Establishment of comprehensive index model based on raster data and its application in the study of regional differentiation

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Abstract

The small grid calculation model was used as the theoretical basis; A variety of meteorological data in 1971-2007 of Chinese Loess Plateau, remote sensing image (TM), DEM and other maps in 2000 were used; factor analysis, raster calculator, variance analysis and other methods in ArcGIS were used; the mathematical model of the latitude and longitude related to the main meteorological elements of the loess plateau and comprehensive index model for regionalization were obtained; the north and south boundaries of the Loess Plateau were determined.

Keywords: factor analysis, analysis of variance, raster data, comprehensive index model, boundaries, loess plateau

1 Introduction

Regional differentiation refers to the mutual differentiation between the unequal-sized earth's crust and its internal similar sections and the resulting differences.[1, 2]. Differences reflect a certain rule, and grasping the rule can guide the production and life, and optimize the layout, plan the developing policies with important significance, thus the deep understanding of regional differentiation, directly or indirectly affects the regional development and sustainability. The study of the regional differentiation is one of the important signs of people's geographic environment cognition depth and natural environment research level, and the delineation of district boundaries has become an important and urgent work, especially in the region with complex, diverse terrain.[3]. Therefore, many scholars have carried out relevant research, and obtained some achievements. [4, 5]. But at present, the study of using the grid and GIS technology, combining with vegetation type, soil type and soil erosion less for natural regional division is quite rare.

2 Overview of the study area

Loess Plateau is located in north and central China, including the vast region of west of Taihang Mountains, north of the Qinling Mountains, east Wushaoling, south of the Great Wall. It is across Shanxi, Shaanxi, Gansu, Qinghai, Ningxia and Henan province, with an area of about 62.3299 million square kilometers. Apart from a few rocky mountains, the Loess Plateau is covered with a deep loess layer with a thickness between 50 to 80 meters, and the thickest layer is up to 150 to 180 meters. The loess are with fine particles, soft soil, rich in minerals, beneficial for farming, Agribusiness history of the basins and valleys is long, and it is the cradle of ancient Chinese culture. However, due to the lack of vegetation protection, and with the concentrated summer rains and storms, the ground has been divided in many broken pieces under long-term water erosion, forming highlands, hillocks, and loess hills in the gully interlocks (Figure 1).

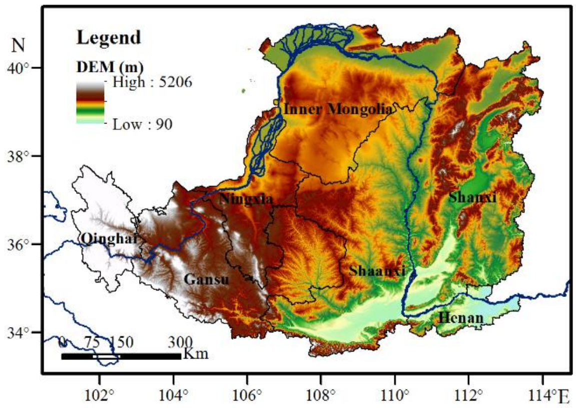

FIGURE 1 Overview of the Loess Plateau

3 Research Methods

3.1 DATA SOURCE AND PRE-PROCESSING METHOD

The data used included the daily precipitation, average speed, maximum speed, average temperature, average pressure, minimum temperature, maximum temperature, sunshine hours and relative humidity of 37 meteorological stations in the Loess Plateau and its surroundings in 1971-2000, the remote sensing (TM), the land use type map, the soil type map and the soil erosion map and DEM data of the Loess Plateau in 2000. First of all, the meteorological

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data of meteorological stations were processed in the aspect of the coarse grain into average monthly data for many years, the processing data of all the meteorological elements, and precipitation and sunshine time in April – September (growing seasons) were obtained. TM images were pre-processed in ERDAS8.7, including splicing, projection transformation, geometric correction and tailoring of the binary images. Then, the normalized model calculation of the vegetation index and soil information extraction index was established.

3.2 EVALUATION OF THE CONSTRUCTION OF FACTOR MODEL

3.2.1 Meteorological index

The data from the each station were used to conduct factor analysis for various meteorological factors to extract the main influence factors. The small grid calculation model was used as the basis, taking the effect of latitude and longitude and height above sea level on meteorological factors into account, so the three geographical factors of longitude, latitude, height above sea level were used as independent variables, climatic factors obtained by factor analysis were used as dependent variables to establish a multiple linear regression model. The model was as follows:

$$F = a_0 + a_1\phi + a_2E + a_3h, \tag{1}$$

where F is the dependent variable of meteorological model. φ, E, h are latitude and longitude and height above sea level respectively. a_0, a_1, a_2, a_3 are regression coefficient, which can be determined with the least square method according to some element value of each meteorological station and the data of latitude and longitude and height above sea level in this station. In which, φ, E, h are latitude layer, longitude layer and DEM respectively in layer calculation, the latitude and longitude layers were created by being imported into ArcGIS cross longitude and latitude data interpolation. The calculation results of various meteorological model layers represent the space distribution of meteorological factors [6].

Because the space change of terrain in the Loess Plateau had an increasing trend from southeast to northwest, the related analysis of meteorological model layers and DEM grid data layer were made, which was realized by the Band Collection Statistics Function of ArcGIS. According to the correlation coefficient obtained, each layer was standardized; negative correlation was standardized with lower effect measure, positive correlation was standardized with upper effect measure, to ensure that each layer changes in the same direction, the specific standard formula was as follows:

Standardization of upper effect measure:

$$Iscore_i = (x_i - x_{min})/(x_{max} - x_{min}). \tag{2}$$

Standardization of lower effect measure:

$$Iscore_i = (x_{max} - x_i)/(x_{max} - x_{min}), \tag{3}$$

where $Iscore_i$ represents the standardization value of an index in the i-th grid; x_i refers to the original data in an index in the i-th grid; x_{max} and x_{min} represents respecttively the maximum and minimum value of an index in all grid [7].

The meteorological index model was established as follows after the above models and standard:

$$MI = \sum_{i=1}^{m} a_i \times F_i, \tag{4}$$

where MI is the meteorological index; F_i is m meteorological elements. a_i is the corresponding weight of m meteorological elements. The weights are determined by the variation coefficient method.

3.2.2 Vegetation index

$$LCI = NDVI \times LT_i, \tag{5}$$

where LCI is the vegetation index; $NDVI$ is the normalized difference vegetation index of the cell; LT_i is the weight of each land use type. Land use types are obtained based on remote sensing image interpretation in 2010; the weight of each type can refer to the researches of Feng Zhiming and others [8].

3.2.3 Soil index

$$ESI = (TM5/TM7)/(TM4/TM3), \tag{6}$$

$$SI = ESI \times ST_i, \tag{7}$$

where ESI is soil information extraction index. TM_i is reflectance value of the corresponding band of remote sensing; SI is soil index. ST_i is the area percentage of each soil type.

Jin Ming et al thought (TM5/TM7)/ (TM4/TM3) not only highlighted the soil information, but also eliminated the influence of vegetation and terrain [9].

3.2.4 Erosion index

$$C = \sum A_i S_i, \tag{8}$$

where C is the comprehensive index of soil erosion in a cell. A_i is the area percentage of i-th soil erosion intensity within the cell. S_i is the corresponding index value of soil erosion intensity.

3.2.5 Comprehensive index

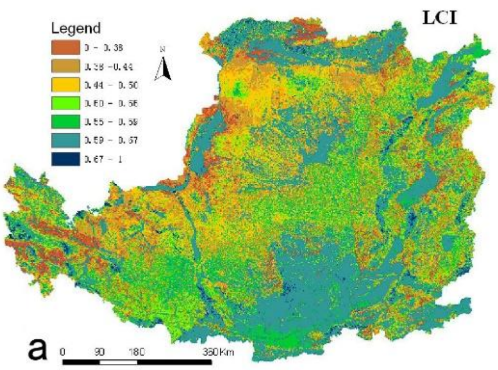
$$AI = \alpha \times NMI + \beta \times NLCI + \chi \times NEI + \delta \times NC, \tag{9}$$

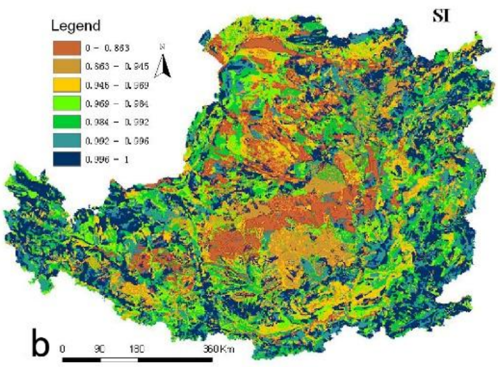
where AI is the comprehensive index for regional division; NMI is the standardized meteorological model corresponding to various meteorological indexes; *NLCI*, *NEI* and *NC* are the standardized vegetation index, soil index and erosion index respectively. α, β, χ and δ is respectively the corresponding weight. Standard method was still calculated based on the correlation coefficient obtained from correlation analysis of DEM, and the weight was obtained by the AHP method.

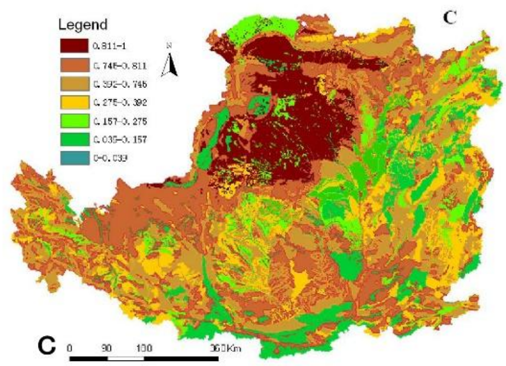
4 Analysis of the Results

4.1 VEGETATION INDEX

Distribution of the vegetation in the space was a geographic unit of complete and continuous, and not repeated vegetation types and their combinations. As can be seen from Figure 2a, the vegetation distribution in the Loess Plateau had a stronger direction; vegetation was gradually in decline from southeast to northwest. Vegetation coverage of the Guanzhong Basin was quite good, in addition, Inner Mongolia, Shanxi, Yanan of Shaanxi and Henan also were distributed, and standardized vegetation index was mainly at 0.59 to 0.67; South and most of Shanxi, Shaanxi, south of Ningxia and southeast of Gansu had a worse vegetation coverage, standardized vegetation index was at 0.50 to 0.59; the vegetation coverage of Midwest of Erdos, Inner Mongolia, center of Ningxia and Dingxi, Gansu was relatively the worst, Qinghai province was also distributed occasionally, and the standardized vegetation index was at 0-0.50. This is mainly because terrain rises from the southeast to the northwest, and moisture decreases.







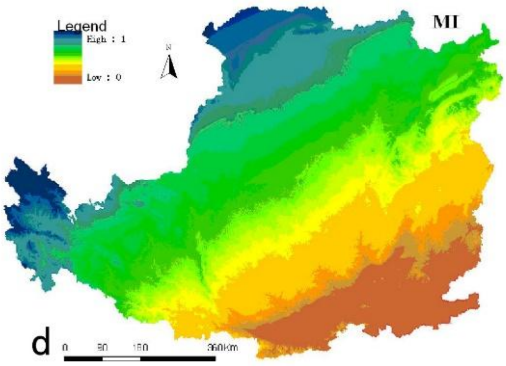


FIGURE 2 Standardized Index of Upper Effect Measure: a) Vegetation; b) Soil; c) Erosion; d) Meteorology

4.2 SOIL INDEX

According to Figure 2b, the spatial distribution of soil index was very scattered, but still has the difference in a certain direction, reducing the content of organic matter from southeast to northwest, and soil was pale in color, texture became light and crude. Among them, the standardized soil index of Shanxi, Guanzhong region of Shaanxi province and Henan, Inner Mongolia, north of Ningxia and Qinghai was at 0.945-1, and soil type was complicated; But the soil types in Shanxi, Guanzhong region of Shaanxi province and Henan had regosols, oil aquilegia soils, aquilegia clay soils, loessial soil, grey loess soils, good loess soils, light brown soils, cinnamon soils, leaching cinnamon soils; the soil types in Inner Mongolia, north of Ningxia and Qinghai had calcaric regosols, light brown soils, chestnut soils, light chestnut soils, light sierozem, chernozem, flow wind sands, cumulated irrigated soils, subalpine meadow soils, and alpine shrub meadow soils; the standardized soil index of Gansu, south central Ningxia, and Shaanxi was at 0-0.945, with a single soil type, mainly was sierozem, loessal soils, good loess soils, sandy loessial soils and grey loess soils.

4.3 EROSION INDEX

The purpose of the classification of soil erosion type is to reflect and reveal the erosion characteristics of different types and the law of regional differentiation, so that appropriate measures can be taken to prevent or mitigate erosion hazard. As can be reflected from Figure 2c, the intensity of Loess Plateau soil erosion also had a certain direction, increased from the southeast to the northwest, and the erosion type was also different. Among them, the erosion intensity of Guanzhong Basin of Shaanxi Province was the weakest, south central Shanxi was also sporadically distributed; the standardized erosion index was at 0.039-0.157; the erosion intensity at the junction of Shanxi and Northern Shaanxi was stronger, in addition, Inner Mongolia, Shanxi and Gansu also were distributed, and the standardized erosion index was at 0.157-0.275; the erosion intensity of Dingxi area, Gansu, most areas of Ningxia and Inner Mongolia obviously increased, and the standardized erosion index was at 0.745-0.811; the erosion intensity of the border between central south of Erdos, Inner Mongolia and Shaanxi was the strongest, and the distribution was concentrated.

4.4 METEOROLOGICAL INDEX

Due to obvious spatial difference of meteorological factors, it is necessary to take meteorological factors into consideration in the natural regionalization. There are many kinds of meteorological factors. However, the dominant factors are emphasized in the principle of natural regionalization, namely, the index of dominant factor reflecting the regional differentiation is selected as the main basis to determine the regional boundary. In this paper, the factors are analyzed, and annual average maximum wind speed and annual average wind speed are eliminated. Thus, other factors are used to establish the meteorological factor model (Figure 2d).

The multivariable linear regression model is established, with climatic factor which is obtained through factor analysis as the dependent variable as well as longitude, latitude and altitude as the independent variables, of which the upper limit measure effect is standardized. Then the other multivariable linear regression model is established, with the standardized climate factor as the dependent variable as well as longitude, latitude and altitude as the independent variable. The influence degree of the independent variable coefficient on dependent variable shall be achieved (Table 1), so as to compare the influence degree of the same independent variable corresponding to each dependent variable. It can be seen from Tab 1, the multiple correlation coefficient R of each model is more than 0.85, $F > F_{0.01}$, the model reaches the level of significance. Except for annual minimum temperature, annual maximum temperature and annual average temperature, the spatial and temporal variation of meteorological elements is very significant:

1) Under the same longitude and latitude, with the increase of altitude, annual average precipitation, precipitation in the growing season (April-September), annual average sunshine duration and relative humidity are increased, and their rates of change are 3.91mm/100m, 3.91mm/100m, 2.96h/100mand 0.13%/100m respectively, but other elements are decreased.
2) Uunder the same longitude and altitude, with the increase of latitude, annual average sunshine duration and sunshine duration in the growing season are increased, and their rates of change are 168.7411h/1°N and 89.3277h/1°N respectively, but other elements are decreased.
3) Uunder the same latitude and altitude, with the increase of longitude, the change of all elements is opposite to that of same longitude and altitude, namely, annual average sunshine duration and sunshine duration in the growing season are decreased, and their rates of change are 33.6667h/1°E and 15.8480h/1°E respectively, but other elements are increased.

In conclusion, combined with the influence degree of independent variables, the influence of longitude factor on annual average precipitation and precipitation of April-September is the most significant, followed by annual average relative humidity and atmospheric pressure. This is mainly because the terrain of high west and low east affects the degree of water vapor transport. With the increase of longitude, the higher the content of water vapor is, the easier it is cloudy and it rains. The influence of latitude factor on an annual average sunshine duration and sunshine duration of April-September is the most significant, followed by annual average precipitation and precipitation of April-September. This is primarily caused by the difference of north and south weather. Most are desert on the earth surface of the north, with no blockage and high wind, so there is a thin atmosphere, more sunny day and long sunshine time; the terrain of the south is gentle, so there is a thick atmosphere, the pollutants difficult to diffuse, low atmospheric visibility, more rainy day, short sunshine duration. In addition, the influence of altitude increasing gradually from the south to the north is also large. The influence of altitude factor on annual average temperature, average minimum and maximum temperature, as well as accumulated temperature of 10 or higher, followed by annual average precipitation and precipitation of April-September. The vertical lapse rate of annual average temperature, average minimum and maximum temperature is about 0.18°C /100m, quite different from the lapse rate of average temperature of free atmosphere (0.65°C/100m). This may be caused by the unique landform of the loess plateau as well as the different combinations of latitude, longitude and altitude. Therefore, it is concluded that the longitude, latitude and altitude affect greatly the natural factors of the loess plateau area.

TABLE 1 Projection model of meteorological factors

Meteorological factors \ Regression coefficient/Degree of influence	a_0	a_1	a_2	a_3	Multiple correlation coefficient R	F (3.33)
Annual average precipitation	-467.2499	29.1348/0.67	-62.3635/0.77	0.0391/0.43	0.9023	48.2119
Precipitation of April-September	-573.7497	24.8187/0.72	-48.5759/0.76	0.0391/0.54	0.8750	35.9348
Annual average minimum temperature	2.3889	0.3840/0.37	-1.0346/0.53	-0.0018/0.81	0.8743	35.6973
Annual average maximum temperature	23.7370	0.1644/0.20	-0.6391/0.41	-0.0018/1.01	0.8561	30.1863
Annual average temperature	10.0353	0.2845/0.32	-0.7993/0.48	-0.0018/0.96	0.8729	35.2251
Accumulated temperature of 10°C or higher	8578.3357	730.2246/0.28	-1264.9502/0.26	-5.5423/1.02	0.8677	33.5060
Annual average atmospheric pressure	-46.4311	10.9787/0.49	-5.8929/0.14	-0.0316/0.67	0.9176	58.5876
Annual average sunshine duration	-124.9959	-33.6667/0.33	168.7411/0.89	0.0296/0.14	0.9318	72.5037
Sunshine duration of April-September	-191.4891	-15.8480/0.34	89.3277/1.02	-0.0103/0.10	0.9321	72.8853
Annual average relative humidity	49.7452	1.1864/0.49	-3.2894/0.73	0.0013/0.25	0.8817	38.4201

Based on meteorological data and the principle of variable coefficient method, the weight of each meteorological factor is obtained. Therefore, the meteorological index model is established. It is difficult to use the actual data to get the weight of ground cover index, soil index and erosion index, so each weight in the composite index model is calculated by using the AHP, among them, the comparative matrix is difficultly obtained. In this paper, based on the importance of each factor, first of all, the preliminary comparative results are obtained, and then the consistency ratio CR is calculated. Then various comparison results in the comparative matrix are adjusted according to the actual situation, until CR<0.1. At this moment, the consistency of comparative matrix is acceptable, as shown in Table 2.

TABLE 2 Comparative matrix of meteorological factors

	Ground cover index	Soil index	Erosion index	Meteorological index	Weight
Ground cover index	1	3	5	0.2	0.1999
Soil index	0.3333	1	2	0.125	0.0802
Erosion index	0.2	0.5	1	0.1111	0.0496
Meteorological index	5	8	9	1	0.6703

4.5 REGIONALIZATION RESULTS

The composite index layer is obtained through Equation 9, and the clustering method is used to divide the composite indexes into three levels from low to high, namely, I-III levels of different types of natural region (Figure 3). The overall distribution situation is a layered distribution from southeast to northwest, and then the regional statistics function of ArcGIS is used for different status values of different meteorological factors in three natural regions.

Level I natural region: The composite index is between 1.11 and 3.00. In this region, the lowest altitude is 91m, the highest altitude is 3681m, its average altitude is 1051.16m, and its pixel standard deviation is 469.435, indicating the change of topographic relief is small. Its land area is 19035376.2640hm^2, accounting for 30.6023% of the total area of Guanzhong region, mainly including Guanzhong region and the southern of Yan'an of Shaanxi, the south of Shanxi (the northern rim is basically the north end of Taiyuan Basin), the northwest of Henan, Tianshui City, Pingliang City and Dingxi area of Gansu Province. Among three natural regions, the precipitation, atmospheric temperature, atmospheric pressure and relative humidity of this region are the highest, but the sunshine duration is the shortest. The main vegetation is the cultivated vegetation, accounting for 54.2647% of the total vegetation area, followed by grasses and broad-leaved forest, and the vegetation coverage is the best. In terms of land use, the area of dry land is the largest, accounting for 40.7759% of the total area, followed by grassland, forest land and cultivated land. In terms of soil, the loessal soil is widely distributed, accounting for 37.5408% of the total soil area, followed by cinnamon soil and Lou soil. The erosion rate is the lowest, the typical erosion is surface erosion, accounting for 52.3126% of the total erosion area, followed by surface erosion-gully erosion-gravitational erosion, and the intensity of runoff erosion is smaller.

Level II natural region: The composite index is between 3.00 and 4.09. In this region, the lowest altitude is 367m, the highest altitude is 4914m, its average altitude is 1570.28m, and its pixel standard deviation is 540.374, indicating the change of topographic relief is the middle one among three natural regions. Its land area is 23810490.7610 hm^2, accounting for 38.2790% of the total area of Guanzhong region, mainly including the north of Yan'an and most parts of Yulin in Shaanxi Province, the north of Shanxi, the south of Ningxia and the southeast of Gansu Province. In addition, a small part of Level II natural region is also distributed in Qinghai Province. In three natural regions, the state of meteorological elements of this region is secondary. The main vegetation is the cultivated vegetation, accounting for 50.8289% of the total vegetation area, followed by grasses and grassland. The area of broad-leaved forest is smaller than that of Level I natural region, but its grassland is quite large, and its vegetation coverage is the better one. In terms of land use, the grassland area is the largest, accounting for 55.2701% of the total area. The area of dry land, forest land and cultivated land is much smaller than that of Level I natural region. In terms of soil, the loessal soil is widely distributed, accounting for 48.5126% of the total soil area, followed by cinnamon soil, aeolian sandy soil, skeleton soil and dark loessial soil, and there is no Lou soil in this region. The erosion rate is secondary, the typical erosion is surface erosion-gully erosion-gravitational erosion, accounting for 52.3126% of the total erosion area, followed by surface erosion-gully erosion-gravitational erosion, and the intensity of gully erosion-gravitational erosion is smaller.

Level III natural region: The composite index is between 4.09 and 5.89. In this region, the lowest altitude is 783m, the highest altitude is 5067m, its average altitude is 1546.96m, and its pixel standard deviation is 655.918, indicating the change of topographic relief is the largest. Its land area is 19356553.9266hm^2, accounting for 31.1187% of the total area of Guanzhong region, mainly including Ordos Plateauof Inner Mongolia and the north of Ningxia. In addition, a small part of Level III natural region is also distributed in Shaanxi, Shanxi, Qinghai and Gansu. The state of all elements of this region is opposite to that of Level I natural region, namely, precipitation, atmospheric temperature, atmospheric pressure and relative humidity are the lowest, but the sunshine duration is the longest. The main vegetation is the grassland, accountting for 26.6676% of the total vegetation area, followed by cultivated land and meadow, and the vegetation coverage is the worst. In terms of land use, the area of grassland is the largest, accounting for 70.9113% of the total area. The area of dry land is much smaller than that of Level II natural region and the area of other land use is still increased. In terms of soil, the aeolian sandy soil is widely distributed, accounting for 25.9494% of the total soil area, followed by chestnut soil, Sierozem soil and skeleton soil. There is no cinnamon soil and Lou soil in this region, but a small part of desert soil and light brown soil is distributed. The erosion rate is the maximum, and the typical erosion is surface erosion, accounting for 29.4586% of the total erosion area, followed by runoff erosion (Figure 1).

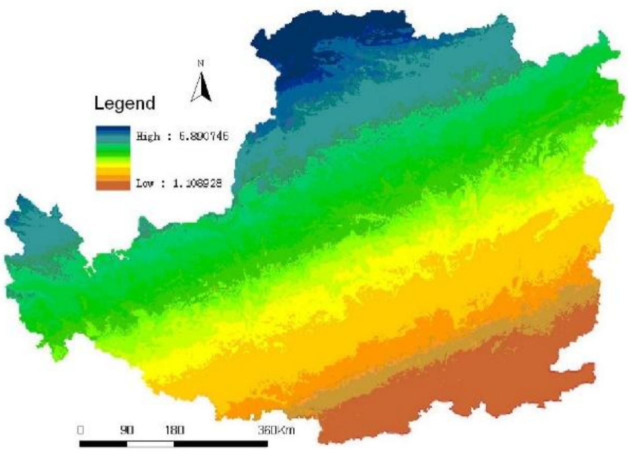


FIGURE 3 Diagram for Natural Regionalization of the Loess Plateau

5 Conclusions and discussion

Factor analysis and composite index are used for calculation to obtain the composite index model of the loess plateau, to determine the south boundary of the loess plateau. The conclusion is as follows:

1) The vegetation, soil and erosion rate have a consistent direction, so the selection of these three factors has a certain scientific nature.
2) The model set up based on meteorological elements, longitude, latitude and altitude is up to an extremely significant level, indicating that the accuracy of meteorological index model is higher. Through analysis, it is concluded that the longitude, latitude and altitude affect greatly the natural factors of the loess plateau area.
3) The overall distribution situation of the loess plateau composite index is a layered distribution from southeast to northwest. The size of meteorological elements is progressively increased or decreased in the sequence of regional level, gradually increasing with the direction of topographic relief. The vegetation coverage is reduced. The content of soil organic matter is decreesed, its color becomes lighter, and its texture becomes light and coarse. The erosion intensity is enhanced in turn. According to the results of the composite index regionalization, the south boundary of the Loess Plateau is basically determined, including Guanzhong region and the southern of Yan'an in Shaanxi Province, the south of Shanxi (the northern rim is basically the north end of Taiyuan Basin), the northwest of Henan, Tianshui City, Pingliang City and Dingxi area of Gansu Province. The north includes Ordos Plateau of Inner Mongolia and the north of Ningxia, Baiyin City and parts of Lanzhou in Gansu Province, Xining City and Haidong area in Qinghai and a few areas in the north of Shaanxi and Shanxi. The rest belongs to the central area of the Loess Plateau.

The research is involved in the modeling of meteorological factors. However, the meteorological data are limited, and only the data from 37 sites are available. Therefore, 12 meteorological factors are adopted to compensate for the inadequacy of data. In addition, the weights in the model of meteorological index and composite index are achieved respectively through two calculation methods, namely, the variable coefficient method and the AHP method. The variation coefficient method uses the actual data to obtain the weights, belonging to an objective weight method. But the partial actual data are difficultly obtained in the composite index model, so the AHP method is used to calculate the weight. Thus, in order to express the difference between regions accurately, besides the fine degree of the data should meet certain requirements, how to acquire the model parameters is also to be further studied.

6 Acknowledgement

National Natural Science Foundation of China(No.: 41301618); Shanxi Provincial Social Science Fund(No: 13D019); Shanxi Provincial Department of Education Science Research Program (No.: 2013JK0851).

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