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Gully Erosion Regionalization of Black Soil Area in Northeastern China

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Abstract: Gully erosion is the frequent and main form of soil erosion in the black soil area of the northeastern China, which is one of the most important commodity grain production bases in China. It is encroaching upon the fertile farmland there. Regionalization of gully erosion can reveal the spatial distribution and regularity of the development of gully erosion. Based on the eco-geographical regional background features of the black soil area, this study combined the regionalization with influencing factors of the development of gully erosion. GIS spatial analysis, geostatistical analysis, spatial statistics, reclassification, debris polygon processing and map algebra methods were employed. As a result, the black soil area was divided into 12 subregions. The field survey data on type, length, volume and other characteristics indicators of gully erosion were used to calibrate the results. Then the features of every subregion, such as where the gully erosion is, how serious it is, and why it happens and develops, were expounded. The result is not only an essential prerequisite for gully erosion surveys and monitoring, but also an important basis for gully erosion prevention.

Keywords: regionalization; gully erosion; soil and water conservation; black soil area; northeastern China

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1 Introduction

Regionalization is the division of an area based on the differences of certain geographical phenomena (Zheng *et al*., 2012). It is an abstract and generalized framework of a phenomenon in a certain area. It is also the prerequisite and basis for further planning. The classification and regionalization of soil erosion were carried out after the year of 1950 in order to understand the spatial differentiation rules of soil erosion and implement the targeted prevention (Huang, 1955; Zhu, 1965; Xin and Jiang, 1982; Zhu *et al*., 1999). Hence, many provincial, regional and national soil and water conservation regionalization (Guan, 1995; The Ministry of Water Resources of the People's Republic of China, 2006) and division results of key control area of soil erosion (The Ministry of Water Resources of the People's Republic of China, 2013) were formed. Those outcomes were obtained by setting the erosion intensity as the main index, combined with the natural geographical background, differences in soil and water conservation measures and goals. However, until now, China has not had zoning outcomes for gully erosion, which is one of soil erosion types. Meanwhile there is a shortage of systematic understanding of regional differentiation characteristics of gully erosion. On the one hand, this is because that the first-hand data of gully erosion surveys require a lot of man power, time and money. Even with the use of remote sensing survey means, it is still expensive for the high spatial resolution remote sensed images that could be more appropriate (Lucà *et al*., 2011; Saxton *et al*., 2012; Tang *et al*., 2013). Also it is still time-consuming for visual interpretation, which is still the major data acquisition method

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(Shruthi *et al*., 2011; 2014; Dotterweich *et al*., 2012; Li *et al*., 2013) as the results from automatic interpretation are difficult to meet the practical needs due to the low precision. On the other hand, the influencing factors of the development of gully erosion, which are often used to establish the index system of gully erosion regionalization, at different spatial scales are not so clear.

Generally, gully erosion is considered as a result of the interaction of land use, precipitation, topography, soils and lithology (Dottweich *et al*., 2013; Conoscenti *et al*., 2014; Superson *et al*., 2014; Luffman *et al*., 2015). Zhang *et al*. (2007) used differential GPS technologies to measure the changes of the erosion gully in Heshan Farm, Heilongjiang Province from 2002 to 2004, and found out that the terrain slope and freezing and thawing processes play an important role in the development of gully erosion in the black soil area in the northeastern China. Yan *et al*. (2005; 2007) and Zhang *et al*. (2015) used Corona and Spot remote sensed images to reveal the influences of elevation, slope, aspect, and landforms on the development of erosion gully at a regional scale. By analyzing the gully density changes along certain distances from road, water system, or residential areas, and the spatial coupling relationships between gully density changes and landscape patterns, Wang *et al*. (2009; 2011) further clarified the regional characteristics that human activities could exacerbate the development of erosion gully. On this basis, the results of Li (2012) showed that gravity and geological factors significantly influence the emergence and development of gully erosion in the black soil area in the northeastern China by means of three-dimensional laser scanning point cloud.

This study aims to: 1) establish the index system of gully erosion regionalization for the black soil area in the northeastern China; and 2) carry out gully erosion regionalization by geographic information system (GIS) methods and clarify the differentiation characteristics of gully erosion in the northeastern China. The results will provide a scientific basis for putting forward control measures and the best configuration for different types of gully erosion subregions, so as to effectively curb the development of gully erosion.

2 Study Area and Methods

2.1 Study area

The black soil area in the northeastern China is an important commodity grain production base. At present, there are commonly narrow and broad definitions of the black soil area. The black soil area in the northeastern China by the narrow definition is known as the typical black soil area, which is described based on the distribution of black soil in the soil classification (Fan and Pan, 2002; Fan *et al*., 2005) (Fig. 1). The black soil area in the northeastern China by the broad definition is defined based on the morphological features (Xie *et al*., 2005), covering the Sanjiang Plain, the Songliao alluvial plain, and the region surrounded by the Da Hinggan Mountains, the Xiao Hinggan Mountains and the Changbai Mountains (The Ministry of Water Resources of the People's Republic of China, 2007) (Fig. 1). In addition to these two definitions, there is a cultural definition of black soil area (Zhang *et al*., 2006) actually, which is delimited according to the relative consistency of historical and cultural background, the close contact with modern economic development, and the integrality and relative independence of geographical boundary. It consists of the entire Northeast China, including Heilongjiang Province, Jilin Province and Liaoning Province, and Hulun Buir City, Hing'an League, Tongliao City and Chifeng City in the eastern Inner Mongolia. In this paper, the black soil area in the northeastern China defined by Zhang *et al*. (2006) was taken as the study area (Fig. 1).

The study area has just developed for more than a hundred years since the large-scale agricultural reclamation. However, it went through highly intensive cultivation and rapid succession processes with the implementation of policies such as 'March into the great grassland' and 'Take grain as the key link' (Li *et al*., 2005; Zhang *et al*., 2006). Coupled with the irrational farming regulations and utilization structures, soil erosion problems have become increasingly prominent in the region. The total area suffering soil erosion was up to 74 326.2 km^2 (Wang *et al*., 2002). It has also resulted in 295 700 large erosion gullies (Fan *et al*., 2013), of which the developing gullies are encroaching arable land at an annual rate of 7.39 km^2 (Bai and Hui, 2015). If we do not timely control the gullies, the scene with fractured ravines in the Loess Plateau may repeated in the black soil area of the northeastern China.

2.2 Index system and data acquisition of gully erosion regionalization

Gully erosion regionalization is the regional division of

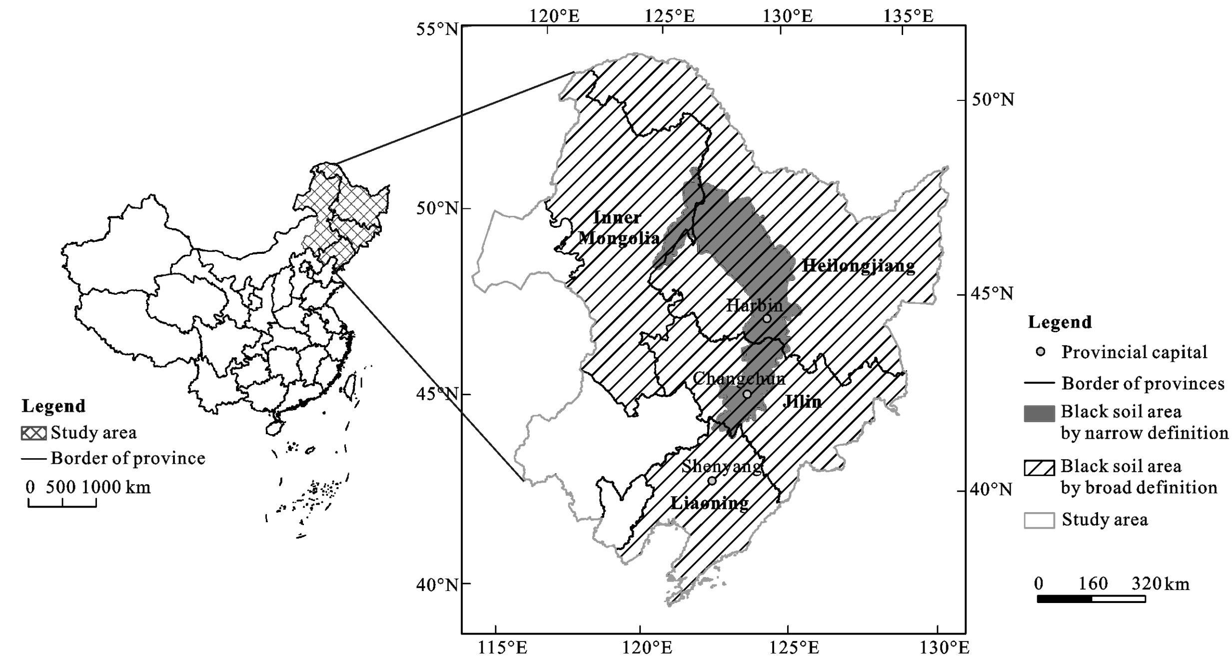

Fig. 1 Location of study area

certain area based on the similarities and differences in factors including gully erosion type, intensity, exogenetic and endogenic forces, risk and socio-economic characteristics. The result could reflect the regional differences in the gully regions with comprehensive characteristics of both natural and human factors. The natural factors are the intrinsic causes and the environmental background for the emergence and development of gully erosion, and the human factors are the external driving forces, deepening the differentiation characteristics of gully erosion to a certain extent. Based on the findings of Yan *et al.* (2005), Wang *et al.* (2009; 2011), Li *et al.* (2010) and Li (2012) on the factors affecting the emergence and development of the black soil area in the northeastern China on the regional scale, topography, soil, lithology, land cover and human interference have significant impact on gully erosion.

Therefore, to reflect the strength of gully erosion, stream power index (SPI) (Fig. 2a), which is a compositive index of runoff, slope and the weight of water, was selected as one of indexes of gully erosion regionalization.

$$SPI = \rho g \cdot q \cdot \tan \beta \quad (1)$$

where ρg is the unit weight of water, generally it is a constant; q is runoff across the unit width of contour; and β is slope (degree).

The types of soils and lithology were chose to present the resistance of gully erosion in the index system. Types of land use (Fig. 2b) and population density (Fig. 2c), which could reflect the intensity and ways of human activities to some extent, constitute human factors of the index system. On the other hand, this study chose eco- geographical zoning elements (Zheng, 2008) including thermal, dry-wet and landforms indexes as eco-geographical part of the index system, to describe the basic geographical background where the gully erosion is. The index system of gully erosion regionalization for the black soil area and data sources and processing methods are shown in Table 1.

2.3 Principles and methods of gully erosion regionalization

The gully erosion regionalization was done according to the common zoning principles, including 1) similar zoning principle, 2) relative consistency of inner-zone, 3) conjugation between different zones, and 4) spatial continuity and integrity (Zheng, 2008; Sangines-Franco *et al.*, 2015).

The gully erosion regionalization in the black soil area of the northeastern China was carried out by both top-down and bottom-up approaches. Firstly, the whole region was divided into thermal zones according to the thermal indexes (including accumulated temperature of ≥10℃, days of ≥10℃, mean temperature of July and mean temperature of January), dry-wet climate zones according to the Penman-Monteith dry index, and

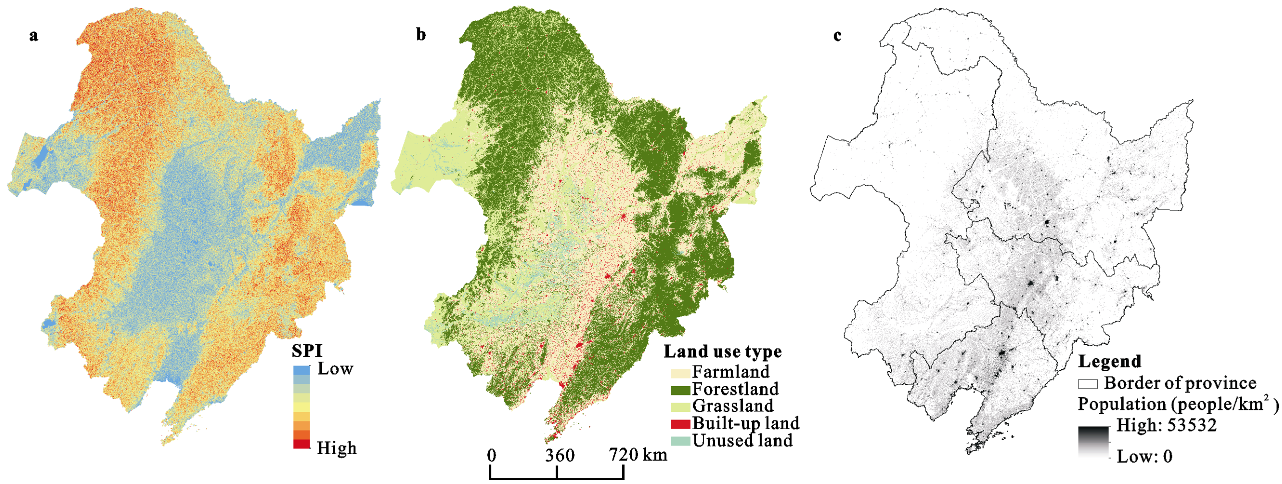

Fig. 2 Indices of gully erosion regionalization of black soil area in northeastern China. a, stream power index(SPI); b, land use of 2010; c, population intensity of 2008

Table 1 Index system of gully erosion regionalization for black soil area and data sources and processing methods

First index	Second index	Third index	Data source	Processing method
Eco-geographical zoning elements	Thermal zone	Accumulated temperature of ≥ 10℃ Days of ≥10℃ Mean temperature of July Mean temperature of January	Daily observation data from 30 meteorological stations in northeastern China in 1960–2010	Reclassification Geostatistics
	Dry-wet zone	Penman-Monteith dry index	Daily observation data from 30 meteorological stations in northeastern China in 1960–2010	Geostatistics Penman-Monteith method (Dirk, 2012) Reclassification
	Landforms	Types of landform	Geomorphologic map of China with scale of 1∶1000000	Human-computer interactive interpretation
		Elevation, slope, relief amplitude	SRTM 90 m digital elevation data	ArcGIS hydrological methods
Factors influencing development of gully erosion	Strength of gully erosion	Stream power index (SPI)	SRTM 90 m digital elevation data	ArcGIS hydrological methods Moore equation (Moore *et al.*, 1991; Kakembo *et al.*, 2009) Reclassification
	Resistance of gully erosion	Types of soil	Soil map of northeastern China with scale of 1∶500000	Digitization
		Types of lithology	Geological map of northeastern China with scale of 1∶500000	Digitization
	Human factor	Types of land use Population density	Landsat TM remote-sensed images of 2010 Statistical yearbook of 2008	Human-computer interactive interpretation Geostatistics

topographical zones according to the topographical indexes (including elevation, slope and relief amplitude) respectively by top-down approaches and reclassification methods. Then, the above three grid files were calculated with reclassified SPI grid file by map algebra method. After re-encoding the above results, we converted it into a vector file. Next, this vector file was overlaid with soil type data, lithology type data and land use type data, which were with vector format too. The result of this processing step generated lots of debris polygons. It was further processed by 'eleminate' and 'dissolve' GIS spatial analysis methods. Afterwards, the polygons with similar properties were merged by bottom-up approaches. At last, the population density data were used as reference to adjust the boundary of the subregions and generate the final regionalization result.

2.4 Naming rules of gully erosion regionalization

Referring to the eco-geographical division of China (Zheng, 2008), 'Soil Erosion Classification and Grading Standard' (The Ministry of Water Resources of the People's Republic of China, 2007), and the naming methods from National Water Conservation Division (The Ministry of Water Resources of the People's Republic of China, 2006), the subregions of the gully erosion regionalization of the black soil area in the northeastern

China were named following naming rules of geographic location + landform + gully erosion status.

3 Results

The zoning scheme of gully erosion regionalization in the black soil area of the northeastern China inherited the part results of national water and soil conservation program and the national eco-geographical regionalization. Based on the above principles, methods and naming rules, from the angles of the type and density of gully erosion in black soil area and the impact of the combined effect of multiple factors that affect the development of gully erosion, this study divided the black soil area into 12 subregions (Fig. 3).

(1) Northern Da Hinggan Mountains with little gully erosion

This subregion belongs to Da Hinggan Mountains area, with an altitude of 1100–1400 m. Under the impact of orographic rain, the mean annual precipitation is more than 600 mm. The basic rocks are mainly volcanic lava rocks, granite and some other volcanic rocks. The area is located in high latitude with cold temperature and moist environment. Forest vegetation is well-grown with relatively little human interference. There is nearly no gully erosion occurs in this region.

(2) Sanjiang Plain with low gully erosion

The main area of this subregion is located in the middle and lower reaches of the Sanjiang Plain, with flat terrain, fertile soil and humid climate. It is an important grain production base of China, and a wetland distribution area, attracting attention at home and abroad. Because large area was used for reclamation and development of mineral resources after the founding of P. R. China in 1949, the land cover has been destroyed heavily. In addition, the underlying layer of soil is the Quaternary sediments, which make gully erosion develop and expand easily. However, considering a relatively flat terrain of the region, timely establishment of rational farming plan and reasonable measures of soil and water conservation can together effectively prevent the development of gully erosion.

(3) Laoye Mountain–Qianshan Mountains with heavy gully erosion

This subregion is located in the narrow strip along Laoye Mountain and southern branches of the Changbai

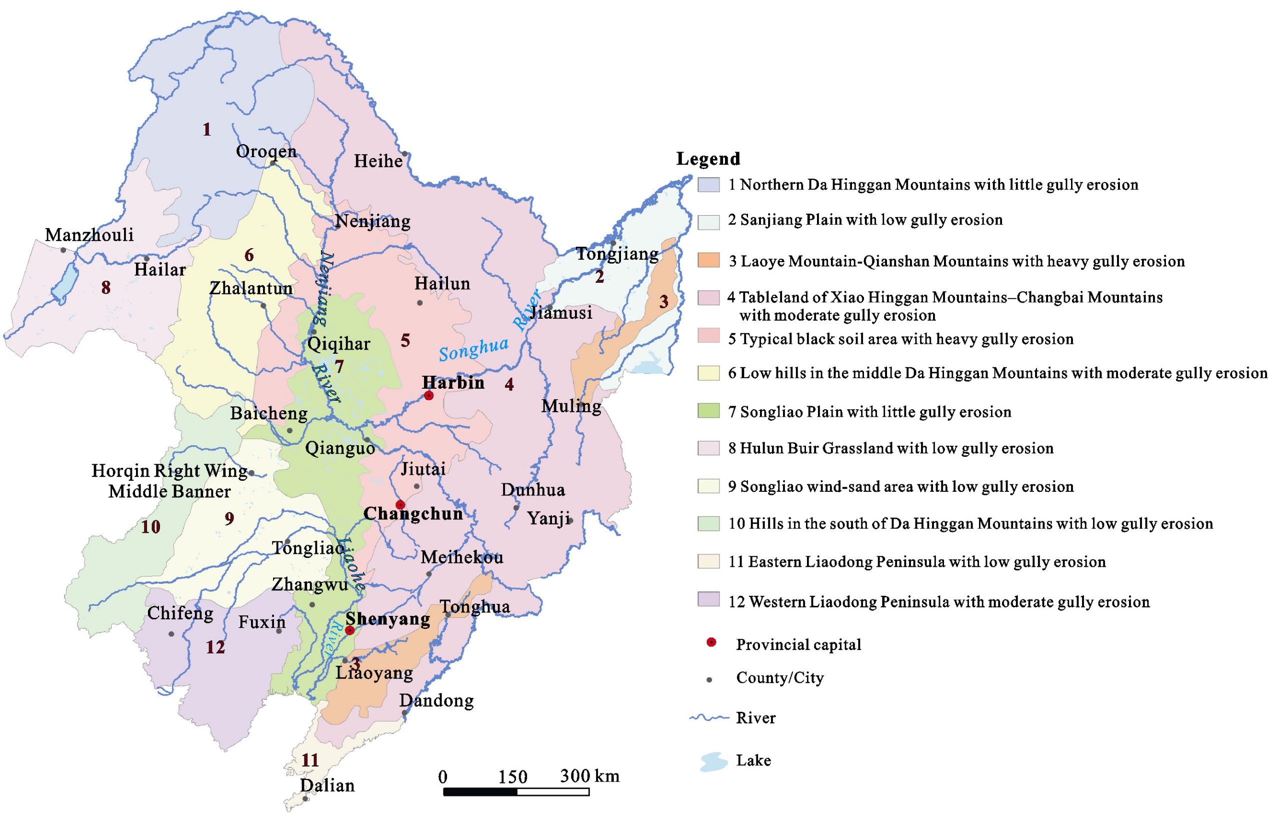

Fig. 3 Gully erosion regionalization map of black soil area in northeastern China

Mountains to the piedmont of the Qianshan Mountains. It has a high and steep terrain and a mean annual precipitation of more than 800 mm on windward slopes. Due to the rich mineral resources in the region, it has always been an important mining base. Besides, with some local excessive deforestation and reclamation in the shallow mountain area in recent years, gully erosion in the region continues to accelerate. In spite of the underlying geological formations mainly being granite and basalt, it is still easy to develop a significant number of gullies.

(4) Tableland of Xiao Hinggan Mountains-Changbai Mountains with moderate gully erosion

The subregion from north to south belongs to the tableland and hills of the Xiao Hinggan Mountains and the Changbai Mountains respectively. It is the subregion with the largest area. It is located in the middle temperate and humid regions, with cold and humid climate and the ground frozen seasonally. The vegetation is mainly mixed forest type. The soils there are dark brown forest soil, meadow albic soil and meadow dark brown soil. The bedrocks are mainly volcanic lava rocks, granite and basalt. With the recent global warming, boundaries of arable regions have moved northward, and land reclamation area has been expanding, so the gully erosion has developed. However limited by the relatively low seasonal precipitation and underground permafrost, the gully erosion there do not become heavy currently.

(5) Typical black soil area with heavy gully erosion

The subregion is the heart of the black soil area in the northeastern China, stretching from the piedmonts of Da Hinggan Mountains and Xiao Hinggan Mountains to the southward, along the eastern Songnen Plain to the Changbai Mountains. It has a semi-circular distribution in the vertical direction. It belongs to the transition zone from dark brown conifer forest soil to meadow chernozem, showing an appearance of long and gentle slope with generally 3°–7° in slope and 800–1500 m in length. The climate is temperate sub-humid, with an mean annual precipitation of 500–600 mm. Owing to the long-term effects of human activities, the vast majority of land has been reclaimed as farmland with a reclamation rate of more than 70%. As for the stratum structure, the upper part is black soil, underlain by the Quaternary alluvial loess-like clayey material. The loess layer becomes thinner and thinner, and the black soil organic matter content increases towards north. The structure of the soil in this subregion is loose, while the underlying clay soil is heavy with poor permeability, therefore, the tillage layer can easily get saturated in this environment matrix in the rainy season, resulting in surface runoff. This coupled with improper soil and water conservation measures, raindrop splash erosion in summer and runoff from snow melt in spring results in massive development of shallow trenches and gullies on the long slope.

(6) Low hills in the middle Da Hinggan Mountains with moderate gully erosion

This area is located in the middle part of Da Hinggan Mountains, between Hailar River valley and Tao′er River valley, with an altitude of 1200–1500 m. The west slope is mild and the east slope has a stepped structure. It has temperate sub-humid climate. The soil type is dark brown soil, and the underground bedrock type is mainly lava and granite. Above conditions make the subregion hardly develop gully erosion. However, gully erosion has developed there because an influx of herders has settled down and reclaimed a large amount of land in the west side of the Halaha River valley in recent years. Meanwhile, due to the irrational farming methods and the lack of soil and water conservation measures, gully erosion could become increasingly serious.

(7) Songliao Plain with little gully erosion

This area includes most of the Songnen Plain and the Liaohe Plain. The geological structure belongs to the Cenozoic depression, receiving sediments from the surrounding hills and middle-upper reaches. The Quaternary sediments in this subregion can mount up to a maximum thickness of 500 m. The climate is temperate sub-humid sub-arid, and the soil type is meadow soil. Vast areas of farmlands are distributed there. The risk of gully erosion is very low due to its flat terrain.

(8) Hulun Buir Grassland with low gully erosion

Hulun Buir Grassland is an integral part of the Inner Mongolia Plateau, at an elevation of 500–700 m, with a very small terrain undulation. Most of the surface has gravelly materials with underlying Quaternary sediments, constituting a special sand landscape. The climate is temperate sub-arid and the main vegetation type is dry grassland, with distribution of chernozem and chestnut soil. According to the relatively flat terrain and instantaneous rainfall in the region, it has almost no risk of gully erosion. While the stratum made the gully erosion prone to develop when negative human disturbance occurred.

(9) Songliao wind-sand area with low gully erosion

The Guiliu River valley marks the northernmost part of this subregion, and the Laoha River marks the southernmost. The subregion is located in the alluvial plain by the Huolin River, Wuerji-Mulun River, Xila-Mulun River and Laoha River and the western Horqin sandy land. The altitude is generally between 200 – 500 m, with a mean annual precipitation less than 400 mm. It belongs to temperate sub-arid climate. Sandy land is widely distributed there. Gully erosion between dune and sand hill can easily formed by runoff. Meanwhile, the gullies can also be easily filled up with sandy soil.

(10) Hills in the south of Da Hinggan Mountains with low gully erosion

The southern section of Da Hinggan Mountains becomes significantly narrow, showing significant differences from northern and central segments. Mostly areas are hilly low mountains, and the slope is not steep-mostly gentle and flat. The mean annual precipitation is about 400 mm, and the climate is temperate sub-arid, with volcanic lava rocks and granite as the main bedrock. Hence the risk of gully erosion is very low. However, due to the relatively large difference in natural conditions on both sides of the mountains, and the existence of the precipitation gradients on the windward slope in the east side, some areas are suitable for cultivation. Once the weak awareness in soil and water conservation and lack of water and soil conservation measures, there could develop a small amount of gully erosion.

(11) Eastern Liaodong Peninsula with low gully erosion

This subregion is located in the southernmost of the northeastern China. It belongs to warm and humid climate. Most of the terrain is undulating hills below 800 m, with moderate stream power. Because the bedrocks are granite, quartzite and slate, gully erosion is difficult to occur.

(12) Western Liaodong Peninsula with moderate gully erosion

The subregion belongs to warm temperate sub-humid climate. Its terrain is slightly higher than eastern Liaoning Peninsula, mainly with low mountains. The bedrock is different from subregion 11. The bedrock of this subregion is composed of volcanic rocks, sandstone and siliceous limestone, which can easily result in gully erosion through continuous erosion.

4 Discussion

4.1 Validation of gully erosion regionalization

In order to verify the rationality of the gully erosion regionalization result, this study implemented a field survey to measure 272 typical field investigative units from 10 typical counties, cities and banners, which were chosen according to the uniform sampling selection method (Fig. 4a). The field survey was carried out in 2012 from May to July. The basic results of the investigation and statistics are shown in Table 2. The number and density of gullies are shown in Fig. 4b, c to show the spatial differences of gullies intuitively.

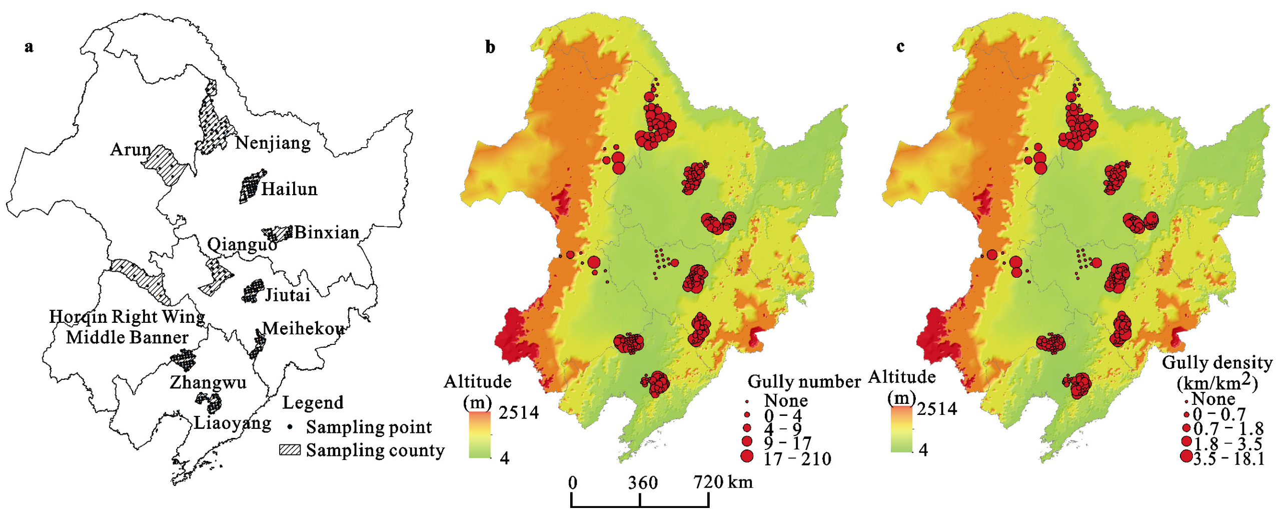

Fig. 4 Survey map of gully erosion. a, sampling points; b, gully number; c, gully density

Table 2 Statistical results of field-surveyed gullies in black soil area of northeastern China

Province	County	Subregion	Number of Sampling points	Gully number	Gully density (km/km^2)	Volume of gully erosion per unit area (m^3/km^2)	Number of shallows per unit area (n/km^2)	Number of gullies per unit area (n/km^2)
Heilongjiang	Nenjiang	4 and 5	41	390	1.52	1886.51	8.80	3.67
	Hailun	4 and 5	44	218	0.98	6637.96	0.88	2.50
	Binxian	4 and 5	36	532	3.52	22 856.18	22.68	11.26
Jilin	Qianguo	7	17	8	0.13	2167.60	0.68	1.14
	Jiutai	4 and 5	31	234	2.03	14 647.10	6.67	18.48
	Meihekou	4	24	272	2.97	6629.69	26.12	20.28
Liaoning	Zhangwu	7	37	297	0.62	11 488.98	4.07	5.16
	Liaoyang	3	29	256	1.70	15 195.72	6.86	8.50
Eastern Inner Mongolia	Arun	5 and 6	5	250	5.40	15 755.30	26.10	19.77
	Horqin Right Wing Middle Banner	9 and 10	8	30	1.46	14 915.53	5.37	7.54
Total/ average			272	2487	1.76	10 684.30	9.50	8.61

The statistical results showed that there has been the maximum number of eroded gullies in the subregion 4 and subregion 5, compared to other subregions. Massive shallow trenches and gullies on the long slope in subregion 5 result in heavy gully erosion. The gully density and volume of gully erosion per unit area of Meihekou, in subregion 4, was lesser. And the shallow erosion dominated in subregion 4. The gully number, gully density and the volume of gully erosion per unit area of Liaoyang, which located in subregion 3, were significantly larger. And the survey showed that a great amount of shallow trenches and gullies have developed in the subregion 3. The gully erosion there was serious. The gully density of Arun, which across the subregion 5 and subregion 6, were largest, up to 5.4 km/km^2. From Fig. 4b and c, we can see that the gully erosion in part area of subregion 6 was slighter than that of subregion 5. The field surveys also found that the gully erosion has developed in Qianguo, which located in subregion 7, and Horqin Right Wing Middle Banner, which across the subregion 9 and subregion 10. Limited to the flat terrain and less human interference, the gully erosion was still light until now. It is noted that the gully number of the sampling county named Zhangwu, which located in subregion 7, was up to 297. While the gully density was only 0.62 km/km^2, belong to little gully erosion.

4.2 Future improvement of gully erosion regionalization

Limited by the accuracy and accessibility of the basic data of gully erosion regionalization, in this study the outcome of gully erosion regionalization of the black soil area in the northeastern China is mainly to reflect the characteristics of the eco-geographical variation of different types of gully erosion. When it is applied to practice, there are some limitations in spatial scale. The result should be used for the macro and regional scale of control planning of gully erosion. For future prevention of gully erosion in specific local regions, it is necessary to deepen the understanding of the development process of gully erosion. Then we need to quantify and fully consider not only the natural factors but also the human impacts on the emergence and development of gully erosion, such as cultivating direction of arable land, cultivation methods and land management. Multiple elements data with fine scales should be integrated to develop a more detailed zoning scheme of gully erosion.

In fact, the wind erosion and surface erosion are also important factors leading to soil loss in the northeastern China. The early outcomes on soil and water conservation regionalization were mainly aimed at surface erosion. Because the influencing factors of gully erosion are understood gradually, especially in the regional scale, more and more gully erosion regionalization will be implemented in the future. The influencing factors of wind erosion are much different from water erosion. Wind erosion is the primary soil erosion mode in the western areas of the northeastern China. Wind power, surface soil texture and coverage may be the significant leading factors of soil erosion there. Therefore, it is necessary to carry out fixed-point ground observation experiment to further discuss and understand soil erosion.

5 Conclusions

Regionalization of gully erosion can reveal the spatial distribution and regularity of the development of gully erosion. It is not only an essential prerequisite for gully erosion surveys and monitoring, but also an important basis for gully erosion prevention. The gully erosion regionalization of the black soil area in the northeastern China was done based on the eco-geographical regional background features, combined with comprehensive influencing factors of the development of gully erosion. Then the field survey data of type, number and density of gullies were used to verify the regionalization result. GIS spatial analysis, spatial statistics, reclassification, debris polygon processing and map algebra methods were employed. The whole region was thus divided into 12 subregions. The result could be helpful for putting forward control measures and configuration of gully erosion. And it provided a scientific basis for effectively curbing the expansion of gully erosion.

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