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Distributions of recent gullies on hillslopes with different slopes and aspects in the Black Soil Region of Northeast China

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Abstract Gully erosion is an important environmental problem worldwide and the main process by which water and soil losses occur in the Black Soil Region (BSR) of Northeast China. At the end of 2012, 295,663 gullies were present in this region. However, few studies have examined the gullies of the Black Soil Region as a whole. Studying the distribution of recent gullies can reveal the pattern of gully distribution and can help predict their spatial development according to the soil and water conservation regionalization of China. This study examines the recorded gullies in the BSR of Northeast China, which is included in the first census of water resources in China and in six sub-regions of the soil and water conservation regionalization of China. Specifically, digital elevation model (DEM) data are combined with data on gullies occurring on hillslopes with different slopes and aspects to study the distribution of these features. The results illustrate that gully density, developing gully density, and the proportion of cutting land initially increase with increasing slope up to some threshold value, then decrease as the slope increases further. The patterns of stable gullies are divided into unimodal and bimodal types. Three patterns of gully intensity are identified. The areas and lengths of gullies are larger on sunny slopes, but larger numbers of gullies are present on shaded slopes. In addition, more space is available for gully development in the Hulun Buir hilly and plain sub-region and the Changbai Mountain-Wanda Mountain sub-region than in the other sub-regions.

Keywords Gully · Distribution · Development space · Black Soil Region of Northeast China

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Introduction

Gullies represent a direct embodiment of water and soil losses. The process of gully development damages roads and bridges, cuts up farmland, reduces the productivity of land, and affects the development of intensive agriculture. Gully development has many negative impacts on the environment, society, and the economy. Consequently, many scholars have examined the distribution of the main processes of gully occurrence and morphological characteristics in recent years (Woodward 1999; Dotterweich 2008; Capra et al. 2009; Ionita et al. 2015). Scholars have studied the relationships between the spatial distribution of gullies and the slope threshold in South Africa by dividing the slopes into five classes (0~4°, 5~9°, 10~14°, 15~19°, and > 20°). The results showed that gullying was predominant in the slope class of 5~9° and was more pronounced in the slope class of 10~14° than in the steeper slope classes of 15~19° and > 20° (Kakembo et al. 2009). The slope-area (S-A) threshold is a topographic threshold used to determine the occurrence and locations of gullies (Vandekerckhove et al. 2000; Poesen et al. 2002, 2003). Morgana used the S-A threshold to define a discriminant function to identify the threshold of gully occurrence in grasslands in central Swaziland (Morgan and Mngomezulu 2003). Some scholars have determined the initial locations of gullies in the Algeria River Basin by collecting data on the slope, aspect, altitude, sediment transport capacity index, stream power index, and topographic wetness index, among other factors (Dewitte et al. 2015).

Wang et al. (2013) extracted the number, length, and area of gullies and analyzed their distributions in different provinces using remote sensing (RS) data, geographic information system (GIS) environments, and Global Positioning System (GPS) units in the Black Soil Region of Northeast China. Gully erosion was shown to be serious in the central part of Heilongjiang Province, on the first and second river terraces in the east-central part of Jilin Province, in the northwestern part of Liaoning Province, and to the east and south of the Guna River in Inner Mongolia. An RS-based study of gully erosion in a typical black soil region, Kebai in Heilongjiang Province, Northeast China (Zhang et al. 2015), showed that gully density first increased and then decreased with increasing slope. The extent of gully erosion on sunny slopes (or windward slopes) was greater than that on shaded slopes (or leeward slopes) due to the effects of freezing and thawing, wind, and solar radiation. In addition, the greatest density of gullies occurred on rolling hills, followed by tablelands, whereas plains displayed the lowest gully density. Li et al. (2012) studied the relationship between gully distribution and terrain characteristics in Jiutai, a city within Jilin Province in Northeast China. The results showed that gully density first increased and then decreased with increasing slope; however, slope was not the main factor controlling the development of erosional channels. On slopes with different aspects, soil erosion was greater on sunny slopes than on shaded slopes and was greater on windward slopes than on leeward slopes. Concave slopes were especially vulnerable to gully erosion, and gullies seldom occurred on convex slopes. Free faces showed the least vulnerability to gully erosion. When different terrain characteristics were combined, the differences in gully density became more obvious (Li et al. 2012). Fan et al. (2013) studied the relationships among the natural environment, human activities, soil erosion patterns, and gully distributions in the seven sub-regions of the Black Soil Region of Northeast China. The results showed that the Southeast Greater Hinggan hilly and gully sub-region (0.56 km/km^2) and the Hulun Buir hilly and plain sub-region (0.36 km/km^2) were the most seriously affected areas. In contrast, the gully density was only 0.08 km/km^2 in the Greater and Lesser Hinggan Mountain sub-region, where the coverage was high and the gully erosion was light. Additionally, the number, area, and length of gullies were large in the Changbai Mountain-Wanda Mountain sub-region and the Northeast China rolling hills sub-region, and the gully density was 0.14 km/km^2.

Vrieling et al. verified the feasibility and accuracy of extracting gullies from QuickBird RS images and field surveys (Vrieling et al. 2007). He Fuhong et al. suggested that the accuracy of the extracted gullies obtained using this method could be improved using technology that merges landscape information with RS data, based on experimental data obtained from QuickBird images (He et al. 2014). Combining the “3S” technologies (RS, GPS, and GIS) to assess soil erosion enables full use of the high speed and precision of GPS, the wide coverage of RS, and the excellent graphics and data processing capabilities of GIS, thus permitting dynamic monitoring of soil erosion. The integration of the “3S” technologies to carry out the integration and complete digitalization of RS, cartography, GIS, GPS, virtual reality technology, and decision support systems has led to new messaging and data processing capabilities and an additional emphasis on information extraction, automation, artificial intelligence, and information sharing in applications (Sun 2008). In this census, gullies are divided into developing and stable categories. However, how to separate gullies into these categories is controversial. Zhang Shuwen et al. monitored gully erosion in the Kebai area and noted that gullies in the developing stage were V-shaped and that either no vegetation or only annual plants were present within these gullies. Moreover, in the quiescent phase, gullies stopped eroding headward, and the valley terrain was relatively broad and contained large amounts of sediment and many plants; some of the affected areas had even been reclaimed as farmland (Zhang et al. 2015).

The Black Soil Region of Northeast China is delineated using both narrow and broad definitions (Wang et al. 2007). The narrow definition is based on the distribution of black soils using the soil classifications, whereas the broad definition is based on morphological features. In addition, the Black Soil Region of Northeast China is mainly within the Songliao River Basin and is one of the three major areas of black soil in the world. This region is one of the major commodity grain bases of China and is known as the “Northern Warehouse.” The capacity of this region to produce food sustainably is an important part of the food security strategy of China. Due to overcultivation and predatory management, soil erosion has become increasingly severe, causing degradation of the black soil and leading to widespread societal concern in recent decades (Cui et al. 2007). The World Reference Base for Soil Resources includes a group called the phaeozems, which includes most of the soils classified as black soils and meadow soils in China. The interim draft of the Chinese soil classification divides black soils into black soils, meadow black soils, albic black soils, and superficial black soils. The black soils of Northeast China are not limited to the black soils in the soil classification. In its report on soil and water loss in the Black Soil Region of Northeast China, the Songliao Water Resources Commission established that the soil types corresponding to black soils in the soil classification are black soils, chernozems, dark brown soils, meadow soils, albic soils, brown soils, brown conifer forest soils, and swamp soils (Wang 2011). The processes by which soil erosion occurs in the Black Soil Region of Northeast China include freeze-thaw erosion, water erosion, and wind erosion. From 1965 to 2005, the number of gullies occurring in cultivated areas increased from 2509 to 14,132, corresponding to 11,623 new gullies. Moreover, gully erosion consumed a land area of 81.83 km^2, which corresponds to an average yearly increase of 2.05 km^2, in the Wuyuer River and Nemoer River basins in the core area of the Black Soil Region of Northeast China. In the Kibai area, it was found that a gully can damage 1.65% of the cultivated land on the hillslope it occupies; under the impact of mechanized farming, the number of gullies cutting across roads, through residential land, and occurring within areas of arable land area has increased markedly (Bai and Hui 2015).

Gully erosion causes numerous environmental and socioeconomic consequences, most of which are negative (Poesen et al. 2003; Valentin et al. 2005; Ionita 2011; Marzolff et al. 2011; Ionita et al. 2015). The hazard associated with gullies rises with increased population pressure and specific human activities. Thus, gullies may be influenced by the natural environment, human activities, or both (Dotterweich et al. 2012). Intensive agriculture is common in the Black Soil Region of Northeast China, which is a major grain-producing area. Moreover, many state forest farm are located in this area. Gullies can develop quickly. For example, the gully density on hills, mesas, and plains in the Kebai region increased by 57.45, 52.91, and 25.32%, respectively, between 1945 and 2000 (Zhang et al. 2015). Although intensive research has been performed on gully erosion within the Black Soil Region of Northeast China, most of these studies have focused on the typical Black Soil Region or portions of this area (Hu et al. 2007; Wu et al. 2008; Tang et al. 2013; An et al. 2014; Li et al. 2016; Wang et al. 2016a). Relatively few studies have examined the distribution of gullies across the entire Black Soil Region (Fan et al. 2013; Wang et al. 2013).

This paper is based on data collected as part of the first census of water resources in China. These data are connected with the development of the soil and water conservation regionalization in China and the spatial distribution of gullies. The objective of this study is to assess the distribution of the number and length of gullies and area per unit area slopes with different slope angles and aspects. In addition, this study is intended to identify the relationship between the distribution of gullies and geographical location and to estimate the space available for gully development in each of several sub-regions. The method of partitioning the soil and water conservation regionalization in China has a scientific basis; the underlying principle is that the characteristics should be similar within each area and differ among the areas. This study focuses on several sub-regions of the soil and water conservation regionalization within the Black Soil Region and investigates the distribution of gullies within the sub-regions from a macro perspective by building on the research of Fan et al. (2013), thereby providing a relevant theoretical basis for future research.

Materials and methods

Study area

The Black Soil Region is surrounded by the Da Hinggan Mountains, the Xiao Hinggan Mountains and the Changbai Mountains (Fan and Pan 2002; Fan et al. 2005; Xie et al. 2005; Yang et al. 2017). The Black Soil Region of Northeast China experiences a variable and cold temperate continental monsoon climate, and the annual precipitation ranges from 300 to 950 mm. The rainfall is distributed unevenly over this area, and the average values in the eastern mountainous area and west of the Liaohe Plain range from 700 to 950 mm and 300 to 4000 mm, respectively. The rainy season occurs between July and August, and the rainfall during that time represents more than 50% of the annual precipitation. Moreover, the rainfall between June and September represents more than 70% of the annual precipitation. Storms account for the majority of the precipitation. There is little difference in daylight hours between the southern and northern parts of the region. But the difference of the east and west parts is obvious. The cumulative temperature above 10 °C is 2400~3000 °C in the north and 2800~3000 °C in the south. High winds occur between March and May, and the maximum wind speeds are generally 20~25 m/s but can reach 40 m/s at times. Numerous rivers and lakes, such as the Liao River, the Songhua River, the Heilong River, and the Yalv River, are present in the region.

A general investigation of gullies in the Black Soil Region of Northeast China was a part of the first census of water resources in China, which covered four provinces (Liaoning Province, Jilin Province, Heilongjiang Province, and the Inner Mongolia Autonomous Region), 36 cities (land, union, and state), and 171 counties (city and district), covering a total area of 94.64×10^4 km^2 (Fig. 1). In addition, the four provinces mentioned above contain the broadly defined Black Soil Region and the soil and water conservation regionalization of China, of which six sub-regions were selected as study areas. These sub-regions are the Greater and Lesser Hinggan Mountain sub-region (I), the Southeast Greater Hinggan hilly and gully sub-region (II), the Northeast China rolling hills sub-region (III), the Hulun Buir hilly and plain sub-region (IV), the Liaoning-Around Bohai mountainous and hilly sub-region (V), and the Changbai Mountain-Wanda Mountain sub-region (VI) (Zhao et al. 2013) (Fig. 1).

Data acquisition

A general investigation of gullies in the Black Soil Region of Northeast China was carried out based on RS images with a resolution of 2.5 m and a 1:50,000 DEM, which was collected in 2011 and provided by the

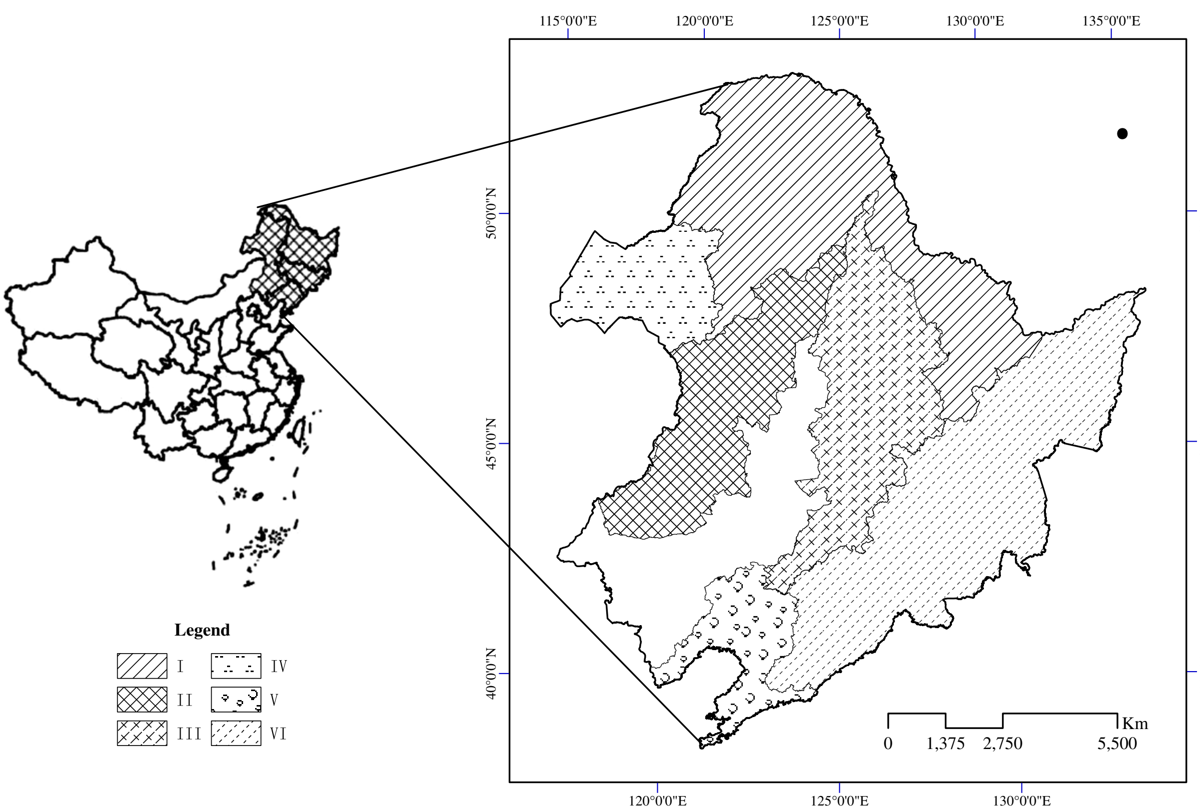

Fig. 1 Study area

water resource census office of the State Department. Interactive GIS techniques were used to extract information on the length, area, type, longitudinal gradient, and locations of gullies. The steps in these interactive GIS techniques include (1) transforming the projection, (2) correcting the RS images to eliminate band and spot errors, (3) joining and splitting the images, and (4) loading the images into a database. The RS data are then checked through interpretation and field surveys to avoid missing data and errors, and an attribute table and spatial data for each gully can then be successfully created. Ten gullies were extracted from each county for field checking. To ensure the quality of the data, the following indicators were examined. (1) The methods of operation should comply with the relevant provisions of RS interpretation and follow the technical requirements of the implementation plan. Lengths ranging from 100 to 5000 m and areas ranging from 0 to 5000 hm^2 were examined. Ranges of longitude and latitude extending from 72° to 136° and from 16° to 54°, respectively, were examined. (2) Gully edges deviated by no more than 2 pixels (5 m). (3) The length deviation was limited to less than 5%. (4) The deviation of the longitude and latitude ranges was limited to within 1 in. (5) All gullies were examined to ensure that they met the requirements and that the type of gully had been correctly identified. (6) The attributes of each gully were entered into the GIS, and the GIS representation of the gully was examined. This general method of investigation provides a means of identifying developing and stable gullies. Stable gullies have stopped eroding headward and have ceased to develop, and the vegetation coverage is greater than 30% over the entire length of the gully. Other gullies are defined as developing gullies. The results of this general investigation are shown in Table 1.

The slopes were divided into nine classes (0~0.25°, 0.25~1.5°, 1.5~3°, 3~4°, 4~5°, 5~8°, 8~15°, 15~25°, and 25~90°) that were derived from the Standard of Water and Soil Conservation in the Black Soil Region (SL-2009). The aspects were divided according to whether the slopes faced north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), or northwest (NW). The DEM was analyzed using ArcGIS 9.3 and the 3D Analyst Toolbox. The digital models of the slope and aspect were converted into polygons and stored as shapefiles to enable extraction of the distributions. In slope distribution analysis, a threshold is a point that indicates system quality, performance, or signs of mutation (Groffman et al. 2006). A certain slope (S) and catchment area (A) is necessary to produce sufficient runoff to cause the initiation of gully erosion. In general, gully density increases with increasing slope when the slope is less than the threshold value. On the other hand, the gully density decreases with increasing slope when the slope exceeds the threshold (Yan et al. 2007).

Results

Effects of slope

Generally speaking, slope increases are consistent with gully density (Fig. 2a) and developing gully density (Fig. 2b). After that, it shows decrease tendency in different region. We regard the slope where the direction of the trend changes as being the slope threshold. The thresholds differ among the sub-regions. The thresholds of gully density and developing gully density in the Greater and Lesser Hinggan Mountain sub-region, which are 5° and 4°, respectively, are the smallest. The slope thresholds of gully density in the remaining five sub-regions are the same as those of developing gully density. Among them, the thresholds of the Southeast

Table 1 Summary of gully erosion in the sub-regions of the Black Soil Region of Northeast China

Sub-regions	Number of gullies	Number of stable gullies	Number of developing gullies	Area of gullies (km^2)	Proportion of developing gullies (%)	Proportion of stable gullies (%)
I	20,029	5067	14,962	469.01	74.70	25.30
II	61,677	4923	56,754	1369.60	92.02	7.98
III	61,818	8554	53,264	563.91	86.16	13.84
IV	5306	306	5000	436.92	94.23	5.77
V	25,916	4504	21,412	138.50	82.62	17.38
VI	120,670	10,131	110,539	669.19	91.60	8.40

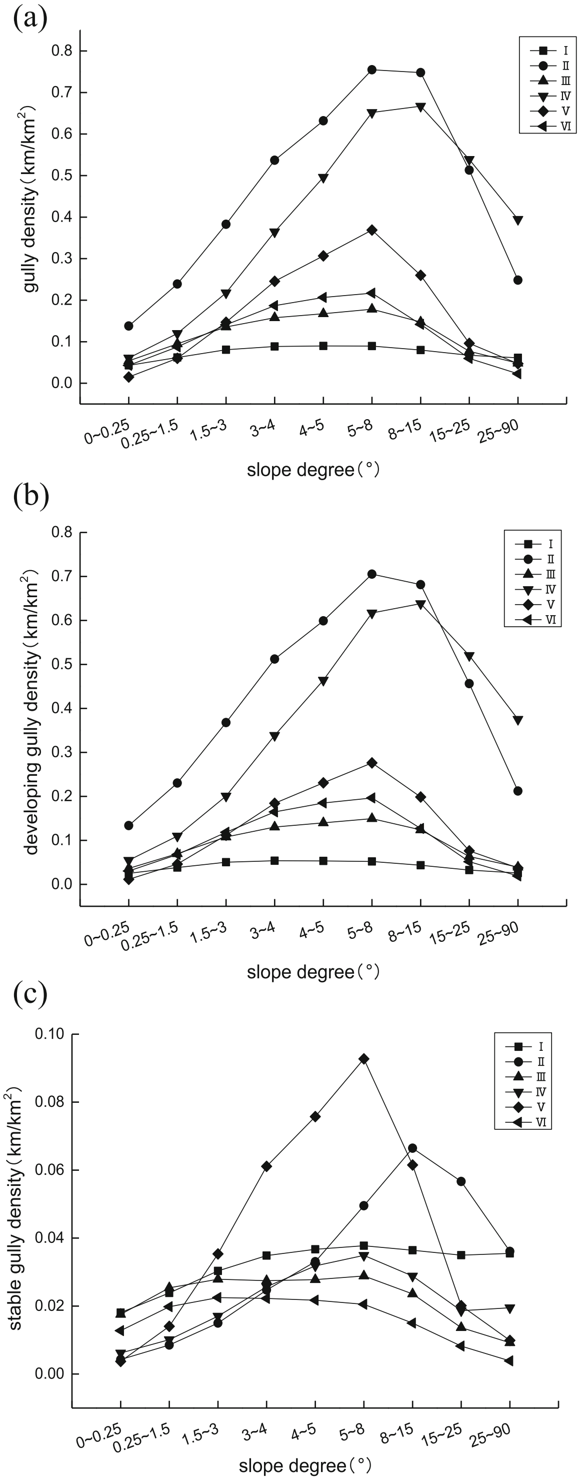

Fig. 2 Curves describing gully density (**a**), developing gully density (**b**), and stable gully density (**c**) for different slope

Greater Hinggan hilly and gully sub-region, the Northeast China rolling hills sub-region, the Liaoning-Around Bohai mountainous and hilly sub-region, and the Changbai Mountain-Wanda Mountain sub-region are 8°, and those of the Hulun Buir hilly and plain sub-region are 15°. The stable gully density displays two distinct patterns (Fig. 2c) as the slope increases. In the first pattern, the stable gully density first increases and then decreases as the slope increases, and there is a definite slope threshold. In addition, the thresholds of stable gully density of the Changbai Mountain-Wanda Mountain sub-region, the Greater and Lesser Hinggan Mountain sub-region, the Liaoning-Around Bohai mountainous and hilly sub-region, and the Southeast Greater Hinggan hilly and gully sub-region are 3°, 8°, 8°, and 15°. The Northeast China rolling hills sub-region and the Hulun Buir hilly and plain sub-region display the second pattern, which is a bimodal curve. The peaks associated with these sub-regions are 3° and 8° for the Northeast China rolling hills sub-region and 8° and < 25° for the Hulun Buir hilly and plain sub-region. In addition, the maximal stable gully density occurs at 8° for these sub-regions.

Gully intensity (Fig. 3) displays three patterns. However, the maximal gully intensity of all of the sub-regions occurs at 5°. The first such pattern is the "W" type, which is displayed by the Southeast Greater Hinggan hilly and gully sub-region, the Hulun Buir hilly and plain sub-region, and the Greater and Lesser Hinggan Mountain Hinggan Mountains sub-region. These sub-regions display two minima at 1.5° and 15° and a maximum at 5°. However, the minimum value of

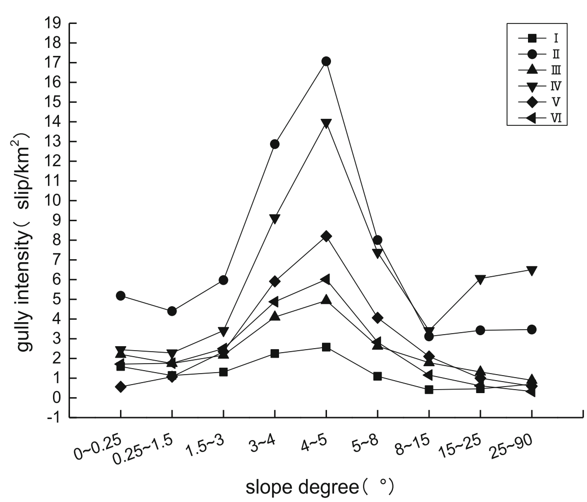

Fig. 3 Curves of gully intensity for different slope

the Greater and Lesser Hinggan Mountain sub-region and the Southeast Greater Hinggan hilly and gully sub-region occurs at 15°, whereas the minimum value of the Hulun Buir hilly and plain sub-region occurs at 1.5°. The gully intensity of the Northeast China rolling hills sub-region first decreases, then increases, and then decreases again as the slope increases, and the two inflection points occur at 1.5° and 5°. The Changbai Mountain-Wanda Mountain sub-region and the Liaoning-Around Bohai mountainous and hilly sub-region display the third type, in which the gully intensity increases with increasing slope before achieving a maximum and then decreasing with increasing slope. The corresponding slope thresholds are 5°.

The proportion of cutting land (Fig. 4) initially increases with increasing slope up to a particular threshold value, then decreases as the slope increases further. The threshold of the Greater and Lesser Hinggan Mountain sub-region, which is 4°, is the smallest value. In addition, the largest threshold is 15°, which corresponds to the Southeast Greater Hinggan hilly and gully sub-region. The thresholds of the remaining four sub-regions are 8°.

It can be seen from Fig. 5 that the proportion of the slope-area as a function of slope angle displays an “M” pattern, and 5° is the inflection point between the two peaks. The Northeast China rolling hills sub-region, the Hulun Buir hilly, and plain sub-region and the Liaoning-Around Bohai mountainous sub-region have greater areas at slope angles less than 5°. In addition, the remaining three sub-regions have greater areas at slope angles greater than 5°. Comparison with Table 6 shows that the maximum gully intensity in each sub-region

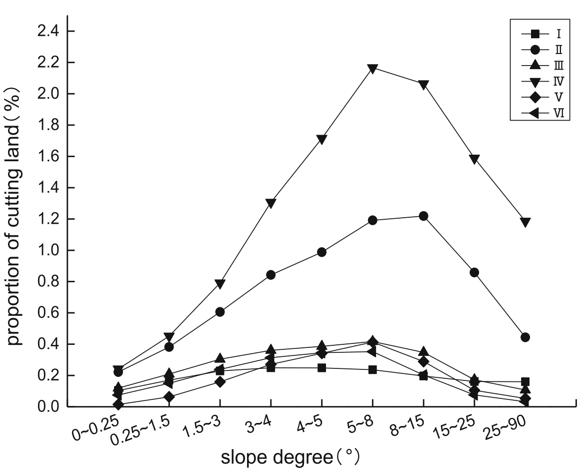

Fig. 4 Curves showing the proportion of cutting land for different slope

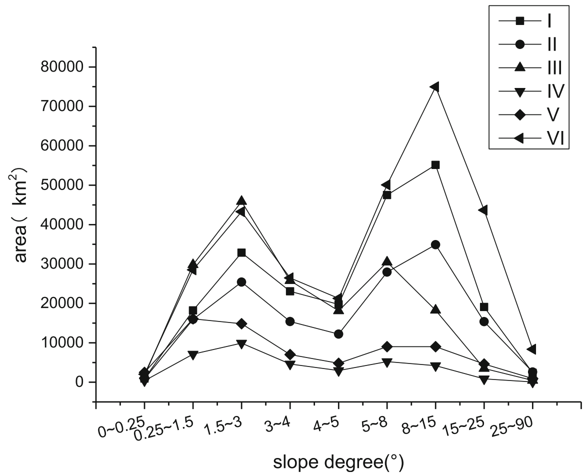

Fig. 5 Curves showing the proportion of the slope-area

occurs at a slope angle of 5°. Further correlation analysis (Table 2) shows that the gully density in the Greater and Lesser Hinggan Mountain Hinggan Mountains sub-region, the Southeast Greater Hinggan hilly and gully sub-region, and the Northeast China rolling hills sub-region is significantly correlated with the slope-area. The developing gully density and the proportion of cutting land are significantly correlated with the slope-area in the Southeast Greater Hinggan hilly and gully sub-region. In addition, the stable gully density is significantly correlated with the slope-area in the Northeast China rolling hills sub-region. These analyses show that the slope is not the main factor restricting the formation of gullies, and the formation of gullies is more strongly influenced by other factors, such as slope shape, aspect, catchment area, and topographic relief (Li et al. 2012; Wang et al. 2012).

At the same time, the correlation with the distribution indexes of the gullies in the different sub-regions is assessed (Table 3). The length, quantity, and area of gullies per unit area are highly correlated with one another at different slope angles in the Northeast China rolling hills sub-region, the Liaoning-Around Bohai mountainous and hilly sub-region, and the Changbai Mountain-Wanda Mountain Changbai Mountains-Wanda Mountains sub-region. At the same time, the gully length per unit area is highly correlated with the area in the Greater and Lesser Hinggan Mountain Hinggan Mountains sub-region, the Southeast Greater Hinggan hilly and gully sub-region, and the Hulun Buir hilly and plain sub-region. In general, the correlation between the length and area of gullies in areas of

Table 2 The correlation between the gully distribution index and slope-area

Sub-region		Gully density	Developing gully density	Stable gully density	Gully intensity	Proportion of cutting land
Slope	I	0.686*	0.65	0.519	−0.247	0.576
	II	0.746*	0.749*	0.536	−0.082	0.745*
	III	0.674*	0.63	0.845**	0.29	0.651
	IV	−0.157	−0.167	0.078	−0.213	−0.085
	V	0.136	0.135	0.138	−0.023	0.126
	VI	0.429	0.44	0.24	−0.134	0.344

*Significance level < 0.05, ** Significance level < 0.01

different slope categories is higher in the Black Soil Region of Northeast China (Wang et al. 2013).

Effects of aspect

The smallest values of the gully density (Fig. 6a), developing gully density (Fig. 6b), and stable gully (Fig. 6c) density in the six sub-regions occur on NW-facing slopes, but the maxima do not coincide. The gully density and developing gully density of the Greater and Lesser Hinggan Mountain sub-region, the Southeast Greater Hinggan hilly and gully sub-region, and the Hulun Buir hilly and plain sub-region display the same trends in each aspect, and their maximum gully densities occur on SE-, S-, and E-facing slopes, respectively. The maximum gully density, developing gull density, and stable gully density of the Northeast China rolling hills sub-region occur on SW-facing slopes but have different trends in each aspect. In the Changbai Mountain-Wanda Mountain Changbai Mountains-Wanda Mountains sub-region, the gully density is largest on SE-facing slopes, the developing gully density is largest on E-facing slopes, and the stable gully density is largest on S-facing slopes. In the Liaoning-Around Bohai mountainous and hilly sub-region, the maximum gully density, developing gully density, and stable gully density occur on SE-facing slopes.

The largest gully intensity (Fig. 7) within all of the sub-regions occurs on N-facing slopes. In addition, the gully intensity of the Southeast Greater Hinggan hilly and gully sub-region is the smallest on NE-facing slopes, and the minimum gully density in the other five sub-regions occurs on NW-facing slopes. However, the proportion of cutting land (Fig. 8) of all of the sub-regions are the smallest on NW-facing slopes. In addition, it is the largest on E-facing slopes in the Greater and Lesser Hinggan Mountain sub-region and the Hulun Buir hilly and plain sub-region. The largest proportion of cutting land of the Liaoning-Around Bohai mountainous and hilly sub-region and Changbai Mountain-Wanda Mountain sub-region is on SE-facing slopes. In the Northeast China rolling hills sub-region and the Southeast Greater Hinggan hilly and gully sub-region, the largest proportion of cutting land occurs on SW- and S-facing slopes, respectively.

Table 3 The correlation analysis of the distribution indexes of the sub-regions

Sub-region	Index	Gully density	Gully intensity	Proportion of cutting land	Sub-region
I	Gully density	–	0.359	0.998**	II
	Gully intensity	0.326	–	0.312	
	Proportion of cutting land	0.976**	0.456	–	
III	Gully density	–	0.453	0.990**	IV
	Gully intensity	0.689*	–	0.521	
	Proportion of cutting land	0.999**	0.680*	–	
V	Gully density	–	0.789*	0.994**	VI
	Gully intensity	0.777*	–	0.830**	
	Proportion of cutting land	1.0**	0.774*	–	

* Significance level < 0.05, ** Significance level < 0.01

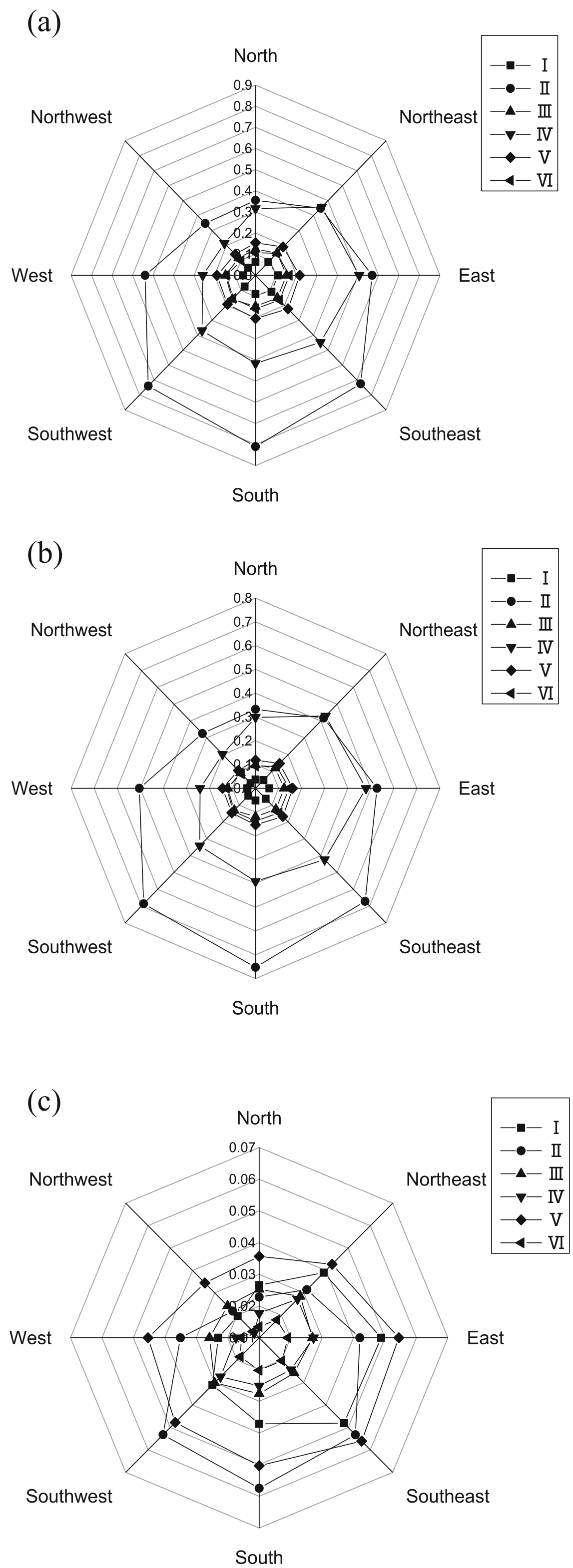

Fig. 6 Curves of the gully density (**a**), developing gully density (**b**), and stable gully density (**c**) as a function of aspect

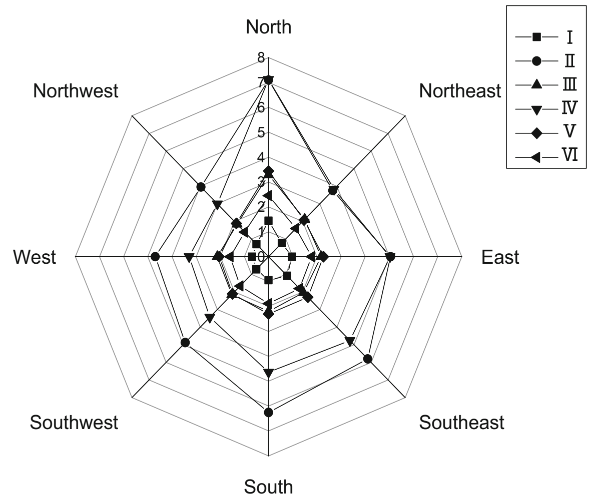

Fig. 7 Curves of the gully intensity for different slope aspect

As shown in Fig. 9, the distribution patterns of each aspect display no significant differences, and the area of the N-facing slopes is the smallest (Fig. 9). Further analysis (Table 4) shows that the gully intensity of only four sub-regions has significant correlation with aspect. These sub-regions are the Northeast China rolling hills sub-region, the Hulun Buir hilly and plain sub-region, the Liaoning-Around Bohai mountainous, and hilly sub-region and the Changbai Mountain-Wanda Mountain sub-region. In addition, analysis of the correlation between the distribution factors of gullies (Table 5) shows that the length is highly correlated with area per unit area. In addition, within a unit area, the number of gullies is weakly correlated with area and length. This

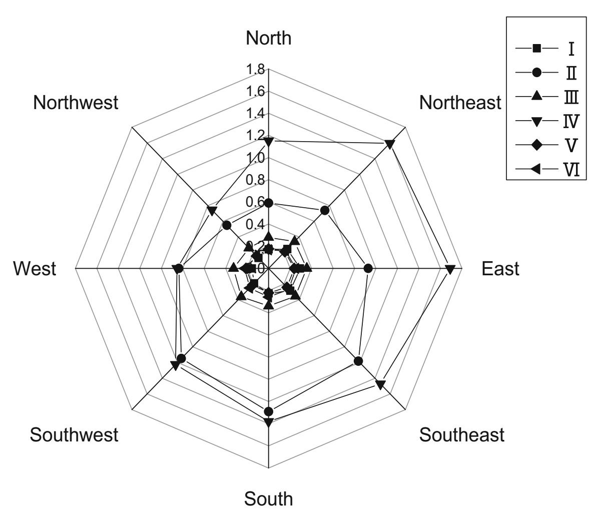

Fig. 8 Curves of the proportion of cutting land for different aspect

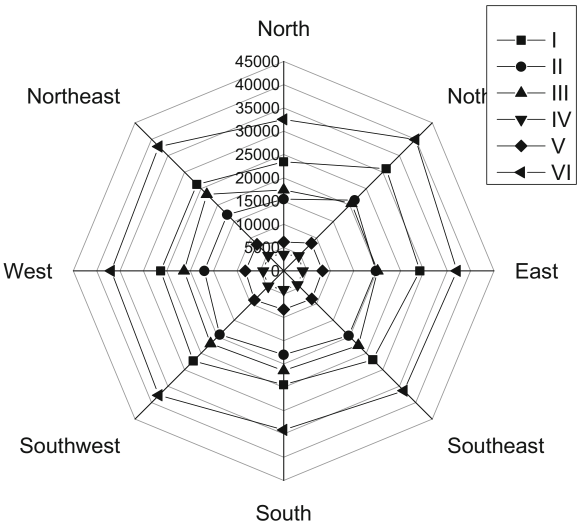

Fig. 9 Curves of the proportion of the aspect area

result is similar to the distribution in terms of slope, in that the correlation between the length and area of gullies in different unit aspect areas is higher in the Black Soil Region of Northeast China (Wang et al. 2013).

Prediction of development space

In addition to the gully distribution and the change in spatial distribution with geographic location, we attempt to estimate the development space, according to the slope threshold estimated from the gully distribution. If the developing gullies toward to stable state when the threshold of stable gullies is larger than that of developing gullies, then the development space is small. In contrast, the developing gullies have exceeded the limit of the gullies' original stability state. That is, the developing gullies are attempting to satisfy a series of naturally or human-imposed conditions to reach stability. Hence, the development space is large. Table 6 shows that the slope threshold of the gully density is between 5° and 15°, the slope threshold of the developing gully density is between 4° to 15°, and the slope threshold of the proportion of cutting land is between 4° to 15°. The slope threshold of the stable gully density, i.e., the slope corresponding to the maximum stable gully density, is between 3° and 15°, and the slope threshold of the gully intensity is 5°. In the Greater and Lesser Hinggan Mountain and the Southeast Greater Hinggan hilly and gully sub-region, the slope thresholds of the stable gully density are greater than those of the developing gully density, indicating that the established gullies and the developing gullies are primarily distributed below the stable slopes, and the development space for gullies is smaller. The slope thresholds of the gully density, developing gully density, and stable gully density are the same in the Liaoning-Around Bohai mountainous and hilly sub-region, indicating that the established gullies tend to be stable and the development space is small. The slope threshold of the gully density is the same as that of the developing gully density in the Northeast China rolling hills sub-region. However, the curves of the stable gully density as a function of slope for this sub-region display two peaks and lack an obvious slope threshold, indicating that the gullies have some potential to develop further. The slope thresholds of the stable gully density in the Hulun Buir hilly and plain sub-region and the Changbai Mountain-Wanda Mountain sub-region are smaller than those of the gully density and the developing gully density. Moreover, the proportions of developing gullies (Table 1) are 94.23 and 91.60% in these regions, indicating that developing gullies are more prevalent than stable gullies. Therefore, the gullies in these areas have considerable development potential.

Table 4 The correlation between gully distribution index and aspect area

Sub-region		Gully density	Developing gully density	Stable gully density	Gully intensity	Proportion of cutting land
Aspect	I	0.438	0.403	0.472	−0.491	0.51
	II	0.361	0.355	0.425	−0.506	0.386
	III	0.172	0.187	0.024	−0.905*	0.142
	IV	−0.151	−0.162	0.054	−0.940*	−0.194
	V	0.594	0.580	0.511	−0.882*	0.574
	VI	0.226	0.237	0.132	−0.841*	0.720

* Significance level < 0.05, ** Significance level < 0.01

Table 5 The correlation analysis of the distribution indexes of sub-regions for different aspects

Sub-region	Index	Gully density	Gully intensity	Proportion of cutting land	Sub-region
I	Gully density	–	0.247	0.997*	II
	Gully intensity	0.227	–	0.273	
	Proportion of cutting land	0.991*	0.234	–	
III	Gully density	–	0.285	0.992*	IV
	Gully intensity	−0.315	–	0.348	
	Proportion of cutting land	0.984*	−0.303	–	
V	Gully density	–	−0.124	0.989*	VI
	Gully intensity	−0.224	–	−0.104	
	Proportion of cutting land	0.996*	−0.214	–	

* Significance level < 0.05, ** Significance level < 0.01

Discussion

The relationship between gully density and slope in Keshan, Kedong, Baiquan, Yi'an, Beian, Wudalianchi, Mingshui, Fuyu, and Nehe from 1965 to 2005 shows that the highest gully density occurs on slopes between 2° and 3°, and the slope range of 3~5° displays the largest change in gully density (Wang et al. 2009). These areas are located in the Northeast China rolling hills sub-region, and 92% of the area with a slope of 3° is primarily arable land. Areas with slopes greater than 3° are primarily forest-covered. Based on the results of this study, the slope threshold reflected by the gully distribution of the Northeast China rolling hills sub-region is 8°, and the slope corresponding to the maximum gully density is higher than that in previous studies. Keshan and the other eight counties (cities) that are located in the Northeast China rolling hills sub-region account for only 24% of the entire area, and small topographic changes can lead to different gully distributions. Some differences exist between the results for these local areas and the study area as a whole. Because the study area extends a considerable distance from north to south, meteorological conditions, vegetation, soil types, and human activities vary considerably over the study area.

Table 6 Maximum slope threshold of gully distribution

	I	II	III	IV	V	VI
Gullies	5	8	8	15	8	8
Developing gullies	4	8	8	15	8	8
Stable gullies	8	15	(8)	(8)	8	3
Gully intensity	(5)	(5)	(5)	5	5	5
Proportion of cutting land	4	15	8	8	8	8

The density (Fig. 6) and proportion of cutting land (Fig. 7) on sunny slopes are greater than those on shaded slopes, but the gully intensity (Fig. 8) on sunny slopes is smaller than that on shaded slopes (Zhang et al. 2015). On sunny slopes, the number of gullies is small, their lengths are larger, and they cover a large area; on shaded slopes, the number of gullies is large, and they are short in length. Chen et al. (2006) who have studied gullies on the Loess Plateau have shown that sunny slopes and shaded slopes show significant differences in terms of their evolution. The degree of evolution of sunny slopes was higher than that of shaded slopes, and the slope aspect is an important terrain factor. Related research has shown that differences exist in the wind direction during the rainy season, rainfall erosivity, soil moisture, and vegetation growth conditions, and significant asymmetries exist in the pattern and intensity of soil erosion on slopes as a function of aspect (Chen et al. 2006). The cause of these asymmetries is related to solar radiation. The daily and annual temperature differences are very large, the winters are cold, and the freeze-thaw process changes the soil structure, reducing the resistance of the soil to erosion. The amount of solar radiation received by sunny slopes differs from that received by shaded slopes. The total amount of solar radiation received by sunny slopes is large. Therefore, the diurnal temperature variation is larger, and the action of freezing and thawing is stronger, on sunny slopes than on shaded slopes. With the spring thaw, runoff occurs more rapidly and becomes relatively concentrated on sunny slopes, resulting in more severe erosion than on shaded slopes. Rainfall is thus the direct reason for the occurrence of gully erosion. The rainfall occurs primarily from June to September, driven mainly by the summer monsoon in the Black Soil Region of Northeast China. The sunny slopes are also the windward slopes, and the angle between raindrops and the hillslope surface is larger on sunny slopes than on shaded slopes. Thus, raindrops strike sunny slopes with more force (Wang et al. 2012).

The gullies are affected by the characteristics of the natural environment, the human activities, and the pattern of soil erosion occurring within each area. The natural environment can vary in terms of soil, climate, topography (Torri and Poesen 2014), and vegetation (De Baets et al. 2008). There are significant differences in the environmental characteristics, which in turn causes the zonal differentiation of gully development characteristics (Fan et al. 2013). The climatic differences are reflected in the differences in rainfall, rainfall intensity, temperature, and other factors, and the regional climate determines the pattern of soil erosion to some extent. In terms of topography, the Black Soil Region of Northeast China is bordered by mountains with low to moderate elevations to the east, north, and west, and its central portion contains large plains. The complexity of the landforms and the topography causes differences in catchment area, leading to differences in gully development (Fan et al. 2013).

The intensities of rainfall and freeze-thaw erosion are determined by the climatic characteristics of the Black Soil Region, and these processes are the main reasons for the development of gullies. Water erosion is one of the main processes by which erosion occurs in the Black Soil Region of Northeast China, and vegetation and soil are important factors that affect water erosion. The Black Soil Region of Northeast China contains black soils, chernozems, meadow soils (Liu et al. 2008), dark brown forest soils, and albic soils, as well as other types. The physical and chemical properties of the soils do not differ strongly among the sub-regions, but because of differences in natural conditions and the impact of human activities, the soil thickness varies. In general, the resistance of soils within the Black Soil Region to erosion is poor (Fan et al. 2013). The results show that the force of rainfall erosion increases gradually from north to south in the Black Soil Region of Northeast China, and it first increases and then decreases from west to east (Zhang et al. 2014). The forest vegetation coverage is generally high in the Black Soil Area of Northeast China, and the area of the forested portion of the Greater and Lesser Hinggan Mountain and the Changbai Mountain accounts for 33% of the total surface volume of the forest land in the whole country. The high degree of vegetation coverage weakens the splashing action of raindrops and the surface runoff through interception by the canopy, and the well-developed plant root systems retain the soil (Fan et al. 2013). Under certain rainfall intensities, vegetation decreases surface runoff (De Baets et al. 2008) and enhances the resistance of topsoil to surface runoff (Guo et al. 2015). Dense vegetation types can protect soil from erosion by means of intercepting rainfall; moreover, rainfall can also be fixed by root soil, improving the physical and chemical properties of soil, increasing water infiltration, and enhancing the corrosion resistance of the soil (Zhang et al. 2014). In its natural state, the vegetation of the black soil area is in good condition. However, in recent years, man-made destruction has intensified. Thus, the local vegetation has been destroyed, and external agents can affect the soil directly, leading to the occurrence of gully erosion. The vegetation coverage is low in the main grain-producing areas, which are the Northeast China rolling hills sub-region and the Southeast Greater Hinggan hilly and gully sub-region; however, there are many forest farm-cultivated forests in the Greater and Lesser Hinggan Mountain sub-region (Fan et al. 2013). And soil and water erosion under trees have become more prominent with human activity (Guo et al. 2012). However, the results of a study on cutting areas within the Tangwang River Basin in the Lesser Hinggan Mountain showed that serious soil erosion occurred along roads used for wood-collecting roads and in areas without ground cover; in contrast, very little soil erosion occurred in areas with good ground cover. Soil erosion was especially serious in cut areas with slopes between 20° and 26°, whereas soil loss was small when the slope was less than 10°. However, the gully density decreased with increasing slope for slopes greater than 5° (Man et al. 1997). Therefore, cutting areas are not the main cause of the development of gullies within the study area.

Freeze-thaw is another important process by which erosion occurs in the Black Soil Area of Northeast China (Wang et al. 2016b). In the Greater and Lesser Hinggan Mountain sub-region in the northernmost part of China, the winters are colder and freeze-thaw persists over a long period. However, in the southernmost of the six sub-regions, the Liaoning-Around Bohai mountainous and hilly sub-region, the winters are shorter and warmer, and the freeze-thaw process operates over a short time (Fan et al. 2013). Konrad (1989) argued that repeated freezing and thawing can change soil structure and damage the binding force between soil particles, allowing soil particles to be rearranged. In addition, the rate of soil disintegration is an important index for evaluating soil erodibility, and the freeze-thaw effect can change soil properties and affect the disintegration rate of soil (Gu et al. 2014). The results of Shanley show that differences in the type of litter covering the ground have an effect on the soil freezing depth (Cheng et al. 2008), and the corresponding order is bare ground > meadow > evergreen coniferous forest > deciduous forest (Shanley and Chalmers 1999). The different types of vegetation found in the different sub-regions produce different types of litter, affecting the soil freezing depth and soil thawing duration and resulting in differences in the intensity of freeze-thaw erosion among hillslopes as a function of slopes and aspect.

At the same time, human activity is one of the main factors that causes gully erosion in the Black Soil Region, and differences in the intensity of human activities and the main type of activity within the different sub-regions have led to the different gully distributions (Fan et al. 2013).

Conclusions and prospects

This paper examines the modern distribution of gullies in the Black Soil Region of Northeast China based on the first National Water Census and sub-regions of the soil and water conservation scheme. The following conclusions have been drawn.

First, from the point of view of the effects of gully distribution, the gully density, developing gully density, and the proportion of cutting land initially increase with increasing slope up to a particular threshold value. They then decrease as the slope increases further. In addition, the stable gully density displays two patterns as the slope increases. In addition, gully intensity displays three patterns.

Gully density, developing gully density, stable gully density, and the proportion of cutting land tend to be higher on SE-, S-, and SW-facing slopes. However, the gully intensity in each sub-region is highest on the N-facing slopes.

Moreover, estimates suggest that the gully development space of the Changbai Mountain-Wanda Mountain sub-region and the Hulun Buir hilly and plain sub-region is likely higher than those of the other sub-regions.

Correlation analysis shows that the slope and aspect are weakly related to part of the distribution index. Therefore, to build on this study, we will continue to study the characteristics of gully distributions in response to different factors.

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References

An, J., Zheng, F. L., & Wang, B. (2014). Using 137Cs technique to investigate the spatial distribution of erosion and deposition regimes for a small catchment in the black soil region, Northeast China. *Catena, 123*, 243–251. https://doi.org/10.1016/j.catena.2014.08.009.

Bai, J. H., & Hui, L. J. (2015). A preliminary investigation on erosion gully development and damage in Black Soil Region of Northeast China (in Chinese). *Soil and Water Conservation in China, 8*, 68–70. 10.14123/J.Cnki.Swcc.2015.0230.

Capra, A., Di Stefano, C., Ferro, V., & Scicolone, B. (2009). Similarity between morphological characteristics of rills and ephemeral gullies in Sicily, Italy. *Hydrological Processes, 23*(23), 3334–3341. https://doi.org/10.1002/hyp.7437.

Chen, H., Fang, H. Y., Cai, Q. G., et al. (2006). Comparison of different aspect of erosion evolvement in the Loess Hilly area: a case study of Wangjiagou catchment of western Shanxi Province (in Chinese). *Resources Science, 28*, 176–184.

Cheng, H. Y., Wang, G. X., Wang, Y. B., & Hu, H. C. (2008). Variations of soil temperature and water moisture of seasonal frozen soil with different vegetation coverages in the source region of the Yellow River, China (in Chinese). *J Lanzhou Univ Sci, 44*, 15–21. 10.13885/J.Issn.0455-2059.2008.02.023.

Cui, M., Cai, Q. G., & Fan, H. M. (2007). Research progress on the soil erosion in black soil region of Northeast China (in Chinese). *Research of Soil and Water Conservation, 14*, 29–34.

De Baets, S., et al. (2008). Modelling increased soil cohesion due to roots with Eurosem. *Earth Surface Processes & Landorms, 33*(13), 1948–1963. https://doi.org/10.1002/esp.1647.

Dewitte, O., Daoudi, M., Bosco, C., & Van Den Eeckhaut, M. (2015). Predicting the susceptibility to gully initiation in data-poor regions. *Geomorphology, 228*, 101–115. https://doi.org/10.1016/j.geomorph.2014.08.010.

Dotterweich, M. (2008). The history of soil erosion and fluvial deposits in small catchments of central Europe: deciphering the long-term interaction between humans and the environment—a review. *Geomorphology, 101*(1–2, 192), –208. https://doi.org/10.1016/j.geomorph.2008.05.023.

Dotterweich, M., Rodzik, J., Zgłobicki, W., Schmitt, A., Schmidtchen, G., & Bork, H. R. (2012). High resolution studies of gully erosion, sedimentation processes, and land use changes since the Late Pleistocene and future trajectories in the Kazimierz Dolny area (Nał˛eczów Plateau, SE Poland), 95, 50–62.

Fan, H. M., Cai, Q. G., Chen, G., & Cui, M. (2005). Comparative study of the soil erosion and control in the three Major Black Soil regions in the world (in Chinese). *Journal of Natural Resources, 20*, 387–393.

Fan, H. M., Gu, G. H., Wang, Y. S., & Zhong, Y. F. (2013). Characteristics of eroded gully development and environment of black soil region in Northeast China (in Chinese). *Soil and Water Conservation in China, 10*, 75–79. 10.14123/j.cnki.swcc.2013.10.021.

Fan, J. R., & Pan, Q. B. (2002). The harm and control measures of soil erosion in typical black soil region of Northeast China (in Chinese). *Technology of Soil and Water Conservation, 5*, 36–38.

Groffman, P. M., Baron, J. S., Blett, T., Gold, A. J., Goodman, I., Gunderson, L. H., et al. (2006). Ecological thresholds: the key to successful environmental management or an important concept with no practical application? *Ecosystems, 9*(1), 1–13. https://doi.org/10.1007/s10021-003-0142-z.

Gu, G., Fan, H., Jia, Y., & Wang, Z. (2014). Study on the disintegration of brown soil in spring thaw period (in Chinese). *Soil and Water Conservation in China, 12*, 45–48.

Guo, W., et al. (2012). Effects of soil and water conservation and its interactions with soil properties on soil productivity. *Journal of Central South University, 19*, 2279–2285. https://doi.org/10.1007/s11771-012-1272-2.

Guo, B., et al. (2015). An estimation method of soil freeze-thaw erosion in the Qinghai-Tibet Plateau. *Natural Hazards, 78*(3), 1843–1857.

He, F. H., Wang, T., Gu, L. J., Li, T., Jiang, W., & Shao, H. (2014). An integrated use of topography with RSI in gully mapping, Shandong Peninsula, China. *Scientific World Journal, 2014*, 1–9. https://doi.org/10.1155/2014/827124.

Hu, G., Wu, Y. Q., Liu, B. Y., Yu, Z., You, Z., & Zhang, Y. (2007). Short-term gully retreat rates over rolling hill areas in black soil of Northeast China. *Catena, 71*(2), 321–329. https://doi.org/10.1016/j.catena.2007.02.004.

Ionita, I. (2011). The human impact on soil erosion and gulling in the Moldavian Plateau, Romania. *Landform Analysis, 17*, 71–73.

Ionita, I., Fullen, M. A., Zgłobicki, W., & Poesen, J. (2015). Gully erosion as a natural and human-induced hazard. *Natural Hazards, 79*(S1), 1–5. https://doi.org/10.1007/s11069-015-1935-z.

Kakembo, V., Xanga, W. W., & Rowntree, K. (2009). Topographic thresholds in gully development on the hillslopes of communal areas in Ngqushwa Local Municipality, Eastern Cape, South Africa. *Geomorphology, 110*(3–4), 188–194. https://doi.org/10.1016/j.geomorph.2009.04.006.

Konrad, J. M. (1989). Physical processes during freeze thaw cycles in clayey silts. *Cold Regions Science and Technology, 16*(3), 291–303.

Li, F., Zhang, S. W., & Li, T. Q. (2012). The spatial distribution relations between erosion gully and terrain factors in the south of typical black soil zone in Northeast China (in Chinese). *Soil Crop, 1*, 148–154.

Li, H., Cruse, R. M., Liu, X. B., & Zhang, X. Y. (2016). Effects of topography and land use change on gully development in typical mollisol region of Northeast China. *Chinese Geographical Science, 26*(6), 779–788. https://doi.org/10.1007/s11769-016-0837-7.

Liu, B. Y., Yan, B. X., Shen, B., et al. (2008). Current status and comprehensive control strategies of soil erosion for cultivated land in the Northeastern black soil area of China (in Chinese). *Science of Soil and Water Conservation, 6*, 1–8.

Man, X. L., Liu, J. C., Li, C. R., & Li, X. H. (1997). Effect of forest cutting on soil erosion and river silt in Xiaoxing'an mountains region (in Chinese). *Journal of Northeast Forestry University, 25*, 36–39. 10.13759/j.cnki.dlxb.1997.04.007.

Marzolff, I., Poesen, J., & Ries, J. B. (2011). Short to medium-term gully development: human activity and gully erosion variability in selected Spanish gully catchments. *Landform Analysis, 17*, 111–116.

Morgan, R. P. C., & Mngomezulu, D. (2003). Threshold conditions for initiation of valley-side gullies in the Middle Veld of Swaziland. *Catena, 50*(2–4), 401–414. https://doi.org/10.1016/S0341-8162(02)00129-7.

Poesen, J., Nachtergaele, J., Verstraeten, G., & Valentin, C. (2003). Gully erosion and environmental change: importance and research needs. *Catena, 50*(2–4), 91–133. https://doi.org/10.1016/S0341-8162(02)00143-1.

Poesen, J., Vandekerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D. J., Verstraeten, G., & Van Wesmael, B. (2002). *Gully erosion in dryland environments. Dryland rivers: hydrology and geomorphology of semi-arid*. Chichester: John Wiley Sons Ltd..

Shanley, J. B., & Chalmers, A. (1999). The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont. *Hydrological Processes, 13*(12–13), 1843–1857. https://doi.org/10.1002/(SICI)1099-1085(199909)13:12/13<1843::AID-HYP879>3.0.CO;2-G.

Sun, C. A. (2008). Application of 3S technology to develop soil and water loss monitoring at home and abroad (in Chinese). *Soil and Water Conservation in China, 6*, 54–57. 10.14123/j.cnki.swcc.2008.06.026.

Torri, D., & Poesen, J. (2014). A review of topographic threshold conditions for gully head development in different environments. *Earth-Science Reviews, 130*(3), 73–85.

Tang, W. J., Liu, H. H., & Liu, B. (2013). Effects of gully erosion and gully filling on soil degradation in the black soil region of Northeast China. *Journal of Mountain Science, 10*(5), 913–922. https://doi.org/10.1007/s11629-013-2560-5.

Valentin, C., Poesen, J., & Li, Y. (2005). Gully erosion: impacts, factors and control. *Catena, 63*(2–3), 132–153. https://doi.org/10.1016/j.catena.2005.06.001.

Vandekerckhove, L., Poesen, J., Wijdenes, D. O., Nachtergaele, J., Kosmas, C., Roxo, M. J., & de Figueiredo, T. (2000).

Thresholds for gully initiation and sedimentation in Mediterranean Europe. *Earth Surface Process and Landforms, 25*, 1201–1220. https://doi.org/10.1002/1096-9837(200010)25:11<1201::AID-ESP131>3.0.CO;2-L.

Vrieling, A., Rodrigues, S. C., Bartholomeus, H., & Sterk, G. (2007). Automatic identification of erosion gullies with ASTER imagery in the Brazilian Cerrados. *International Journal of Remote Sensing, 28*(12), 2723–2738. https://doi.org/10.1080/01431160600857469.

Wang, E. H. (2011). *Effect of machinery tillage and seasonal freeze-thaw on soil structure in black soil region (in Chinese)*. Harbin: Northeast Forestry University.

Wang, R. H., Zhang, S. W., Pu, L. M., Yang, J., Yang, C., Chen, J., et al. (2016a). Gully erosion mapping and monitoring at multiple scales based on multi-source remote sensing data of the Sancha River catchment, Northeast China. *ISPRS International Journal of Geo-Information, 5*(11), 200. https://doi.org/10.3390/ijgi5110200.

Wang, W. J., Zhang, S. W., & Fang, H. Y. (2012). Coupling mechanism of slope-gully erosion in typical black soil area of Northeast China (in Chinese). *Journal of Natural Resources, 27*, 2113–2122.

Wang, W. J., Zhang, S. W., Li, Y., & Deng, R. X. (2009). Dynamics and effect factors of gully in the black soil area of northeast during the past 40 years (in Chinese). *Journal of Soil and Water Conservation, 23*, 51–55. 10.13870/j.cnki.stbcxb.2009.05.020.

Wang, X., Zhao, X. L., Zhang, Z. X., Yi, L., Zuo, L., Wen, Q., et al. (2016b). Assessment of soil erosion change and its relationships with land use/cover change in China from the end of the 1980s to 2010. *Catena, 137*, 256–268. https://doi.org/10.1016/j.catena.2015.10.004.

Wang, Y. S., Wang, N. Z., Zhong, Y. F., et al. (2013). The gully distribution characteristics cross-province in the Black Soil Region of Northeast China (in Chinese). *Soil and Water Conservation in China, 10*, 67–69. 10.14123/j.cnki.swcc.2013.10.018.

Wang, Y. S., Wang, Y. X., & Li, H. X. (2007). Determination of black earth region boundaries and prevention and control tactics of soil and water conservation (in Chinese). *Soil and Water Conservation in China*, 12, 11–13+68. doi:10.14123/j.cnki.swcc.2007.12.014

Woodward, D. E. (1999). Method to predict cropland ephemeral gully erosion. *Catena, 37*(3–4), 393–399. https://doi.org/10.1016/S0341-8162(99)00028-4.

Wu, Y. Q., Zheng, Q. H., Zhang, Y. H., Liu, B., Cheng, H., & Wang, Y. (2008). Development of gullies and sediment production in the black soil region of northeastern China. *Geomorphology, 101*(4), 683–691. https://doi.org/10.1016/j.geomorph.2008.03.008.

Xie, Y. J., Wang, Y. S., & Wang, Y. X. (2005). Defining of chernozem area and zoning of soil and water conservation in Northeastern China (in Chinese). *Bulletin of Soil and Water Conservation, 25*, 48–50. 10.13961/j.cnki.stbctb.2005.01.013.

Yan, Y. C., Zhang, S. W., & Yue, S. P. (2007). Classification of erosion gullies by remote sensing and spatial pattern analysis in black soil region of eastern Kebai (in Chinese). *Scientia Geographica Sinica, 27*, 193–199. 10.13249/j.cnki.sgs.2007.02.012.

Yang, J. C., Zhang, S. W., Chang, L. P., Li, F., Li, T., & Gao, Y. (2017). Gully erosion regionalization of black soil area in northeastern China. *Chinese Geographical Science, 27*(1), 78–87. https://doi.org/10.1007/s11769-017-0848-z.

Zhang, S. W., Li, F., Li, T. Q., Yang, J., Bu, K., Chang, L., et al. (2015). Remote sensing monitoring of gullies on a regional scale: a case study of Kebai region in Heilongjiang Province, China. *Chinese Geographical Science, 25*(5), 602–611. https://doi.org/10.1007/s11769-015-0780-z.

Zhang, X., Gu, G., Fan, H., & Zhang, L. (2014). Research on the relationship between rainfall erosivity and gully development in provinces in northeast black soil region (in Chinese). *Journal of Shenyang Agricultural University, 45*(2), 249–252. https://doi.org/10.3969/j.issn.1000-1700.2014.02.027.

Zhao, Y., Wang, Z. G., Sun, B. P., Zhang, C., Ji, Q., Feng, L., et al. (2013). A study on scheme of soil and water conservation regionalization in China. *Journal of Geographical Sciences, 23*(4), 721–734. https://doi.org/10.1007/s11442-013-1040-8.