Using laboratory experimentation to evaluate the sensitivity of gully sidewall expansion to rainfall and topography: A geomorphic perspective

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1. Introduction




- Gully sidewall expansion – also called as gully sideward extension, sidewall retreat, and gully bank retreat – is attributed to the combined effect of gravity erosion and water erosion.
- Sidewall moves to hillslope (retreat), releasing sediment to gully, decreasing the cultivated area around the gullies and exposing new gully wall to erosion, ultimately resulting in a hidden threat to local ecology and food security.
- Gully sidewall extension is an important process in gully development, and its dynamic process can be reflected by the change of both gully shoulder-line and slope gradient of sidewall .

Introduction

- Previous studies have paid little attention to the direct effects of topography and rainfall factors on gully sidewall expansion, and most studies have mainly focused on the expansion rate of the gully sidewall by using remote sensing images, and the protection measures of the gully sidewall expansion
- The aim of this study was to determine the dominant erosion patterns that caused the land loss in the hillslope, and to evaluate the susceptibility of the change of slope gradient of gully sidewall and the retreat rate of gully shoulder-line on the rainfall and topography, which will provide a scientific basis for reducing gully expansion and improving the effectiveness and sustainability of land management in the gully region on the Loess Plateau.

2. Materials and Methods

- **Experimental conditions:**

  10 sets of experiments, and three factors were considered: three rainfalls (60 mm, 48mm and 24mm), two initial slope gradients (70° and 80°) and two slope heights (1 m and 1.5 m).

- **Experience equipments:**

  SX2009 sprayer-type rainfall simulator

  MX-2010-G topography meter

- **Parameter:**

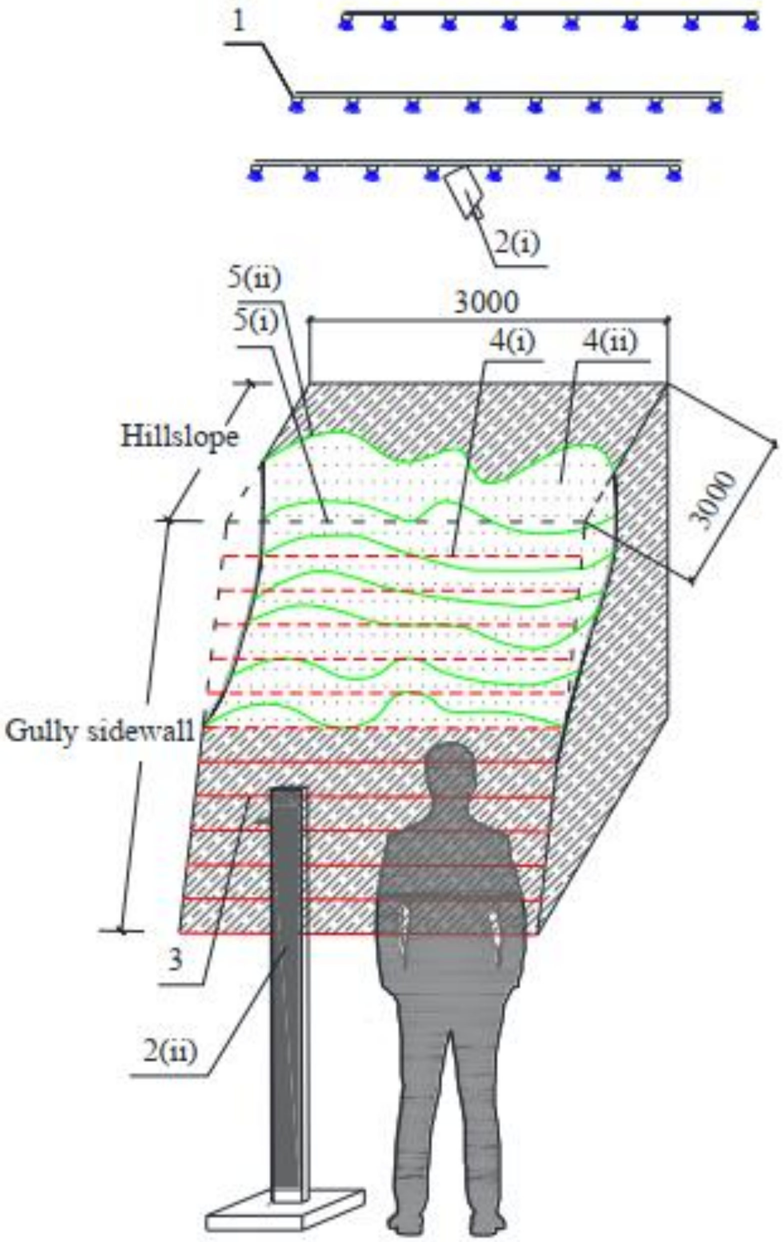
  Area of land loss on the hillslope

  Shoulder-line retreat rates

  Variations of slope gradient of the sidewall

- **Method of sensitivity analysi**

  An increase-rate-analysis method



1 – rainfall simulator

2 – topography meter (*i* – camera with collimator, *ii* – laser source)

3 – equidistant horizontal projections

4 – model slope (*i* – initial model slope, *ii* – model slope after sidewall expansion

5 – gully shoulder-line (*i* – original gully shoulder-line, *ii* – gully shoulder-line after sidewall expansion)

6 – positioning marks.

Fig.1 Landscape simulator in which the rainfall simulation experiments were conducted.

2. Materials and Methods

Testing program

Test number	Sidewall configuration		Rainfall		
	Height (m)	Gradient (°)	Intensity (mm/min)	Duration (min)	Runs
L1	1	70	2	30	5
L2	1	80	2	30	5
L3	1.5	70	2	30	5
L4	1.5	80	2	30	5
L5	1	70	0.8	60	5
L6	1	80	0.8	60	5
L7	1.5	70	0.8	60	5
L8	1.5	80	0.8	60	5
L9	1	70	0.8	30	5
L10	1	80	0.8	30	5

$$A_R = \sum_{j=1}^{5} A_{Rj} \quad (1)$$

$$V_R = \sum_{j=1}^{5} \frac{A_{Rj}}{LT} / 5 \quad (2)$$

$$D_g = D_{g0} - D_{g5} \quad (3)$$

A_{Rj} (in cm^2) is the area of the land loss on the hillslope between the gully sidewall shoulder line before and after the j^{th} rainfall;
T (in min) is the rainfall duration;
L (in cm) is the linear distance between the two end points of the original gully shoulder line;
D_{g0} (in degree) is the slope gradient of initial gully sidewall;
D_{g5} (in degree) is the slope gradient of the gully sidewall after the fifth rainfall.

2. Materials and Methods

Increase-rate-analysis method

To assess the effects of the initial landform geometry and rainfall on D_g and V_R, 10 sets of experiments were divided into the following seven experimental groups:

1. Ga(L1,L2,L5,L6) vs Gb(L3,L4,L7,L8), the slope height in Ga and Gb were 1.0 m and 1.5 m, respectively。
2. Gc (experiments L1, L3, L5, and L7) vs Gd (experiments L2, L4, L6, and L8), the initial slope gradients in Gc and Gd were 60° and 70°, respectively.
3. Ge (experiments L5 and L6) vs Gf (experiments L9 and L10), the rainfall duration in Gc was 30 min, while the Ge was 60 min.
4. Gf (experiments L9 and L10) vs Gg (experiments L1 and L2), the rainfall intensity in Gc and Gd were 0.8 and 2.0 mm/min, respectively.

$$R_t = (T_a - T_b)/T_b \quad (4)$$

$$R_i = (I_a - I_b)/I_b \quad (5)$$

$$S = R_t/R_i \quad (6)$$

S is the sensitivity coefficient for analyzing the sensitivity of the D_g or V_R for the triggering elements, R_t (in %) is the increased ratio of the D_g or V_R, T_a is the D_g (in degree), or V_R (in cm/min) in an experiment group before the triggering element was changed, and T_b is that after the triggering element was changed,I is one of the triggering elements (e.g., slope height, initial slope gradient, rainfall duration and rainfall intensity), R_i (in %) is the increased ratio of the triggering element, I_a is the value before being changed in an experimental group, and I_b is that after being changed.

3. Results and discussion

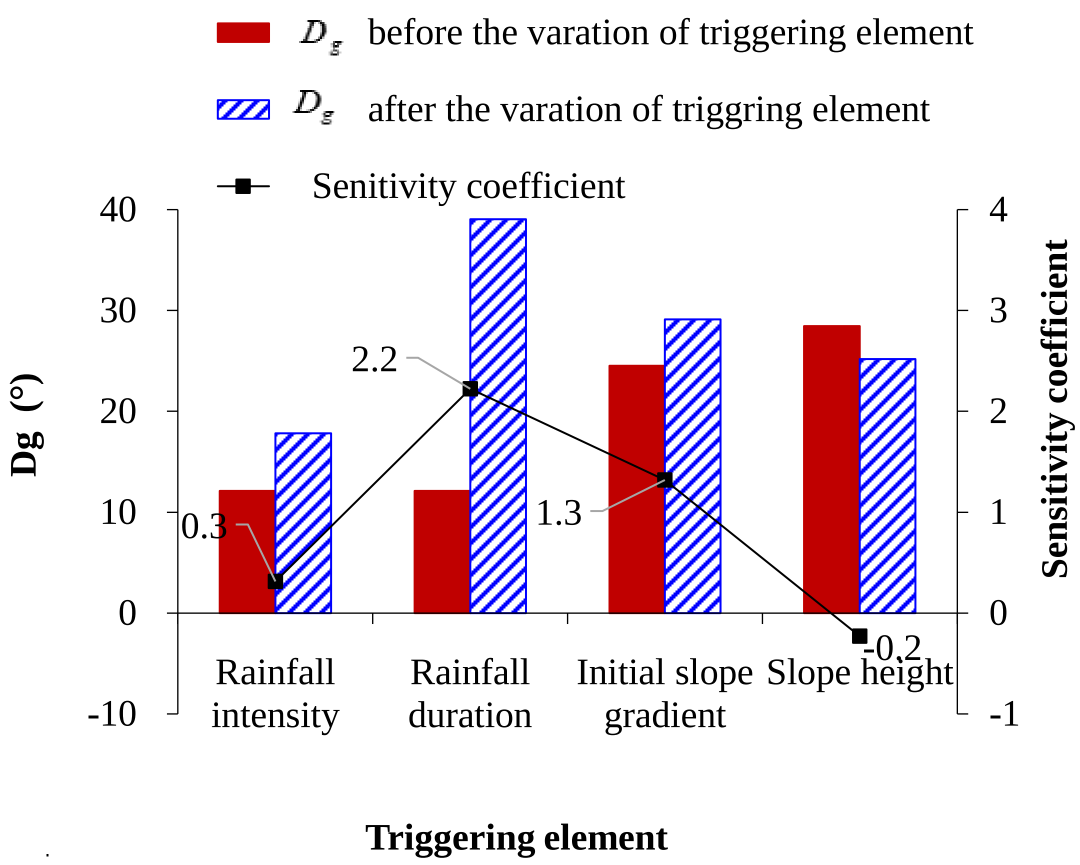


Fig. 2. Sensitivity analysis of the changes in slope gradient of gully sidewall for the triggering .

- The sensitivity coefficients of the variations of slope gradient of the sidewall on the rainfall duration, initial slope gradient, rainfall intensity and slope height were 2.2, 1.3, 0.3, and -0.2, respectively.
- The rainfall duration and initial slope gradient had significant influences on the change of slope gradient of landform in the experiments.
- Mass failures led to a remarkable change in slope gradient in the process of sidewall expansion

3. Results and discussion

- The gully shoulder-line is always located in the most active part of a gully, and its dynamics reflects the gully development and evolution.

- The retreat rate of the gully shoulder-line mirrors not only the outward appearance of the developing gully, but also the internal mechanism of gully development.

- In this study, the retreat rate of the gully shoulder-line was applied to quantitatively describe the process of the gully sidewall expansion.

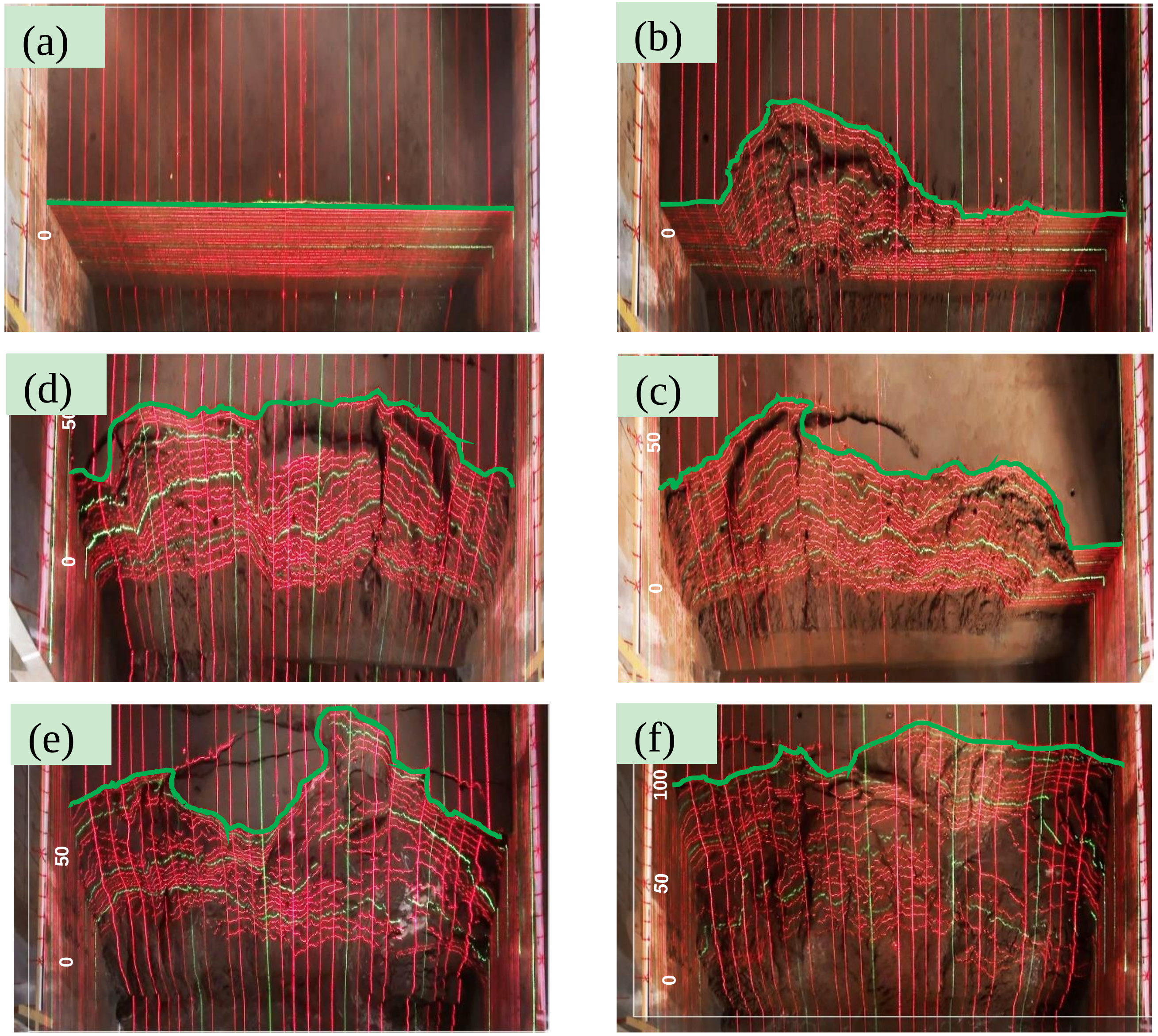


Fig.3 Images of the sidewall retreat for the experiment L6

3. Results and discussion

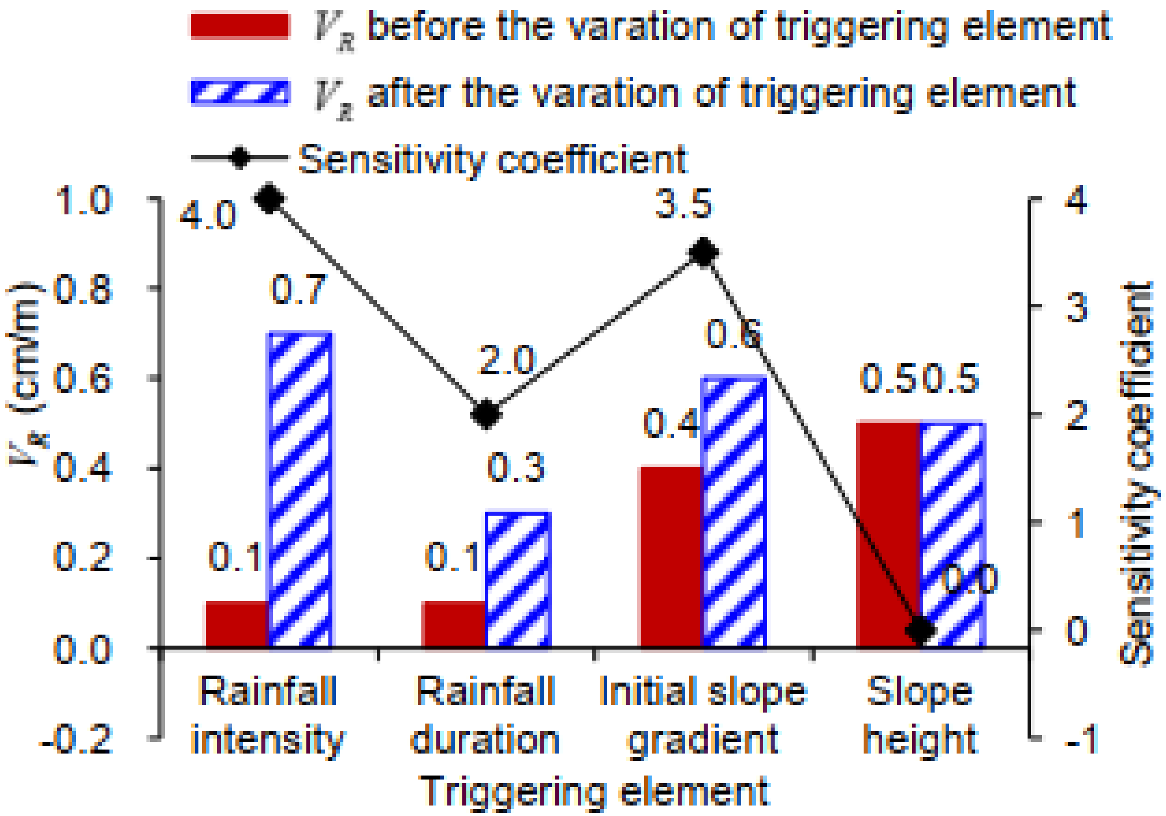


Fig. 4 Sensitivity analysis of the retreat rate of gully shoulder-line for the triggering elements.

- The sensitivity coefficients of the retreat rate of gully shoulder-line on the rainfall intensity, initial slope gradient, rainfall duration and slope height were 4.0, 3.5, 2.0 and 0.
- The most significant factors affecting the retreat rate of gully shoulder-line were the rainfall intensity and initial slope gradient.
- Runoff velocity rose as the slope gradient and rainfall intensity increased which leads to the component of tractive force of flowing water parallel to the slope surface to be greater than the soil resistance, eventually causing the retreat.

3. Results and discussion

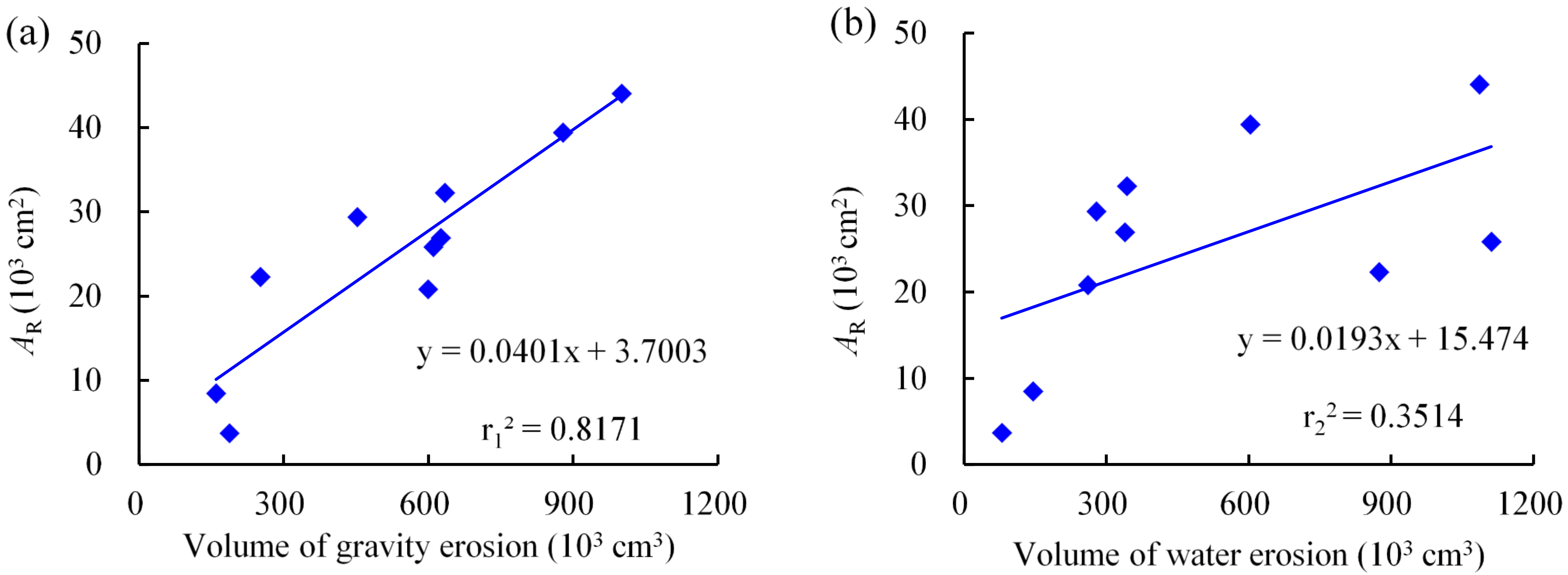


Fig. 5 The correlation between the volume of different erosion types and the area of land loss in the hillslope.

3. Results and discussion

- The correlation coefficient between the volume of gravity erosion and the area of land loss in the hillslope, r1, was 0.91.
- The correlation coefficient between the volume of water erosion and the area of land loss in the hillslope, r2, was 0.59.
- The area of land loss on the hillslope was positively correlated with the volume of gravity erosion.
- This shows that the mass failure was the main cause to induce the land loss of the hillslope in the process of sidewall expansion.
- Because the soil in the hillslope was separated from a sloped face under the effect of gravity, and then accumulated on the down slope or gully, resulting in irreversible land resource loss.

3. Results and discussion

Before the 'Grain-for-Green' programme

- the average rate of sidewall retreat was 0.84 m. a^{-1} in Xingzi River catchment in Yan'an city from 1958 to 1978, and the annual loss of the inner-gully area was about 1886.7 hm^2 (**Meng 1996**)
- About 333 - 400 hm2.a-1 of land was lost due to the gully sidewall expansion in Guyuan City, Ningxia (**Meng 1996**)

After the 'Grain-for-Green' programme

- From 2003 to 2010, the maximum retreat rates of gully sidewall in the 30 investigated catchments in the southeastern part of the Loess Plateau ranged between 0.23 and 1.08 m. a^{-1}, with an average of 0.51 m. a^{-1} (**Li et al. 2015**)

3. Results and discussion

- It is clear that whether before or after the 'Grain-for-Green' programme in China, the area of land loss in the hillslope caused by gully sidewall expansion is serious.
- With the vegetation restoration on the Loess Plateau of China, the amount of soil erosion in the hillslope will decrease, but the amount of erosion on the gully sidewall will become more prominent.
- Gully development caused by sidewall expansion is the greatest threat to the agricultural watersheds not only in China, but also in other countries of the world
- A field investigation in the Umbulo catchment of Southern Ethiopia indicated a rapid, downslope development of gullies over the last 30 years with an average rate of soil loss from 11 to 30 t. ha^{-1}. a^{-1} (**Moges and Holden 2008**).

4. Conclusions

- This study observed the process of gull sidewall expansion during rainfall to explore the mechanism and influential factors of gull sidewall expansion.
- Gravity erosion was the main cause to induce the land loss in the hillslope in the process of sidewall expansion. The area of land loss in the hillslope was positively correlated with the volume of gravity erosion.
- The cause of a remarkable change in the slope gradient of gully sidewall was the mass failure. The rainfall duration and initial slope gradient had significant influences on the change of slope gradient of gully sidewall in the experiments.
- The retreat rate of gully shoulder-line was highly susceptible to the rainfall intensity and initial slope gradient.

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Thank you for your attention!