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Effects of Topography and Land Use Change on Gully Development in Typical Mollisol Region of Northeast China

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Abstract: Due to high intensity agricultural exploitation since the middle of the 20th century, farmland gullies have become a pervasive form of water erosion in Northeast China. Yet few researches are concentrated on how topography and land use affect long-term gully development in this region. In this study, gully distribution in a village with an area of 24.2 km^2 in the central Mollisols area of Northeast China in different times were compared by Aerial photography (1968), Quickbird image (2009) and field survey, and factors affecting gully development including land use and topography were analyzed. The results showed that the total gully number decreased from 104 to 69, while occupying area rose from 34.8 ha to 78.4 ha from 1968 to 2009. Fundamental gully distribution had been formed by 1968 as most of 2009′s gullies were evolved from 1968′s gullies′ merge and width expansion process, and new gullies those initiated after 1968 occupied only 7% of total gully area in 2009. Gully area increasing ratio in grassland was the highest and that in forestland was the lowest. The threshold catchment area between simple and complex gully development was around 15 ha to 25 ha. This threshold value sets apart catchment areas that will develop simple or complex gullies in areas with similar environmental conditions. Gully control measurements were urgent because if appropriate gully control implements would not be applied, present gully erosion crisis could be doubled within 50 years.

Keywords: gully erosion; land use; topographic threshold; Mollisols; Northeast China

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1 Introduction

Water erosion, a serious global ecological problem, is a significant consequence of anthropogenic land-use change. Priority has been given to sheet and rill erosion research in the past decades; however gully erosion, as a major part of the land degradation process, is attracting growing research interest (Poesen *et al.*, 2003; Valentin *et al.*, 2005). Field gully formation is commonly regarded as a sign of severe soil erosion (Poesen *et al.*, 2002). Gullies in the farmland can transfer agricultural pollution, cause farmland fragmentation and disturb normal framing operations (Nachtergaele and Poesen, 1999; Kirkby *et al.*, 2003).

Farmland gully formation and development are commonly associated with topography and land use. Previous studies addressed that gully erosion initiation is a threshold phenomenon (Horton, 1945; Montgomery and Dietrich, 1994). A necessary topographic threshold combination of upland drainage area (A) and slopeness (S) is required to produce sufficient runoff to cause gully erosion in a given landscape with a given climate and land cover (Patton and Schumm, 1975). Land use change is another important factor on gully development

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since it can affect vegetation cover on gully (Martínez-Casasnovas *et al.*, 2009; Wei *et al.*, 2012). Research about gully processes under different land uses in New Zealand shows that the needed catchment area under pasture for gully initiation is less than that under indigenous forest, and land use change can shift topographical threshold for gully development (Parkner *et al.*, 2006). Aerial photography is an efficacious means to investigate land use change effect on gully evolvement, especially for the medium-time scale (10–70 years) gully development analysis (Wijdenes *et al.*, 2000; Nachtergaele *et al.*, 2002; Oostwoud Daba *et al.*, 2003; Chaplot *et al.*, 2005; Descroix *et al.*, 2008; Moges and Holden, 2008; Frankl *et al.*, 2013).

Northeast China is the bread basket of this large country, where fertile and productive Mollisols (also called black soils) are primarily distributed. More than 80% of the land was transformed from native vegetation into farmland in the past century. This region is located in the north temperature zone, and its average rainfall precipitation is 530 mm, of which 65% occurs from June to August. Its representative landscape is rolling hills with long slope length and level plains. Excessive cultivation, long slopes, erosion-susceptible soil, high-intensity summer rainstorms, and lack of soil and water conservation measures have caused concentrated runoff and severe water erosion, which lead to extensive gully erosion in this region (Liu *et al.*, 2010; Kravchenko *et al.*, 2011; Gong *et al.*, 2013). In 2010 there were 290 000 gullies in Northeast China, occupying more than 5000 km^2.

Chinese researchers have investigated short-term ephemeral gully development using GPS in Mollisols region (Zhang *et al.*, 2007; Wu *et al.*, 2008). However, few reports focused on the long-term gully development accompanying with land-use change (Li *et al.*, 2012). Documenting long-term gully development is important not only for understanding gully erosion mechanisms involved, but also for identifying costs and benefits to the local government when making sustainable strategies for protecting grain production in the region. The objective of this study was to evaluate the effects of topography and land use on long-term gully development in a typical Chinese Mollisols region from 1968, by which time almost all indigenous trees were cleared, to 2009 when some afforestation occurred.

2 Materials and Methods

2.1 Study area

The study area is located in the Guangrong Village (24.2 km^2), Hailun City, Heilongjiang Province (Fig. 1), which is in the center of the typical Mollisols zone in Northeast China. Land reclamation of this region started in 1897, and the first gully was recorded around the 1930s (Zhao *et al.*, 2004). More than 4.5% of farmland in this region was lost due to gully erosion by 2012 (Li *et al.*, 2012). This area is in the north temperature zone with continental monsoon conditions (cold and arid in winter, hot and rainy in summer). From March to October in 2002–2015, average rainfall precipitation was 530 mm, of which 65% occurred from June to August with an average value of 474.3 mm. Average annual temperature is 1.5℃. The seasonal precipitation from 2002 to 2014 in the study area is presented in Fig. 2. The soils are typical Mollisols (Udolls) with silty clay loam texture, high clay content and high soil organic matter (SOM) (Chen *et al.*, 2011). The gentle hilly terrain was developed in Quaternary lacustrine deposits by subsequent fluvial. Eighty percent of the area′s landscape is rolling hills, and the other 20% is flat plain.

2.2 Data sources

The land use and gully distribution within the study area were obtained from aerial photographs on September 16, 1968 and Quickbird images on July 4, 2009. The flight scale of 1968′s aerial photography was 1∶15 000 and ground resolution was about 0.60 m. The ground resolution of Quickbird panchromatic image was 0.66 m, which was similar with that of the 1968′s aerial images. The 1968′s aerial photographs were georeferenced with 2009′s Quickbird′s image through same objects. Land-use and gully distribution were delineated by visual interpretation. The location and dimension of land-use and gully interpreted from 2009′s images were validated in the field first. Then the ground features′ distribution in 2009 was applied as priori knowledge in 1968′s visual interpretation, and 1968′s result was validated through consulting with local people. Vegetation cover was determined using a variety of visual cues including vegetation height, patch shape, crown texture and form, projected shadow, and location. Gully vegetation was identified by overlaying the land-use layer after all gullies were identified on the landscape.

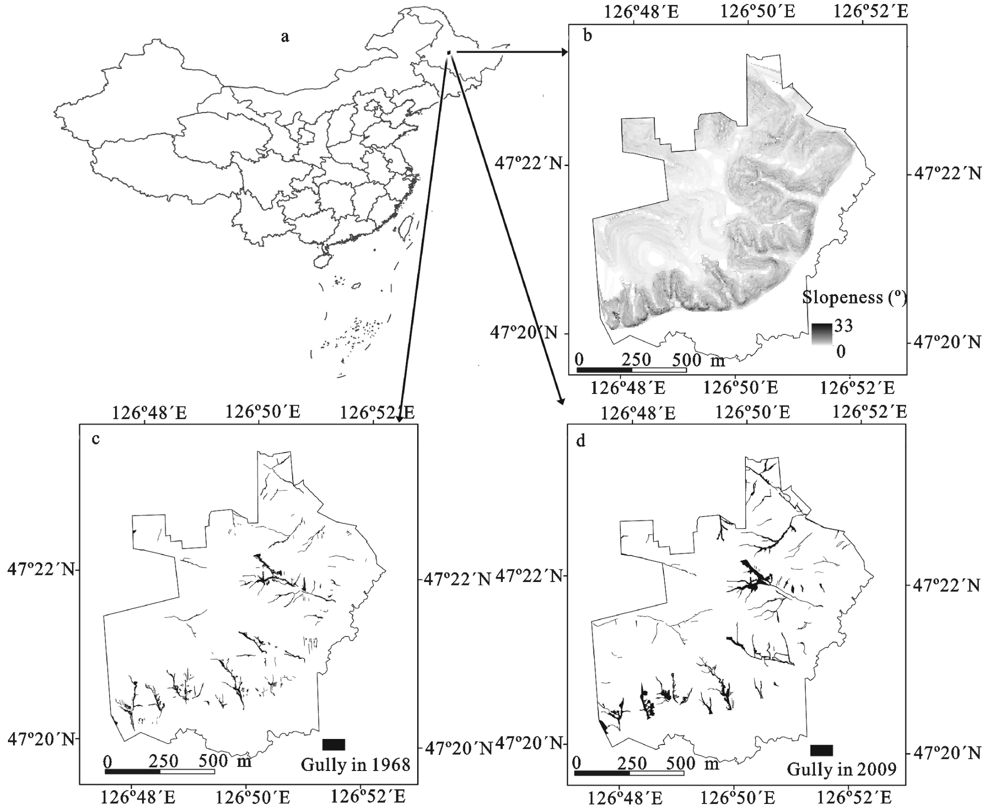

Fig. 1 Sketch of location (a), slopeness (b) and gully distribution (c, d) of Guangrong Village in center of Mollisols area in Northeast China

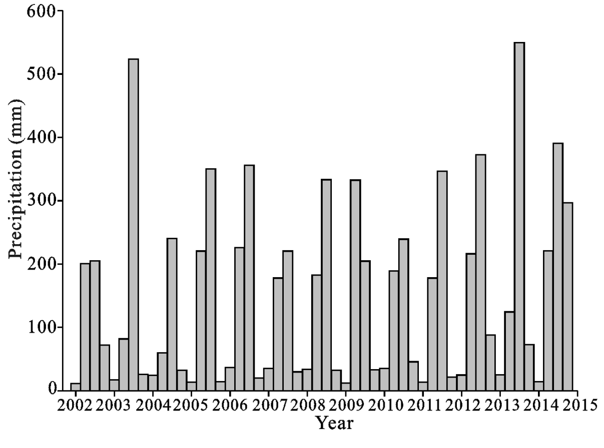

Fig. 2 Seasonal precipitation from 2002 to 2015

Eight complex gullies were randomly selected and measured to determine the gully depth, width and length in order to obtain a general understanding of 2009′s gully morphology. The interval distance of sampled cross-sections for each gully was set to 20–30 m, and cross sections were measured manually using a 50-m surveyor′s ruler. Gully width and depth in the deepest position of each gully cross-section were measured using a meter ruler. Additional measurements were obtained whenever the cross-section of the gully changed abruptly.

The terrain data were extracted from a 1984 1-m interval contour map using the ESRI ArcGIS. The topographic data represent the region′s terrain for both 1968 and 2009 as no basic topographic change occurred outside of the gullied area during this time period.

2.3 Data analysis

Each gully was assigned a discreet number so that it could be cross-referenced between 1968 and 2009 data sets. Gullies that did not exist in 1968 but appeared in 2009 were classified as new gullies. Gullies presented both in 1968 and 2009 were classified as remaining gullies and they were subdivided into simple and complex gullies further (De Oliveira, 1989). Simple gullies were individual, isolated gullies that developed on a single hill slope (Billi and Dramis, 2003). Complex gullies were the results of more than one gully expansion and merging into a single gully unit. As the result, gullies in 1968 were classified as simple and complex gully, and gullies in 2009 were classified as new, simple and complex gully.

Land uses in 1968 and 2009 were classified as farmland, forestland, grassland, shrubland, construction land, and ponds (GBT21010-2007, 2007). Land use change and gully development, especially classified gullies development, were analyzed from 1968 to 2009.

Gully formation and evolution were largely controlled by the generation of sufficient runoff volume (i.e., upslope contributing area) as well as energy (i.e., high slopeness value) (Dietrich *et al.*, 1992; Desmet *et al.*, 1999). The topographic threshold relationship for gully development can be described by

$$S = a \times A^{-b} \tag{1}$$

where S is the mean catchment slopeness (°); A is the whole catchment area (ha); a is a constant coefficient; and b is an exponent.

The whole catchment area and mean catchment slopeness were obtained from DEMs to evaluate topographic thresholds associated with gully merging processes where coefficients a and b represent environmental effects on gully development. The log-log relationship between S and A was determined for watersheds with simple gullies and complex gullies in the study area.

3 Results

3.1 Gully distribution in 1968 and 2009

Substantial changes occurred in gully number, mean length, mean width, and area from 1968 to 2009 (Table 1). Gully density was 1.9 km/km^2 in 1968 and 2.4 km/km^2 in 2009 with an average annual increase of 0.01 km/km^2 during this period. Although gully density increased only by 0.5 km/km^2 during the 41 years, the mean gully length doubled from 452.2 m to 854.3 m. Gully number decreased from 104 to 69 during the 41 year period, while the gully area relative to the total study area increased from 1.4% to 3.2% (34.8 ha to 78.4 ha) (Fig. 3).

The area of new gullies, which initiated after the year of 1968, occupied 6.9% of total gullies area in 2009. The 34 remaining gullies in 2009, which initiated before 1968 and detected from 1968's image, were divided into two types, simple (17) and complex (17), and corresponding areas were 13.4 ha and 59.6 ha. Among the 104 gullies in 1968, 87 combined into 17 complex gullies in 2009, and the total complex gully area increased from 27.0 ha to 59.6 ha. The 17 simple gullies in 1968 did not combined with other until 2009, while the total simple gully area increased from 7.8 ha to 13.4 ha.

Table 1 Gully parameters in 1968 and 2009

Year	Number	Mean length (m)	Density (km/km^2)	Mean width (m)	Area (%)
1968	104	452.2	1.9	7.4	1.4
2009	69	854.3	2.4	13.3	3.2

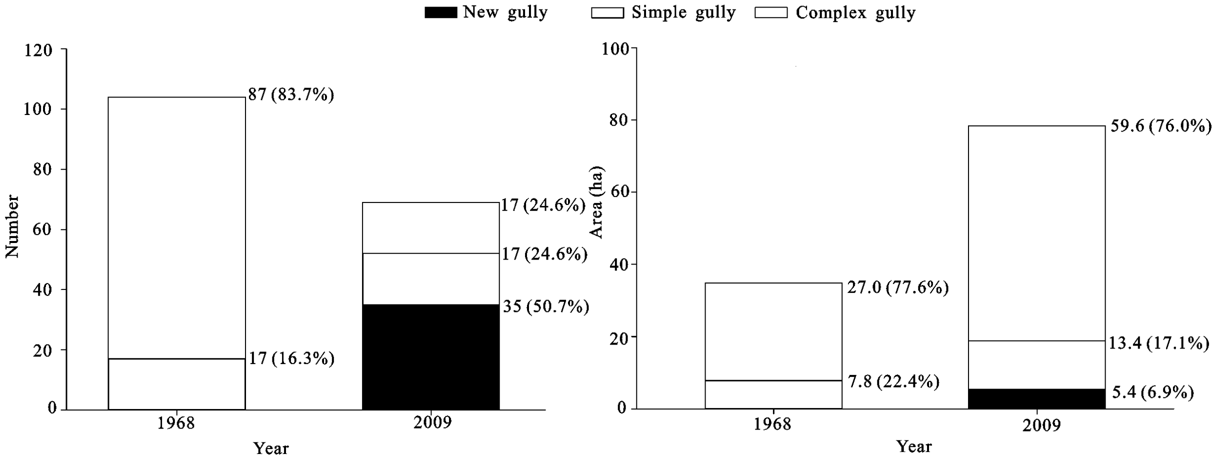

Fig. 3 Total number and area of different types of gullies in 1968 and 2009

The remaining gully development from 1968 to 2009 could reflect the main gully development process because they occupied more than 93% of total gully area in 2009. Table 2 shows that the main gully development processes during the 41 years were gully merging and width expansion. The average number of multiple gullies that merged into one gully was five, ranging from 2 to 18. The other 17 were simple gullies formed by linear development without merging with other gullies, and each simple gully expanded its area during the 41 years. The total remaining gully area increased from 34.8 ha to 73.0 ha, of which simple gullies and complex gullies increased from 7.8 ha to 13.4 ha and from 27.0 ha to 59.6 ha, respectively. The largest complex gully in 2009 resulted from the merging of 18 gullies as well as gully expansion (Table 2), and the area of the original 18 gullies increased from 8.5 ha to 16.4 ha during the merging process. Accompanied with gully merging, average gully area increased significantly. For the gullies in 2009 that developed from six gullies, the average gully area increased by 27 times compared with that of 1968.

Eight of the 34 remaining gullies in 2009 were sampled randomly to measure length, width and depth in the field to gain a general understanding of gully depths in the year 2009 because gully depth could not be measured directly from the remote images (Table 3). Mean measured gully width was 10.0 m, ranging from 6.2 m to 15.5 m, and mean gully depth was 1.5 m varying from 1.1 m to 1.9 m according to the survey. In general the depth and width of longer gully tended to be larger than shorter ones. Gullies 5 and 7 had the largest values of depth, width as well as length. The values of depth and width of gully 5 were higher than those of gully 7, while the gully length of the latter was the largest among all sampled gullies.

3.2 Effects of land-use change on gully development

The main land use type in the study area were farmland, grassland and forestland at the beginning and end of the study period (Table 4), which averagely occupied 84.2%, 5.6% and 5.3% of the rolling hill region, and 58.8%, 25.1% and 2.7% for the flat plain region, respectively. The distribution of land uses varied in the study period, particularly for the area of grassland and forestland, as well as farmland in the flat plain region. In the rolling hills the grassland area reduced by 5.0 percentage points while the forestland area increased 6.7 percentage points. In the flat plain similar trends were observed, although grassland decreased by 38.0 percentage points and forestland increased by 3.3 percentage points due to agricultural expansion. In addition a slight reduction of farmland occurred in the rolling hills (1.9 percentage points), while that in the flat plain increased by 37.9 percentage points. By 2009 the land use patterns of the rolling hills and the flat plain were similar. Farmland occupied about 80% of the study area, while the sum of grassland and forestland approximately accounted for 10%.

Table 2 Remaining gully development from 1968 to 2009

Merging gully number[a]	Gully number[b]	Total gully area in 1968 (ha) [c]	Total gully area in 2009 (ha) [d]	Average gully area in 1968 (ha)	Average gully area in 2009 (ha)
1	17	7.8	13.4	0.5	0.8
2	2	0.6	0.4	0.2	0.2
3	6	7.4	11.4	0.4	1.9
4	2	2.9	8.8	0.4	4.4
5	2	1.9	9.0	0.2	4.5
6	1	0.3	2.8	0.1	2.8
7	2	1.8	6.1	0.1	3.1
9	1	3.6	4.7	0.4	4.7
18	1	8.5	16.4	0.5	16.4

Notes: a, the number of gullies in 1968 that merged into one gully in 2009; b, the number of gullies in 2009 that developed from the gullies of 1968; c, total area of gullies in 1968 that merged into one gully in 2009; d, total area of gullies in 2009 that developed from gullies of 1968.

Table 3 Field measurement of gully parameter in 2009

No.	Length (m)	Width (m)	Depth (m)
1	355	6.3	1.3
2	356	6.2	1.5
3	435	6.5	1.1
4	440	6.3	1.1
5	895	15.5	1.9
6	530	10.5	1.7
7	1132	11.5	1.8
8	345	7.1	1.2

Table 5 shows a detailed analysis about gully area change related to land-use change in the two periods. The increase ratios of gully area under various land-uses were different, and that of grassland had the maximum value. The land use of grassland in 2009 was made up of the land-use changes of farmland to grassland and grassland remaining, and they had the maximum gully area increase ratio of 286.7% and 164.7%, respectively. The farmland was consisted of farmland remaining and grassland to farmland, and the gully area increase ratios under them were 137.5% and 138.3%, lower than those in grassland. The land-use changes of grassland to forestland as well as forestland remaining had the lowest gully area increase ratios of 51.9%, and 23.1%, respectively.

3.3 Effects of topography on gully development

In this research the topographic effect on gully development was investigated by comparison of *S-A* relationships between simple and complex gullies (Fig. 4) since the gully area of these two gully types occupied more than 93% of total gully area in 2009. Because morphology, climate, land use and erosional systems (i.e., rilling, gullying) (Vandaele *et al*., 1996; Torri and Poesen, 2014) were similar across the study area, the exponent *b* of the critical slope-area relationships for simple and complex gullies were almost identical (–0.251 and –0.245). The values of coefficient *a* for simple gully and complex gully are 4.230 and 7.995, respectively. This indicated that the catchment area for a given mean slopeness was systematically larger for complex gullies than that for a simple gully.

4 Discussion

4.1 Gully development within 41 years

From the gully development, two results could be concluded. First, most of the gullies in 2009 were positioned as those in 1968. 93% of the 2009 gully occupied-space matched that of 1968; and new gully area accounted for less than 7% of the total gully area. Second, the relatively small differences in gully density between these two dates suggested that the fundamental gully distribution had been formed by 1968 and most of gullies in 2009 were developed from gully structures existing in 1968. From the 1930s to 1968 the gully density increased from approximately 0 to 1.9 km/km^2, and from 1968 to 2009 this number increased from 1.9 km/km^2 to 2.4 km/km^2 (Table 1). Gully channel formation can be very rapid during the period of gully initiation when morphological characteristics of a gully are far from stable (Sidorchuk, 1999).

The mean gully size changed as the gully number and occupying area varied from 1968 to 2009. Obvious differences of mean gully size in 1968 and 2009 could be obtained from Table 2. The number of new gullies initiated after 1968 occupied more than half number of total

Table 4 Land-uses in rolling hill and flat plain: in 1968 and 2009

Land-use	Rolling hill				Flat plain			
	1968		2009		1968		2009	
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
Farmland	1646.4	85.1	1609.2	83.2	194.9	39.8	380.4	77.7
Grassland	157.7	8.1	60.5	3.1	216.0	44.1	29.7	6.1
Forestland	37.5	1.9	165.9	8.6	5.1	1.0	20.9	4.3
Shrubland	3.7	0.2	0.4	0.0	72.6	14.8	23.8	4.9
Infrastructure	90.0	4.7	97.5	5.0	1.1	0.2	1.1	0.2
Pond	0.0	0.0	1.8	0.1	0.0	0.0	31.7	6.9

Table 5 Gully area distribution due to land-use change

Land-use change class	Gully area in 1968 (ha)	Gully area in 2009 (ha)	Increase ratio (%)
Farmland to grassland	1.5	5.8	286.7
Grassland remaining	6.8	18.0	164.7
Farmland remaining	8.0	19.0	137.5
Grassland to farmland	6.0	14.3	138.3
Farmland to forestland	3.3	7.7	133.3
Grassland to forestland	7.9	12.0	51.9
Forestland remaining	1.3	1.6	23.1

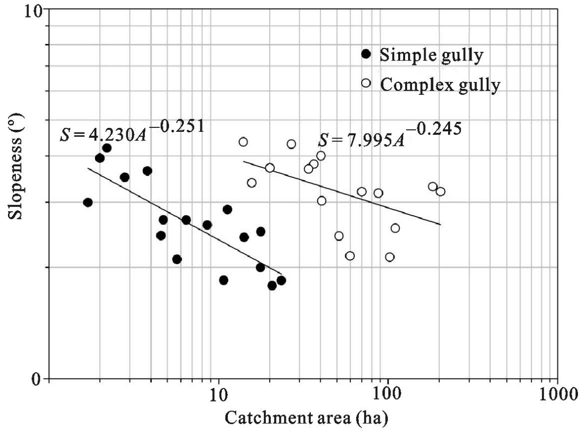

Fig. 4 Relationships between total catchment area (*A*) and mean catchment slopeness (*S*) and corresponding threshold lines for simple and complex gullies

2009 gullies, but they accounted for only 7% of total gully area. In 2009, the mean size of new gullies (0.2 ha) was less than 10% of the mean size of remaining gullies (2.1 ha). In 1968 the mean gully size was 0.4 ha, which was larger than that of new gullies. Small-size gullies were more easily to be treated in this local area; they could be eliminated by tillage or shallow depth land leveling (Gomez *et al.*, 2003). With improving economic conditions farmers increasingly used farming machinery for tillage instead of human power to easily erase gullies in their ephemeral stage (Nachtergaele and Poesen, 2002). Appropriate gully control implements are urgent for these small-size gullies. Present gully erosion could be doubled if these 35 new gullies reached similar size with remaining ones.

4.2 Gully evolvement responding to land use changes

Grassland in this region could not restrain gully development during research period. More than half grassland in 1968 was reclaimed to farmland, and most of the remaining grassland dispersed around gullies. Field investigation showed that the grass buffer zones between the farmland and gully edge were usually less than 1-m width. The disperse-distributed grassland with limited width made the gully edge being prone to collapse because of concentrated runoff from the furrows, causing gully width expansion. Besides, the mean gully depth in 2009 was more than 1 m, which was too deep (Table 3) that the grassland could not restrain gully development, and hence gully area in grassland doubled from 1968 to 2009. The gully increase area in the farmland was similar with that in the grassland. Forestland had the lowest gully area increase ratio because the reduction of gully area under vegetation cover was a function of canopy size and type, as gully stabilization responded to forest reversion in New Zealand (Gomez *et al.*, 2003; Marden *et al.*, 2005). The Returning Farmland to Forestland policy was applied in the rolling hills region and farmland area reduced while forestland increased since the 1980s. However, the reversion process effect on gully stabilization was slowed by the common patchy distribution of the forest, which influenced the hydrology of erosion activity within gullies (Marden *et al.*, 2012). Artificial poplar occupied most of forestland with few secondary deciduous trees by 2009. In this region farmers tended to plant dense trees for more income, which resulted in low-effectiveness of vegetation cover on gully erosion control. Patchy distribution, limited area and low effectiveness of forest cover could only stabilize gully in local area but not in total gully distribution region.

4.3 Gully evolvement responding to terrain

The ultimate gully width after single runoff event was determined with peak runoff rate, which was the function of time of concentration, runoff coefficient and catchment area (Woodward, 1999). Previous research showed that larger-size catchment tended to cause gully width expansion by providing the channel more concentrated runoff with total runoff volume and peak runoff rate (Chanasyk, 2003). In our research most simple gullies′ catchment area were less than 25 ha, while those of complex gullies were larger than 15 ha. This suggested that the needed catchment area for complex gully was larger than that of simple gully, and the threshold catchment area between simple and complex gullies was around 15 ha to 25 ha. Gullies in New Zealand′s mountain region were also classified as gully, gully complex and gully slide in terms of catchment area (Parkner *et al*., 2006; 2007). The connection/merging processes of gullies in neighboring catchments changed not only the size of catchment area but also the mean catchment slopeness (Poesen *et al*., 2003). When multiple gullies merged to be one gully each gully′s catchment were merged also, and mean catchment slopeness could decrease. In the study the catchment area of simple gullies ranged from 1 ha to 25 ha, which were much lower than 15 ha to 200 ha for complex gullies. Besides, for gullies with similar catchment area, the mean catchment slopeness of complex gully was larger than that of the simple gully also. This shows that compared with the mean slopenesss, the catchment area was more important for gully formation.

5 Conclusions

In this research the increase ratio of gully area in forestland was the lowest among the farmland, grassland and forestland in the study area from 1968 to 2009, and that in grassland was the highest. Vegetation cover could slow gully evolvement but limited area with only patchy distributed forestland restricted the vegetation-cover effect on gully control.

In gully initiation stage gully length increased rapidly and by 1968 the fundamental gully distribution was formed. After that the main gully development processes were gully merging and width expansion, and 93% of gullies in 2009 were developed from gullies that already existed in 1968.

The mean catchment slopeness for complex gully and simple gully were similar while the mean catchment area for the former is larger than that for the latter, which showed that the catchment area was more important than slopeness for gully development. Furthermore, catchment area and mean slopeness had a coupled effect on gully erosion and both of them needed to be considered for gully development. In this region the threshold catchment area between simple and complex gullies was 15 ha to 25 ha. Use of this threshold value permits prediction of which development process, linear or lateral expansion process, might occur in a specific catchment area with similar environmental settings. The result in this paper extended the application of the *S*-*A* relationship to reveal the topographic effects on gully development processes, and demonstrated that the topographic thresholds changed with gully development process transformation.

Construction measurements such as check dam should be taken accompanied with ecological restoration for gully erosion control since the existent gully size was too large. Gully control measurement was urgent because half of present gullies in number only occupied less than 7% of total gully area. It implied that potential gully erosion could be doubled if appropriate gully control implements were not applied.

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