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Remote Sensing Monitoring of Gullies on a Regional Scale: A Case Study of Kebai Region in Heilongjiang Province, China

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Abstract: Gully erosion is one of the major causes of land degradation in most areas and attracts increasing attention from researchers. We monitored gullies in the Kebai region in Heilongjiang Province of China by using remote sensing data and found that gully density increased with the increase in slope when the slope was less than 3°. Gully density in sunny slopes or windward slopes was greater than in shady slopes or leeward slopes because of the impacts of freezing and thawing, wind and solar radiation. Specifically, the gully density in northeast slope was the greatest and in southwest was the smallest. Gully density was reduced with increasing slope length and the longer the slope length, the less the gully density changed between 1965 and 2005. Affected by runoff, gullies most easily to occur in concave slopes and the critical elevation for gully erosion was 250–275 m. Moreover, hilly regions had the greatest gully density, followed by tableland regions, whereas the gully density in flatlands was the lowest. However, the gully density of these three types of landforms all increased between 1945 and 2000, and the portion of increase was 57.45% (hill), 52.91% (mesa) and 25.32% (plain), respectively.

Keywords: gully density; gully erosion; monitoring; remote sensing; Kebai region, China

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1 Introduction

Gully erosion, which is one of the most critical and most destructive water-made erosion types, results in displacement, sedimentation and degradation of soil. In recent years, this has drawn more and more attention from researchers (Valentin *et al.*, 2005; Salleh and Mousazadeh, 2011; Shellberg *et al.*, 2013). Poesen *et al.* (2003) collected sediment yield data of gully erosion in 56 different areas and found that gully erosion produced the proportion of total sand accounts for watershed sediment yield in these areas from 10% to 94%. The gullies damaged the landscape and increased the connectivity of rills that exacerbated the surface runoff. Gullies also eroded farmland and destroyed the integrity of the land, which resulted in land degradation and caused great damage to land resources (Yan *et al.*, 2006; 2009; Wang *et al.*, 2008; 2011; 2012). Researchers currently use a variety of methods to monitor gullies and analyze the critical erosion impact factors of gullies, such as slope gradient, slope length, slope shape and slope aspect (Morgan and Mngomezulu, 2003; Vanwalleghem *et al.*, 2003; Gutiérrez *et al.*, 2009; Nazari *et al.*, 2010) and the development process and morphological characteristics of gullies and gully erosion prediction, prevention and control (Betts *et al.*, 2003; Daba *et al.*,

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2003; Ndomba *et al*., 2009; Perroy *et al*., 2010). The ecological restoration of gully erosion also contributes to a broader understanding of the formation and development mechanism of gullies (Lesschen *et al*., 2007; Kertész and Gergely, 2011).

Therefore, choosing an appropriate method to monitor the development process of gullies is important for the in-depth understanding of the gully development processes and gully prevention measures (Beavis, 2000; Baruch and Filin, 2011). The initial methods of gully monitoring were manual measurement, such as the grain-size contrast method (Li *et al*., 2006), the volume method (Zhang *et al*., 2008) and using a topographic needle instrument (Ding and Zhang, 2006). These methods were conducive to data acquisition and processing, but they were greatly influenced by artificial factors and there was a large deviation between analysis result and the actual situation. Furthermore, the measurement process destroyed the gully morphology and increased the inaccuracy of the measuring results (Bremer and Sass, 2012).

The development of remote sensing provided an efficient method for gully measurement which could obtain gully information on a large scale at different times (Conoscenti *et al*., 2014; Corporation, 2014; Teasdale and Barber, 2014). Because the spatial resolution and temporal resolution were low, the gully morphology data obtained from aerial photos often did not properly reflect the small-scale changes and variability of the gully (Ries and Marzolff, 2003; Bouaziz *et al*., 2011). Some scholars monitored gully changes at the centimeter level by using hot air balloons, kites and aerial radar, which showed great potential for the use of these devices in gully monitoring on a small scale (Ritchie *et al*., 1994; Marzolff and Poesen, 2009). For monitoring gullies on a larger scale, satellite remote sensing imaging is a better choice. As the space and time resolution was constantly improved, satellite images has had a broad application potential in large scale gully monitoring (Muñoz-Robles *et al*., 2010). Though aerial photography used in gully studies has been used for a long time, and commercial satellite data recently became available with the spatial resolutions needed to depict gully development, both methods are less effective in areas covered by heavy foliage, especially where abrupt and frequent surface changes were present (James *et al*., 2007). 3D laser scanning technology is a newer technology that came into use in the mid-1990s. Using this technology in monitoring gullies can quickly and accurately rebuild gullies in 3D and obtain the erosion rate of gullies through continuous scan measurements (Alho *et al*., 2011; Zhang *et al*., 2011).

The fine spatial-temporal resolution of satellite images made it possible to identify gullies with complex surroundings as well as a wide range of factors which control the development and distribution of gully erosion, such as land-use, soil surface roughness, slope, slope aspect, slope shape, slope length and drainage area (Mousazadeh and Salleh, 2014a; 2014b; Teasdale and Barber, 2014). Such data could, however, also be obtained from remote sensing data and digital elevation model (DEM) technology (DeRose *et al*., 1998; Ramos *et al*., 2004; Li *et al.,* 2007; Shruthi *et al*., 2011). Usually, researchers performed their gully research on a small scale, using ground surveys or aerial photo interpretation to monitor short-term changes of gullies. The study of the distribution and dynamic changes of gullies on a large spatial-temporal scale was still rare (Yan *et al*., 2005; Seeger *et al*., 2009). For this study, we selected a typical black soil region (the Kebai region in Heilongjiang Province that has been seriously destroyed by gully erosion) as the study area and used satellite image data and ground measurement data at different times to monitor the distribution, development and trends pertaining to this gully. We specifically focused on finding a useful method to get gully data over time, which is very important in order to understand the relationship between gullies and human activity.

2 Material and Methods

2.1 Study area

The Kebai region in Heilongjiang Province (47°01′–48°56′N, 124°00′–127°54′E) is located in the western part of the Heilongjiang Province, mainly consisting of two cities (Nehe, Bei′an) and six counties (Keshan, Kedong, Fuyu, Yi′an, Baiquan and Mingshui), with a total area of 32 856.7 km^2. Located in the southwest area of the Xiao Hinggan Mountains and on the northeast margin of the Songnen Plain, this area is the transition zone from low hills to plains and the typical black soil hilly area. Most of the area is covered by typical black soil, meadow soil and marsh soil. The elevation ranges from 139 m to 875 m; the northeast consisting of undulating terrain and hilly areas; the southwest consists of undulating plains. The Kebai region in Heilongjiang Province has a continental monsoon climate with an average annual temperature of 0.2℃–1.5℃ (significant changes during the year) and annual precipitation of 550–600 mm (concentrated in July, August and September). The average annual runoff was about 75 mm (Fig. 1).

2.2 Data and processing

Basic data used herein included 1∶100 000 topographic maps (1945, 1950s, and 2000), U.S. Corona reconnaissance satellite images (1965), Landsat Enhanced Thematic Mapper Plus (ETM+) multi-spectral remote sensing images (2000), Systeme Probatoire d′Observation de la Terre-5 (SPOT-5) satellite images (2005), 1∶100 000 administrative maps of the Heilongjiang Province and Digital Elevation Model (DEM) data (90 m × 90 m). Corona, Landsat ETM+ images and SPOT-5 satellite images used in this study were remote sensing images with higher spatial resolution. After digitization, geometric correction and projection conversion in ArcGIS 10.0, these data were projected using a Beijing 54 coordinate system using the Gauss-Kruger projection. The 1∶100 000 topographic maps were used to extract gully data from 1945. The data source of gully data in 1965 was Corona black and white images from 1965, and the best ground resolution was 2.75 m. We obtained gully data from 1965 by combining surface features, such as image texture, size and distribution, with gully data interpreted from SPOT-5 satellite images from 2005, topographic maps from the 1950s and other field survey data. Gully data for 2000 were based on topographic maps and Landsat ETM+ images. In order to highlight the topography information on ETM+ images, we stacked the 4, 3 and 2 bands in image processing software with image resolution of 28.5 m. Based on simulated true color images with a resolution of 2.5 m fused from SPOT-5 panchromatic and multispectral image and interpretation marks established through field surveys, we extracted gully data from 2005 by visual interpretation.

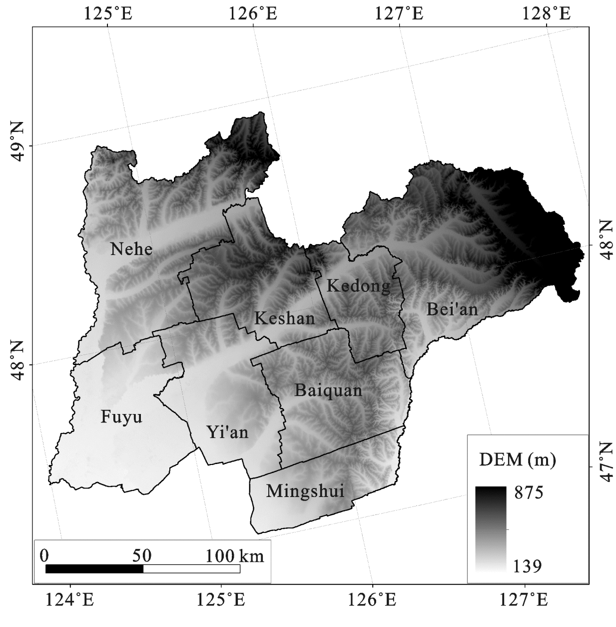

Fig. 1 Location of study area and its elevation distribution. DEM is digital elevation model

Interpretation signs on Corona images. The Corona images from 1965 were black and white, which made it impossible to determine the condition of the vegetation in the gully, so only gully length could be derived. Gully dynamics can also be obtained by comparing with the gully length in SPOT-5 images (Fig. 2).

Interpretation signs on SPOT-5 images. According to the condition of the vegetation cover in the gully on SPOT-5 images, the gullies in the study area in 2005 were classified as either an active gully, a semi-active gully or a stable gully. Active gullies were often covered by bare soil and the color was bright white on SPOT images (Fig. 2a2). The sapping speed of semi-active gullies slowed down and there were some deposits and vegetation, showing as light green on SPOT-5 images (Fig. 2b2). Stable gullies stopped sapping and there was a lot of plant growth such as shrubs and small trees, presenting as green on SPOT-5 images (Fig. 2c2).

Interpretation signs on Landsat ETM+ images. 1) Gullies in the development stage were V-shaped and there was no vegetation across the gullies or only annual plants existed, which made them stand out more clearly from the surrounding farmlands due to the gullies being gray or yellowish-white on the standard false-color composite image (Fig. 2a3); 2) Gullies in the resting phase stopped headward erosion and the valley terrain was relatively broad, including a lot of sediments and plants; some places had even been reclaimed to farmland. The color of this type of gully on standard false-color composite images was green or light green, and it was difficult to recognize the gully from arable land (Fig. 2b3).

Gully density was taken as an indicator of gully dynamic analysis in this article, which is defined as the

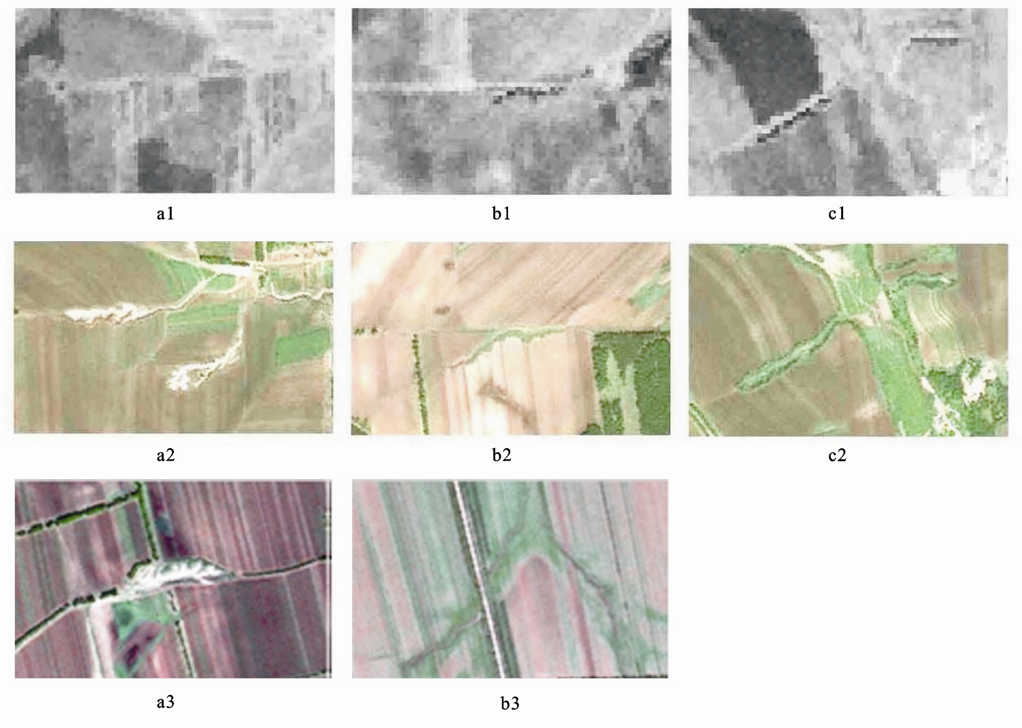

Fig. 2 Interpretation signs of gully on Corona images (a1, b1, c1), Systeme Probatoire d'Observation de la Terre-5 (SPOT-5) images (a2, b2, c2) and Landsat Enhanced Thematic Mapper Plus (ETM+) images (a3 and b3)

total length of gully per unit area, reflecting the degree of land surface fragmentation and the severity of soil erosion. Considering the consistency of climatic, vegetation, geology and other factors within the study area, the most important natural factors influencing the distribution and dynamics of the gully were landforms and terrain. In order to monitor the distribution and dynamics of the gully in regions with different landform characteristics, we selected slope, slope aspect, slope length, slope shape, elevation and terrain as impact factors, and analyzed the spatial-temporal distribution characteristics of gullies and the gully density changes on different landforms by using gully data obtained from different data sources from 1945 to 2005.

3 Results and Analyses

3.1 Impact of slope on gullies

Given a certain slope (S), a critical drainage area (A) was necessary to produce sufficient runoff to start gulling. A threshold line ($S = aA^b$) was determined by the scientists (Poesen and Valentin, 2003) with the constant a and the exponent b depending on environmental characteristics (Poesen *et al.*, 2003). Generally, there was a threshold slope for the increase in gully density. When the slope was less than the threshold, gully density increased with the increase in slope; otherwise, it would decrease (Yan *et al.*, 2007).

The slope in the study area was generally less than 5° and there was no gully on flat ground, therefore we divided the slope into 6 grades (<1°, 1°–2°, 2°–3°, 3°–5°, 5°–8° and >8°) and calculated the average density of the gully in different slope ranges in different years (Fig. 3). The results showed that the threshold value for the increase in gully density in Kebai region was 3°.

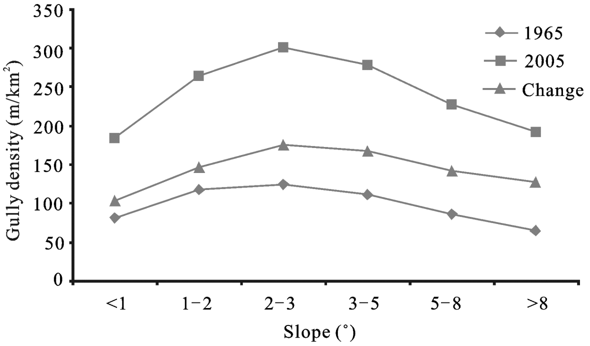

Fig. 3 Gully density and its change between 1965 and 2005 with different slopes

When the slope was less than 3°, the gully density increased with the increasing slope gradient. When the slope was greater than 3°, the gully density decreased as the slope increased; the slope was not the major factor during the formation of the gully. The gully formation was more affected by other terrain factors, such as slope length, catchment area and slope morphology. In addition, it can be seen from the change curve of gully density between 1965 and 2005 that the change amount of gully density in these 40 years in each slope grade was greater than 100 m/km^2, showing that the reclamation of land exacerbated the gully erosion in the study area. It is worth noting that the greatest change of gully density happened when the slope was 3°–5°, reflecting that humans gradually reclaimed land with greater slope in order to meet the demand for food (Wang *et al.*, 2009).

To further analyze the influence of the slope on gullies, gully distribution data from 1945 and 2000 from four counties (Keshan, Kedong, Baiquan and Mingshui) were obtained from topographic maps and Landsat ETM+ multispectral remote sensing images, dividing slopes into 10 gradients (0.5°–1.0°, 1.0°–1.5°, 1.5°–2.0°, 2.0°–2.5°, 2.5°–3.0°, 3.0°–3.5°, 3.5°–4.0°, 4.0°–4.5°, 4.5°–5.0°). The results indicated that the gully density on every slope gradient in 2000 was 2 to 3 times that of the gully density in 1945. Gully density tended to decrease in the area where the slope was greater than 4.5° in 1945; there was, however, an increase in 2000 (Fig. 4). This reflects the impact of human activity on the occurrence and development of gullies in northeastern China. Humans continually reclaimed wasteland as arable land due to population growth, which destroyed the original structure and the nature of the soil and resulted in an upward trend in critical slope of increase in gully density (Yan *et al.*, 2005; Li, 2012).

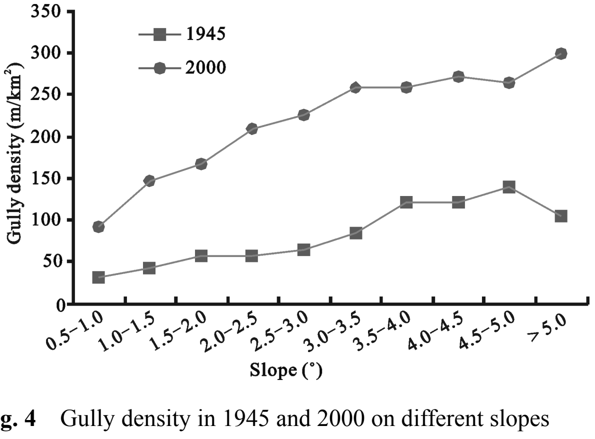

Fig. 4 Gully density in 1945 and 2000 on different slopes

3.2 Impact of slope aspect on gullies

Slope aspects were among the main factors affecting the flow of surface runoff and the redistribution of ground sunlight energy. The main effects of slope aspect on gully development were the difference in vegetation growth and land use caused by different hydrothermal conditions and precipitations, eventually leading to different gully densities. It could be observed that there was a great difference in the distribution of gullies due to different slope aspects. We focused on the black soil region of the eastern Kebai for a case study, and obtained the distribution of gullies pertaining to different slope aspects in 2005 (Fig. 5). Considering the influence of mountains, monsoons, solar radiation and freezing and thawing, we concluded that the gully density in sunny slopes was greater than in shady slopes; similarly, gully density in windward slopes was greater than in leeward slopes (Yan *et al.*, 2007).

In order to explore the change of gully density for different slope aspects, we divided the slope aspects of four counties (Keshan, Kedong, Baiquan and Mingshui) into eight aspects (north, northeast, east, southeast, south, southwest, west and northwest) and superimposed them over gully distribution maps from 1945 and 2000, respectively; thereby finding the spatial distribution and changes of gully density for different slope aspects (Fig. 6). Gully density in 2000 was greater than in 1945 for every aspect. Moreover, the maximum gully density change between 1945 and 2000 occurred in southwest

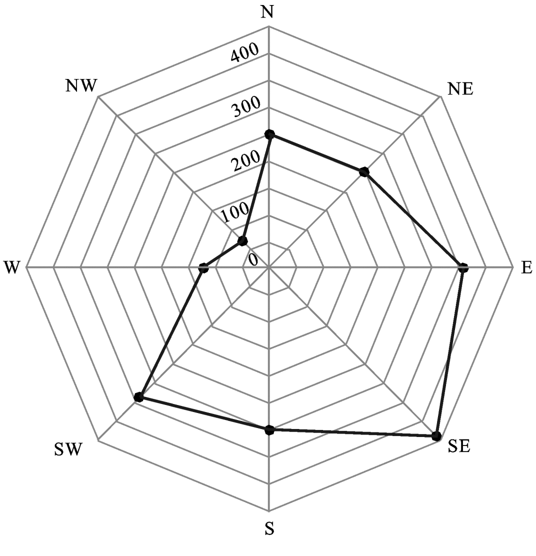

Fig. 5 Gully density (m/km^2) for different aspects. N: north; NE: northeast; E: east; SE: southeast; S: south; SW: southwest; W: west; NW: northwest

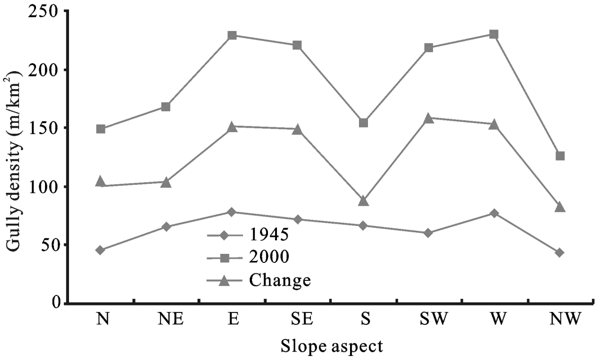

Fig. 6 Relationship between gully density and slope aspects in Kebai region, Heilongjiang Province. N: north; NE: northeast; E: east; SE: southeast; S: south; SW: southwest; W: west; NW: northwest

slopes, whereas the change of gully density for south slopes was very small. These spatial distributions and dynamic changes were mostly caused by land use change resulting from human activity, especially for southwest slopes (Yan *et al.*, 2005).

3.3 Impact of slope length on gullies

Slope length was also an important terrain factor that influenced the occurrence and development of gullies. As indicated by hydrology and soil erosion theory, we extracted slope lengths for each watershed from DEM by using digital terrain analysis and analyzing the process of surface runoff and sediment mass transfer. Then we graded the slope length in the Kebai region in order to investigate the impact of slope length on the formation and development of gullies.

It was found that gully density distribution trends for different slope lengths were similar in each period; in general, gully density was reduced with increasing slope length (Fig. 7). The maximum gully density occurred in the regions where the slope length was less than 1000 m. This was mainly because arable land is mainly found in this area. However, the reason why the gully density sharply increased in the region with a slope length of 2000–2500 m was not clear. It might relate to land use, vegetation and other factors in the area (Wang *et al.*, 2009). In addition, the relationship between gully density changes (y) from 1965 to 2005 and slope length (x) can be simulated by a linear function:

$$y = -0.022x + 136.89 \quad (R^2 = 0.938) \qquad (1)$$

As is shown in Equation (1), for 40 years, the change of gully density was negatively correlated with slope length: The greater the slope length, the smaller the gully density change. Therefore, the slope length was not the only factor influencing gully erosion; soil, vegetation and land use all played an important role in the process of gully development.

3.4 Impact of slope shape on gullies

The slope shape can be extracted from DEM; it generally includes concave slope, straight slope and convex slope. When superposed on gully data, the distribution of gullies in different slope shapes can be monitored clearly and precisely. The results of our study show that the probability of erosion ditches occurring in a concave slope was almost 10 times higher than in a straight slope. A convex slope had a minimal probability of the occurrence of a gully (Table 1).

3.5 Impact of elevation

On the basis of DEM data, we divided the elevation in the Kebai region of Heilongjiang Province into eight grades (Fig. 8) in order to analyze the vertical different characteristics of gullies. It was found that the vertical distribution curves of gully density in 1965 and 2005 were similar; both increased first and then decreased with increase in elevation. There was a maximum gully density at elevations between 250–275 m (81.49 m/km^2 and 387.67 m/km^2, respectively, for 1965 and 2005), which showed that gully erosion in black soil areas was most likely to occur at elevations between 250–275 m. This elevation was considered to be the critical value in the development of gully erosion (Fig. 8).

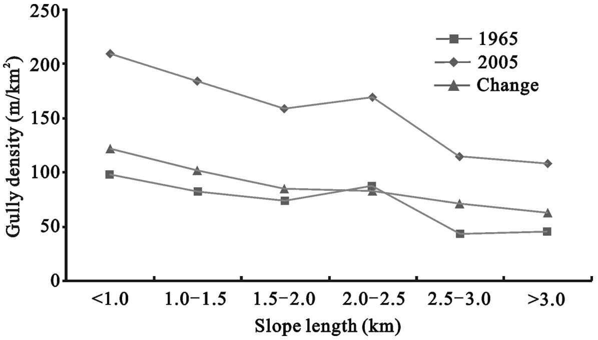

Fig. 7 Relationship between gully density and slope length

Table 1 Distribution of gullies in different slope shapes

Slope shape	Gully area (m^2)	Class area (km^2)	Gully density (m^2/km^2)
Concave slope	607 500	44.06	13 789.30
Straight slope	12 402 000	8174.87	1517.09
Convex slope	37 800	43.10	877.12

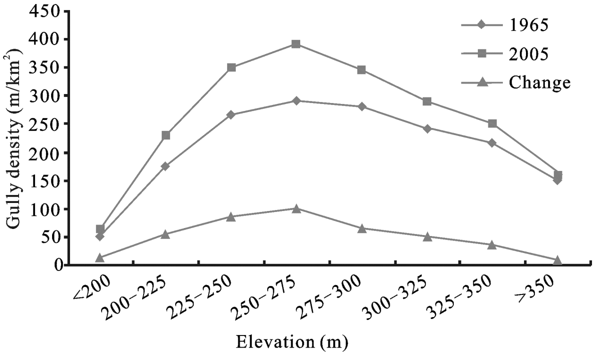

Fig. 8 Gully density and its change between 1965 and 2005 at different elevations

4 Discussion

Experimental research and monitoring research of gullies are important methods for obtaining gully data. The majority of the experimental studies were carried out on a relatively small spatial and temporal scale, while the temporal and spatial scales of monitoring studies were relatively large, pertaining to regions generally larger than 10 km^2 and over a period over two years.

Gully erosion on a regional scale is a complex natural process affected by many factors, including soil, geology, vegetation and human activities. Although a lot of studies pertaining to the understanding of single factors have been conducted, their composition and change within a larger geographic system remain unclear. An important method for gully erosion monitoring and forecasting on a large scale is scale conversion theory and technology. Gully erosion monitoring on a large scale has important practical applications for strengthening the control of soil erosion. Inspection and use of results from microscopic studies were also important in order to better understand the change in status of gully erosion under global climate change.

This study monitored and analyzed the distribution and changes of gullies in the last 60 years in the Kebai region in Heilongjiang Province, based on topographic maps and satellite remote sensing images. Results show that the slope threshold value of the gullies in the study area was 3°. The study by Li *et al.* (2004) reached similar conclusions and found that the critical slope gradient for rills (< 0.3 m deep), shallow gullies (0.3–2 m deep) and deep gullies (> 2 m deep) were 2°, 5° and 8°, respectively. The critical slope for gullies in northeastern China was significantly less than that in the Loess Plateau due to the different farming history of these two regions. There are more than two thousand years of farming history in the Loess Plateau, whereas the cultivation of black soil land in northeastern China generally started within the latest hundred years, mainly distributed in flat areas (Li *et al.*, 2012).

In general, there are great differences in gully density for different slope aspects. The density of gullies on sunny slopes (windward slopes) was greater than that of shady slopes (leeward slopes). The reasons were: 1) the terrain in study area; 2) the solar radiation on sunny slopes and shady slopes was different, resulting in different microclimates in different aspects (according to some studies on freeze-thaw erosion, the total amount of solar radiation on sunny slopes was greater than that of shady slopes, leading to a greater temperature difference between day and night, so there was a stronger freeze-thaw action on sunny slopes than on shady slopes; besides, the snow on sunny slopes melted more quickly than on shady slopes in spring, causing more gully distribution on sunny slopes); 3) due to summer monsoons, rainfall in the study area is mainly concentrated in June, July, August and September. Also, the sunny slopes are the windward slopes in the Kebai region, thus the included angle between raindrops and slope surface on sunny slopes was greater than on a shady slope, resulting in a greater strike on sunny slopes.

Gully erosion mostly occurred in concave slopes. This was because the slope shape determined the surface runoff, aggregating the gully erosion process. Convergence of runoff would increase the under shear which can result in gully erosion; on the contrary, divergence of runoff was often accompanied by infiltration and transpiration which was against the occurrence of gullies. When comparing straight and convex slopes, concave slopes were most likely to form aggregation runoff when taking its convergence role in runoff into account, resulting in gully erosion. Therefore, the gully density in concave slopes was the greatest, while the convex slope had the lowest gully density (Li, 2012).

Gully density first increased and then decreased with increase in elevation. The distribution pattern of gully erosion in the vertical direction mainly reflected in the following aspects: 1) it was mainly newer deposition where the elevation was low, such as valley plains and depressions; 2) there was no significant erosion occurring in the mesa hills which were higher than plains and had a gentle slope and a small catchment area; 3) the hillock zones between tablelands, hills and flatlands and depressions were the main areas where gully erosion occurred and distributed. The geomorphic types in the Kebai region consist of tableland, hills and plains, and are characterized by rolling hills. We superimposed gully erosion maps from 1945 and 2000 on geomorphologic maps and calculated the average gully density in different landscape regions. Results showed that the hilly regions had the greatest gully density, followed by tableland regions, whereas the gully density in the flatland was the lowest (Table 2). For the change of gully density between 1945 and 2000, gully density of these three types of landforms all increased, and the rate of increase was 57.45% (hill), 52.91% (mesa) and 25.32% (plain), respectively. Mesas and hilly areas, especially low hilly areas, should be the focus of future governance and protection in terms of both gully density and the rate of increase.

This study has some limitations. We could only get the length and area data of gullies from satellite remote sensing images, and it was therefore difficult to estimate the erosion amount of a gull. Thus, there might be errors in the assessment of soil erosion risk and the analysis of damage of gullies to arable land. Besides, limited by the low resolution of historical satellite images, gully area data extracted from satellite images in 1965 were not suitable for analyzing. In order to compare the distribution of gullies and analyze the changes of gullies at different times, we applied gully length as the basic data which inevitably resulted in the results being less comprehensive.

The interpretation methods of gully data need to be improved. Gully data for this study were obtained through time-consuming visual interpretation, and the accuracy of the interpretation results highly depended on the image interpreter. It is therefore necessary to utilize automatic interpretation of gullies, using remote sensing on a larger scale (national, intercontinental and global scales). Because of the characteristics of gullies, it was difficult to identify the gully from other ground objects (arable land, rivers, roads, *etc.*) on the satellite remote sensing images. It is therefore important to combine gully physical parameters (such as temperature, humidity, *etc.*) as well as spectral features of gullies on satellite remote sensing images in order to develop new gully automatic interpretation methods.

Table 2 Gully density change in different morphogenetic regions in Kebai region, Heilongjiang Province from 1945 to 2000

Landform	Area (km^2)	Gully density (m/km^2)		Increase rate (%)
		1945	2000	
Plain	4882.57	61.12	76.60	25.32
Mesa	5195.89	135.03	206.48	52.91
Hill	1310.11	216.26	340.50	57.45

Due to the crown cap coverage, it was difficult to monitor gullies developing under woodlands by using satellite remote sensing images. In addition, when monitoring gullies using satellite images it is important to select images within appropriate seasons. In general, images in spring and autumn are appropriate, because gullies are difficult to recognize from summer images (there is vegetation in the gully) and winter (the gully is covered by snow).

5 Conclusions

We monitored the gully erosion in a typical black soil region, Kebai region in Heilongjiang Province of the northeastern China, using remote sensing data. We reached the following conclusions: 1) gully density first increased and then decreased with the increase of slope; the critical threshold of slope being 3°; 2) the extent of gully erosion of sunny slopes (or windward slopes) was greater than that of shady slopes (leeward slopes) due to the impact of freezing and thawing, wind and solar radiation; 3) the longer the slope length, the smaller the gully density changes between 1965 and 2005; 4) concave slopes were especially vulnerable to gully erosion, and gullies seldom occurred in convex slopes; 5) when elevation was less than the threshold value of altitude (250–275 m), the density of a gully was proportional to elevation, whereas when the elevation was greater than this value, the density of a gully was inversely proportional to elevation; 6) regarding terrain characteristics: The density of gullies on rolling hills was the greatest, followed by tableland, whereas plains had the lowest gully density.

Moreover, applying high-resolution aerial and satellite images and topographic surveying instruments, for example 3D laser scan technology, to carry out large-scale monitoring of gully erosion is still an important approach. In the long term, developing physical models of the gully erosion process for gully erosion prediction at different spatial and temporal scales based on the monitoring of gully erosion is the most important aspect pertaining to the future development of gully research.

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