoll, middle and northern parts; the loess ridge, northern and western parts. The loess tableland is divided by morphology; the loess knoll, valley shape; the loess ridge, both the morphology and valley, which has the most sub-types. The types are systematic, but their distribution status has large difference. For example, the loess wide acclivitous ridge with shallow and low valley only has two units with the area of 62.6 km^2; whereas the loess knoll ridge with shallow and high valley has 47 units with the area of 11872.3 km^2. The difference is due to the geomorphologic distribution characteristics in the study area.

4. Results

Digital index system is firstly constructed based on the digital geomorphologic database, and then the transitional relationships are achieved for the typical loess geomorphologic types.

4.1 Digital index system for the typical loess geomorphologic types

In this research, the digital index system for the typical loess geomorphologic types includes the topographic indexes, the quantitative indexes based on the topographic profile methods and the remote sensing indexes.

4.1.1 Topographic indexes

The topographic indexes are computed based on the SRTM1 DEM data, which include elevation, relief, slope and curvature indexes.

4.1.1.1 Elevation index

Elevation is a basic topographic index, which can be acquired directly from the SRTM1 DEM data. The spatial distribution of the elevation index can be seen in Figure 2. Through making a numerical statistics for the elevation index of every typical loess geomorphologic type, the results are in Table 2.

Table 2. Numerical statistics for elevation index of typical loess geomorphologic types (m)

Code	Min	Max	Range	Mean	Std.
11	770	1414	644	1200.2	87.1
12	421	1408	987	936.7	128.4
13	516	1631	1115	1017.4	145.9
21	484	1509	1025	950.2	130.2
22	684	1684	1000	1182.0	155.4
23	609	1592	983	1117.2	202.8
24	587	1401	814	830.4	124.6
25	515	1345	830	839.7	145.3
26	779	1689	910	1430.0	126.5
27	784	1740	956	1181.7	175.9
28	532	1819	1287	1182.5	150.0
29	446	1598	1152	1153.8	115.3
31	840	1739	899	1226.5	180.3
32	610	1638	1028	1066.5	156.4
33	721	1553	832	1111.5	98.3

Table 2 shows that the typical loess geomorphology types mainly distribute from 400 m to 1800 m; the mean elevation value ranges from about 800 m to 1400 m. The standard deviation value increases from 11 to 13, but decreases from 31 to 33 evidently; as to the loess ridge type, it increases from 21 to 23, decreases from 27 to 29, but undulates from 24 to 26. The morphology type of the typical loess geomorphology types changes at every three types (Table 1), so we analyze the statistics characteristics of the topographic indexes at the group of every three types.

4.1.1.2 Relief index

Other than elevation, the flat degree of the topography is a more important factor in determining the loess geomorphologic types. So the relief index is adopted here. Based on SRTM1 DEM data, the relief index is computed using neighborhood statistics under the spatial analyst tools in the ArcGIS software. Conducting a numerical statistics to the relief index, the results of the typical loess geomorphologic types are in Table 3.

Table 3. Numerical statistics of relief index for typical loess geomorphologic types (m)

Code	Min	Max	Range	Mean	Std.
11	6	202	196	91.9	39.6
12	9	280	271	127.1	35.2
13	10	273	263	133.3	26.6
21	23	310	287	119.6	28.5
22	26	292	266	125.8	34.6
23	49	276	227	143.0	26.7
24	46	299	253	117.8	25.7
25	18	300	282	108.9	30.4
26	36	262	226	148.6	27.9
27	26	288	262	144.6	25.0
28	13	276	263	124.2	32.2
29	24	264	240	113.8	29.8
31	11	293	282	127.9	27.0
32	17	287	270	119.4	26.2
33	14	254	240	113.2	25.3

Table 3 shows that the relief range changes from about 200 m to 300 m. The characteristics of the mean value are similar, but not consistent with that of the standard deviation value of the elevation index. For example, from 11 to 13, the mean value increases, but the standard deviation value decreases.

4.1.1.3 Slope index

Slope index can affect the rate of the movement down slope, which is an important index in reflecting the undulating degree of topography. It is applied in many studies, especially in the Loess Plateau region (Wolinsky & Pratson, 2005; Bue & Stepinski, 2006; Zhou et al., 2010). The slope index is computed based on SRTM1 DEM data using 3D Analyst Tools in ArcGIS software.

For every typical loess geomorphologic types in the study area, the numerical statistics results of slope index are in Table 4.

Table 4. Numerical statistics of slope index for typical loess geomorphologic types (°)

Code	Min	Max	Range	Mean	Std.
11	0.0	54.4	54.4	8.3	9.2
12	0.0	58.7	58.7	16.4	9.4
13	0.0	62.3	62.3	18.0	8.7
21	0.0	65.7	65.7	15.2	7.0
22	0.0	63.9	63.9	16.5	8.0
23	0.0	67.4	67.4	18.8	8.4
24	0.0	51.7	51.7	15.5	6.7
25	0.0	51.3	51.3	13.8	6.7
26	0.0	58.7	58.7	19.4	8.3
27	0.0	66.7	66.7	19.3	8.4
28	0.0	62.9	62.9	17.2	8.3
29	0.0	57.9	57.9	16.3	7.9
31	0.0	66.2	66.2	16.8	8.5
32	0.0	66.2	66.2	17.1	8.0
33	0.0	62.7	62.7	16.6	8.0

Table 4 shows that the typical loess geomorphologic types distribute in middle slope region, whose mean value ranges from about 10° to 20°. The standard deviation value mainly ranges 6° to 10°. The mean value increases from 11 to 13 and from 21 to 23, but decreases from 27 to 29, and undulates from 31 to 33 and 24 to 26.

4.1.1.4 Curvature index

Compared to slope index, the curvature index can affect the acceleration and deceleration of flow, so as to influence the erosion and deposition process (Moore et al., 1991; Zeverbergen & Thorne, 1987). Using 3D Analyst Tools in ArcGIS software, the curvature index is computed based on SRTM1 DEM data. Making a numerical statistics of curvature index for every typical loess geomorphologic types in the study area, the results are in Table 5.

Table 5. Numerical statistics of curvature index for typical loess geomorphologic types (m^{-1})

Code	Min	Max	Range	Mean	Std.
11	-11.5	9.2	20.7	0.1	0.9
12	-25.5	18.6	44.1	0.0	1.4
13	-20.0	22.9	42.9	0.0	1.5
21	-22.9	20.1	43.0	0.0	1.2
22	-24.7	19.5	44.2	0.0	1.3
23	-15.8	17.3	33.1	0.0	1.4
24	-7.6	8.1	15.7	0.0	1.2
25	-10.3	10.2	20.5	0.0	1.1
26	-12.6	13.7	26.3	0.0	1.4
27	-19.8	21.4	41.3	0.0	1.4
28	-20.0	21.9	41.9	0.0	1.4
29	-17.8	18.3	36.0	0.0	1.3
31	-23.4	23.8	47.2	0.0	1.2
32	-26.2	20.3	46.6	0.0	1.4
33	-17.9	23.5	41.4	0.0	1.4

Table 5 show that the mean value of the curvature index is about 0.0 m^{-1}; the standard deviation value mainly changes from 0.9 m^{-1} to 1.5 m^{-1}. As to the range, it increases from 24 to 26, but undulating from other groups.

4.1.2 Quantitative indexes from digital topographic profile method

The subtypes of the loess ridge and loess knoll are classified by their morphology and valley shape (Table 1), which are quantified tentatively by using the digital topographic profile method. To represent the morphologic change of the valley, the position of the topographic profile line is selected to perpendicular to the trend of the ridge (Cheng et al., 2013). Taking the type of loess narrow acclivitous ridge with deep and high valley as an example, the position of the topographic profile line is in Figure 5 in the remote sensing images.

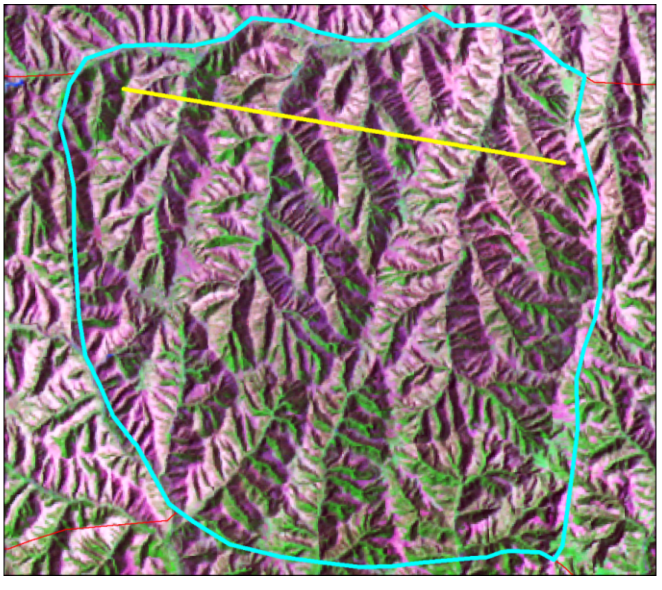

Figure 5. Position of the digital topographic profile line in the remote sensing images.

In Figure 5, the yellow line is the topographic profile line. Based on SRTM1 DEM data, the topographic profile is drawn to quantify the valley change using ArcGIS software (Figure 6).

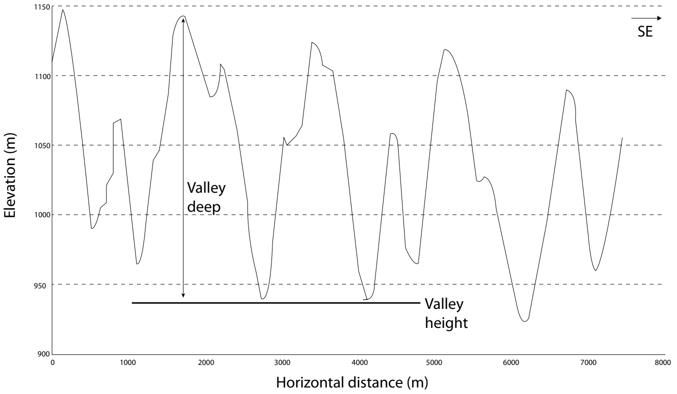

Figure 6. Topographic profile line in loess narrow acclivitous ridge with deep and high valley.

Figure 6 shows the valley height of about 940 m and valley deep of about 200 m. Through making a calculation to all the loess ridge and loess knoll types, the results are in Table 6.

Table 6. Valley shape for loess ridge and loess knoll types (m)

Type	Valley height	Valley depth	Type	Valley height	Valley depth
21	725	120	27	1000	140
22	1080	170	28	1100	220
23	940	200	29	850	150
24	760	110	31	1020	150
25	850	105	32	960	120
26	1300	220	33	960	210

Table 6 presents the valley height and valley depth for the subtypes of loess ridge and loess knoll, which are generally consistent with the valley shape of the types, although some minor contradictions exist. The existence of the contradictions may be due to the valley shape is acquired from the distribution of the types, but they may have a little change in different regions.

4.1.3 Remote sensing indexes for typical loess geomorphologic types

Remote sensing indexes include both the remote sensing characteristics and the spatial distribution pattern in the remote sensing images for the typical loess geomorphologic types.

4.1.3.1 Remote sensing characteristics

Based on the spatial distribution of the typical loess geomorphologic types and the Landsat TM/ETM+ images, the remote sensing characteristics for the typical loess geomorphologic types are acquired. Remote sensing images are the fundamental data for acquiring the distribution status of typical loess geomorphologic types. So the remote sensing characteristics reflect the change and transition in colour and texture in the remote sensing images for the typical loess geomorphologic types.

4.1.3.2 Spatial distribution pattern in remote sensing images

Other than the remote sensing characteristics, the spatial distribution of the typical loess geomorphologic types in the remote sensing images is helpful to understand the transition and change relationship among them. Figure 7 presents an example of this transition: from right to left, the typical loess geomorphologic types change from loess residual tableland to loess beam tableland, and then the loess knoll ridge with shallow and high valley.

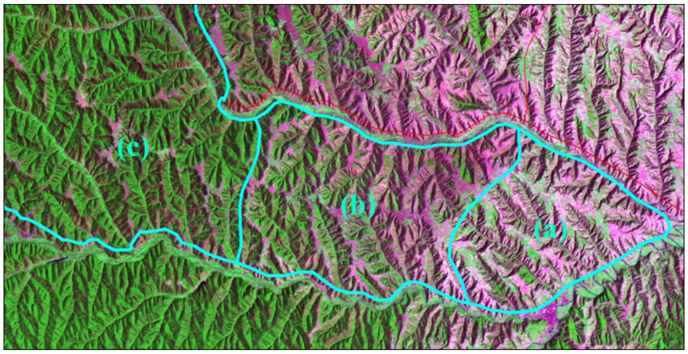

Figure 7. Spatial distribution pattern of the typical loess geomorphologic type (a. loess residual tableland; b. loess beam tableland; c. loess knoll ridge with shallow and high valley).

Through exploring and analyzing the spatial distribution pattern of the typical loess geomorphologic types in the remote sensing images, we attempted to construct the transitional relationship among them.

4.2 Transitional relationship exploration

Referencing the previous research based on the slope spectrum (Zhao & Cheng, 2014), we explored to construct the transitional relationships among the typical loess geomorphologic types by using the digital index systems (Fig. 8).

Figure 8 shows that the loess tableland may transform to loess ridge or to loess knoll, and loess ridge may transform to loess knoll. For the subtypes of the loess tableland, the loess tableland may transform to loess residual tableland, and then transform to loess beam tableland. For the morphology of loess ridge, the wide acclivitous types transform to narrow acclivitous, and then transform to knoll types. The valley shape transforming status is the same for both loess ridge and loess knoll: shallow and high valley transforms to deep and high valley, and then transform to shallow and low valley.

5. Discussions

5.1 Comparison with relevant researches

This research is compared with international relevant researches, the relevant researches in the Loess Plateau and the transitional relationship exploration among loess geomorphologic types.

5.1.1Comparison with internal relevant researches

International relevant researches mostly focus on morphologic analysis, pattern analysis, classification, reconstruction and identification for geomorphologic types (Werner, 1999; Kocurek & Ewing, 2005; Saito & Oguchi, 2005; Bishop, 2007a, 2007b, 2009; Hashimoto et al., 2008; Hampton & Cole, 2009; Bullard et al., 2011; Dragut & Eisank, 2012). Nevertheless, these researches mainly studied on sole geomorphologic type and the spatial distribution of the geomorphologic type was not acquired in advance, which seldom pay attentions to the relationships among geomorphologic types. In this research, the transitional relationships among typical loess geomorphology are constructed based on the digital index system.

5.1.2 Comparison with the relevant researches in the Loess Plateau

In this research, the spatial distribution of typical loess geomorphologic types can be acquired from digital geomorphologic database at 1:1,000,000 scale; meanwhile, the transitional relationships among typical loess geomorphologic types were explored based on the constructed digital index system. The achievement of the relationship among different geomorphologic types is a meaningful research method compared with international relevant researches.

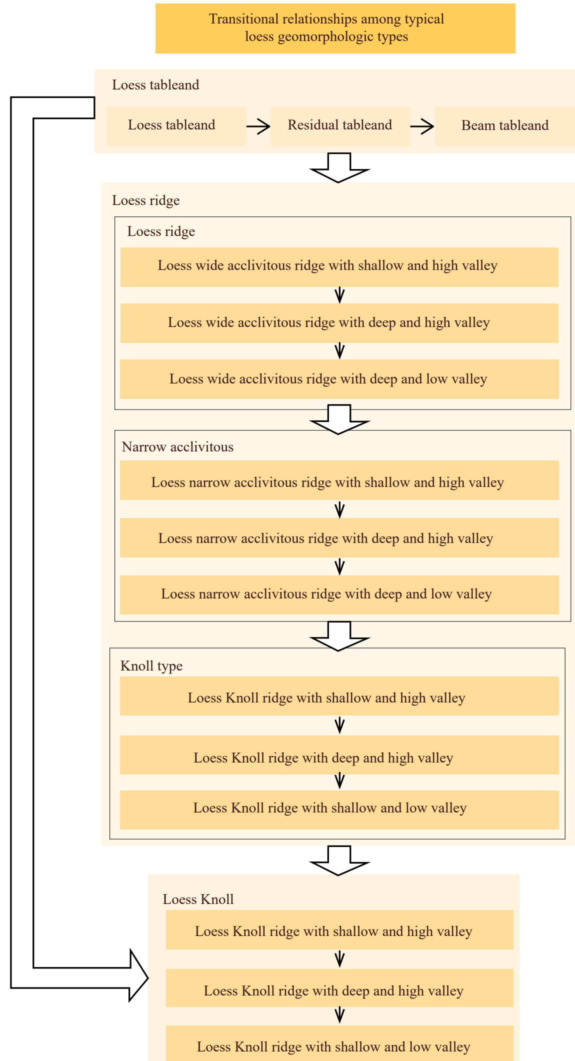

Figure 8. Transitional relationship among typical loess geomorphologic types.

In the loess Plateau of China, loess geomorphology forms due to soil erosion and water and soil loss, so they have close relationship. Most researches based on DEM datasets attempted to classify the typical loess geomorphologic types and analyze their characteristics, especially for morphologic characteristics (Tang et al., 2005, 2008; Zhou et al., 2010). In this research, the classification and accurate distribution can be acquired from digital geomorphologic database, and our aim is to explore the transitional relationship among typical loess geomorphologic types based on the constructed digital index system. Compared with previous research in the Loess Plateau, this research has more close relationship to soil erosion problems, which is one of the most serious problems in the Loess Plateau (Ma, 1996; Liang et al., 2004; Sang et al., 2007).

5.1.3 Comparison with the transitional relationship exploration researches

Compared with the previous research about the transitional relationship exploration among the typical loess geomorphology by Zhao & Cheng (2014), this research selects the typical test area in Loess Plateau, where distribute dense and typical loess geomorphologic types; in addition, the digital geomorphologic database is revised and improved using visual interpretation and remote sensing images, which guarantees the spatial distribution accuracy of typical loess geomorphologic types; meanwhile, digital index system is construct, which provide more reasonable transitional relationships among typical loess geomorphologic types; furthermore, typical loess geomorphologic types have more subtypes and are subdivided by morphologic type and valley shape type, which makes this research much more meaningful compared with previous research. Overall, this research is a developed and improved version of the research by Zhao & Cheng (2014).

5.2 Prospects about this research

Based on this research, the future researches can be conducted on the following three aspects:

Firstly, choose more reasonable study area. The subtypes for the typical loess geomorphologic types are not complete in this research (Cheng et al., 2011b). For example, there is another valley shape type: deep and low valley, which has limited distribution and does not exist in the study area However, more geomorphologic types' distribution means much more big study area, which will increase the workload and decrease the accuracy of the research (Cheng et al., 2011a), especially in digital geomorphologic database improvement and topographic profile line selection. So it is important to seek the balance between the size of the study area and the distribution of the typical geomorphologic types.

Then, construct digital index system using more indexes. This research adopts topographic indexes, digital indexes from topographic profile method and remote sensing indexes. Other than the indexes in this research, there are many other indexes which are useful, such as slope angle and its other derivations, complexity, point pattern, spacing and so on (Werner, 1999; Székely & Karatson, 2004; Bishop, 2007a, 2007b; Bullard et al., 2011). Indexes are the basis for exploring the transitional relationship among the typical loess geomorphologic types, so using more indexes may help deeply understanding the relationship among geomorphologic types.

Finally, besides the loess geomorphology types, digital index system and relationship exploration can also be studied for other geomorphologic types. Taking Aeolian sand dune for example, its point pattern, sand-dune pattern, morphometry and complexity are studied in previous researches (Werner, 1999; Kocurek & Ewing, 2005; Bishop, 2007b; Bullard et al., 2011). Digital index system construction and relationships exploration helps understanding the nature of the geomorphologic types much further.

6. Conclusions

Based on 1:1,000,000 digital geomorphologic database in China, the spatial distribution of the typical loess geomorphologic types is revised and improved using remote sensing images in the test area of Loess Plateau; then, the digital index system is constructed for the typical loess geomorphologic types based on topographic analysis methods and remote sensing characteristics; finally, the transitional relationships among the typical loess geomorphologic types are explored based on the digital index system and previous research. Through this research, the following conclusions can be acquired:

Through boundary improvement, revision to the mis-clssifying units and selection to the typical units, the improved digital geomorphologic database has the typical loess geomorphologic types including loess tableland, loess ridge and loess knoll. Due to the morphologic types, the loess tableland is divided into loess tableland, loess ridge and loess knoll; the loess ridge is divided into narrow acclivitous types, wide acclivitous types and knoll types. As to the valley shape, the loess ridge and loess knoll are divided into shallow and low valley, shallow and high valley and deep and high valley.

Digital index system includes topographic indexes, quantitative indexes from topographic profile and remote sensing indexes. In the test area, the typical loess geomorphologic types mainly distributes in the elevation of about 1000 m, relief of about 250 m and middle slope region; as to the curvature index, it has mean value of 0.0 m^{-1} and standard deviation values from 0.9 m^{-1} to 1.5 m^{-1}. The topographic profile presents the valley height and valley depth for the typical units of all the types. The remote sensing indexes include the remote sensing characteristics of all the types and the spatial distribution pattern in the remote sensing images, which is helpful to construct the transitional relationships among typical loess geomorphologic types.

The loess tableland may transform to both loess ridge and loess knoll, and the loess ridge may transform to loess knoll. As to the morphologic types, loess tableland may transform to loess residual tableland, and then to the loess beam tableland; the loess wide acclivitous ridge transform to loess narrow acclivitous ridge, and then to loess knoll ridge. For the valley shape types of the loess ridge and loess knoll, the shallow and high valley may transform to deep and high valley, and finally transform to shallow and low valley.

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