Journal of Hydrology: Regional Studies 2 (2014) 69–83

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Assessment of soil erosion and conservation on agricultural sloping lands using plot data in the semi-arid hilly loess region of China

T.X. Zhu[a,*], A.X. Zhu[b]

[a] Department of Geography, Urban, Environment and Sustainability Studies, University of Minnesota-Duluth, Duluth, MN 55812, USA
[b] Department of Geography, University of Wisconsin-Madison, 550 North Park Street, Madison, WI 53706, USA

ARTICLE INFO

Article history:
Received 26 January 2014
Received in revised form 16 August 2014
Accepted 26 August 2014
Available online 30 September 2014

Keywords:
Soil loss
Slope angle
Recurrence interval
Soil conservation practice
Loess Plateau
China

ABSTRACT

Study region: Semi-arid hilly loess region of China.
Study focus: The objectives of this study were to investigate soil and water loss on agricultural sloping lands and to evaluate the effectiveness of soil conservation practices in controlling erosion using plot data.

Runoff and soil loss were measured from the short slope plots (SSP) (7 m long) and the long slope plots (LSP) (20 m long) at various slope angles as well as from cropland and soil conservation plots (SCP) under natural rainfalls.
New hydrological insights for the region: The results revealed that runoff per unit area slightly increased with slope angle on SSP, but reached a maximum at 15° and then decreased with slope angle on LSP. Soil loss per unit area increased with slope angle on both SSP and LSP. An average of 36.4% less runoff but only 3.6% less soil loss per unit area was produced on LSP than on SSP. The *S* factor calculated using the slope factor equations in USLE/RUSLE was significantly greater than that estimated from the measured soil loss on the plots. Rainstorms with recurrence intervals greater than 2 years were responsible for more than two thirds of the total soil and water loss. The effectiveness in reducing surface runoff by five types of conservation practices was mixed. However, all the conservation practices yielded much less soil loss than cropland.

* Corresponding author. Tel.: +1 218 726 8480.
E-mail address: tzhu@d.umn.edu (T.X. Zhu).

http://dx.doi.org/10.1016/j.ejrh.2014.08.006
2214-5818/

1. Introduction

Soil erosion remains one of the biggest environmental problems worldwide, threatening both developed and developing countries (ISCO, 2002). Erosion by rainstorms in agricultural areas not only strips the fertile topsoil on site, but also degrades water quality and clogs streams, rivers, and reservoirs off site (Zhu et al., 2013). As a result of increasing population, cultivation has been expanded to steep sloping lands in many developing countries in the world (Liu et al., 1994, 2000; Turkelboom et al., 1997; Rumpel et al., 2006; Podwojewski et al., 2008; Mugagga et al., 2012), which causes major types of environmental damage with dramatic consequences in terms of soil fertility decrease and water availability (Lal, 1998). This is particularly so in semi-arid areas which are characterized by intense rainstorms and medium to poor soil fertility.

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its revised version (RUSLE) (Renard et al., 1997), originally developed in the US, have been employed in many countries for the assessment of soil loss from agriculture because of their simplicity and low requirements for input parameters (Fox and Bryan, 1999). The intimate integration with land use and soil conservation measures in the models can also provide guidance in land use management and planning (Laflen et al., 1978). However, the models are typically applicable to areas with gentle slope gradients between 3% and 18%, a normal probability distribution of annual rainfall, and cropping management systems similar to the US (Wischmeier and Smith, 1978; McCool et al., 1987; Mannaerts and Gabriels, 2000; Kinnell, 2010). When applied to areas where environmental conditions and farming techniques, as well as soil conservation practices significantly differ from the U.S., variables in the USLE/RUSLE models need to be modified to accommodate local characteristics (e.g., Lu and Higgitt, 2001; Hoyos, 2005; Zhu et al., 2013).

In semi-arid areas, most of rainfall events are non-erosive and often relatively few storms generate runoff and cause soil loss each year. Thus it is important to evaluate the relative contributions of large and small storms to total soil loss. From the practical standing point, it is essential to design conservation measures and strategies that are effective in controlling soil losses in those large events. For examples, Larson et al. (1997) suggested that conservation systems should be designed for limiting soil loss (namely, tolerance) to the value corresponding to a return period variable from 10 to 20 years. Mannaerts and Gabriels (2000) emphasized that adding a probability of recurrence to erosion events is essential for successful erosion assessment in semiarid zones.

The present study was conducted in the hilly region of the Loess Plateau in China, which is among the most severely eroded regions in the world, with a mean erosion rate of 150 Mg ha^{-1} yr^{-1} (Chen and Luk, 1989). The region has a semi-arid climate, characterized by strong spatiotemporal variability of rainfall occurrence. The rainfall in the region shows a pronounced skew instead of normal probability distribution (Zhu, 2013). Due to the high density of population and the rugged terrain conditions in the region, the cropland parcels owned by individual households are characterized by short slope lengths and a wide range of slopes up to more than 30°. The lands are also ploughed by animals instead of tractors. The various types of field boards between land parcels (i.e. earth banks, small ditches, etc.) interrupt storm flows on slopes. The profound difference in climates, terrain conditions, and farming techniques between this region and the US has become a major barrier to a wide application of the USLE models in the region.

The objectives of this study include: (1) to examine runoff and soil loss at slope angles of 5°, 10°, 15°, 20°, 25°, and 30° on short and long slope plots; (2) to evaluate the relative contributions of storms with various recurrence intervals to total soil loss; (3) to test the validity of the slope equations used in the USLE/RUSLE models; and (4) to assess the effectiveness of different soil conservation measures in reducing runoff and soil loss.

2. Study site and field settings

The study was conducted at the experimental watershed of the Shanxi Institute of Soil and Water Conservation (SISWC) in Lishi, Shanxi Province of China (Fig. 1). The watershed, Wangjiagou, is located in the hilly region of the Loess Plateau, with a drainage area of 9.1 km^2. The climate is semi-arid warm temperate, with mean annual precipitation of about 500 mm, of which about 80% falls in the rainy

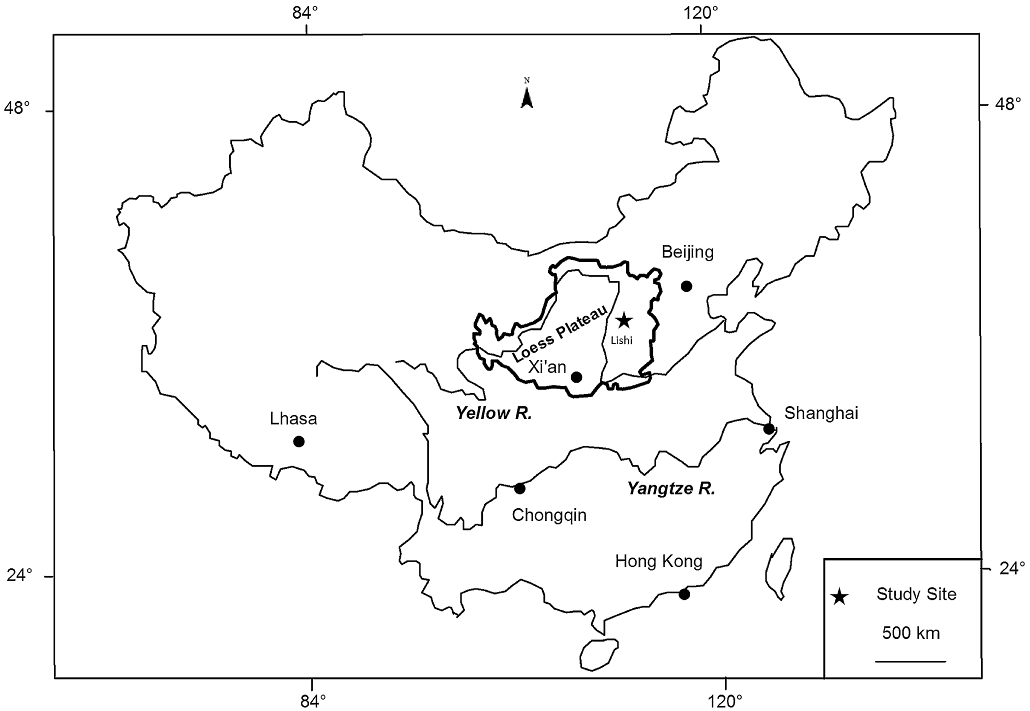

Fig. 1. Location of study site.

season from May to September (Zhu et al., 1997). The soil is derived from the loess deposit which was believed to be wind-blown dusts in the Quaternary period (Liu, 1964). The proportions of particle sizes are 13.5% (>0.0 5 mm), 58.1% (0.05–0.005 mm), and 28.4% (<0.005 mm), respectively. The soil has a bulk density ranging from 1.13 to 1.19 g/cm^3 and a mean organic matter content of 1.029%. The hillslopes in the watershed can be divided into four vertical zones from divides to valley bottom (Zhu, 2003). Zone 1 is dominated by gentle slope with gradients of less than 5°. The landuse types include terrace, and cultivated land, and forest land. Zone 2 is varied in slope gradients from about 10° on the upper parts to up to 30° on the lower part, dominated by cultivated slopelands and some of the slopelands have been converted into terraces and earth banks. Zone 3 is marked by a sharp break in slope and is characterized by a substantial increase in gradient up to 60°. This section of slope is either barren lands or covered with shrubs including Caraganan korshineski, Abortanum Lavanduaefolia and Periploca Sepium, because it is too steep to be cultivated. Zone 4 is valley bottom consisting of alluvial deposits. Check dams were built on some valley bottoms. Accordingly, flat lands have developed behind the check dams due to sediment deposition and some of these flat lands are now being cultivated. The crops in the cultivated lands include maize, corns, beans, potato, sunflower, and millet. 84.1% of the croplands have slope gradients greater than 10° (or 15% in steepness), and 56.9% of the watershed area has slope gradients greater than 25° (or 46.8% in steepness) (Fig. 2). Therefore, more than half of the croplands are beyond the range of slope gradients, 3–18%, of the erosion plots that were used to develop USLE/RUSLE, which necessitates to test the validity of the slope equations used in USLE/RUSLE.

To investigate erosion from sloping lands and to evaluate the effectiveness of various soil conservation measures in reducing soil erosion, runoff and soil loss from three sets of erosion plots were measured under natural rainfall in three periods. The first set, short slope plots (SSP), were laid out with a dimension of 2 m in width and 7 m in length at slope angles of 5°, 10°, 15°, 20°, 25°, and 30° (Fig. 3). All the plots were tilled bare soil. The plots were monitored in 7 years out of the period from 1985 to 2003. Storm flows from each plot were collected by an underground brick-built pool. After

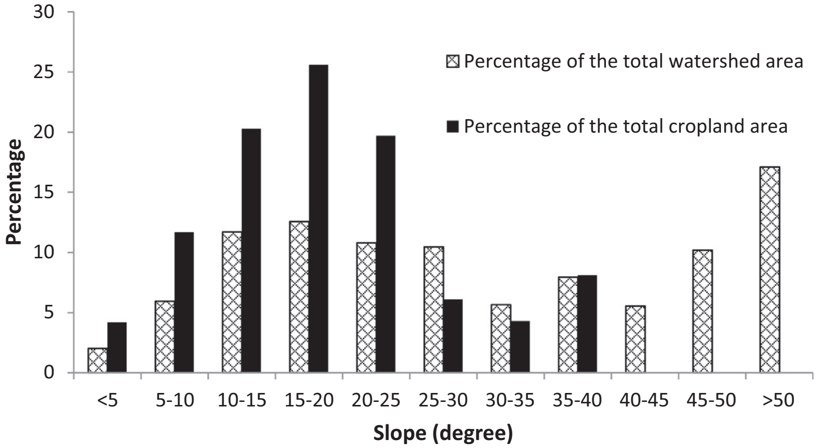

Fig. 2. Slope classification of watershed and cropland in Wangjiagou.

each runoff-generating rainfall event, storm water in the pool was first thoroughly stirred and three water samples were then taken from the pool to determine the average sediment concentration for that event in the lab. The total flow discharge for each event was calculated by measuring the volume of storm water in the pool. Flow discharge and sediment concentrations were eventually used to determine the total soil loss for each event. The second set, long slope plots (LSP), were laid out with a slope length of 20 m and a width ranging from 3 m to 10 m at the same slope angles as the first set of plots (5°, 10°, 15°, 20°, 25°, and 30°). Runoff and soil loss from LSP were measured under natural rainfall by SISWC over 5 years (1957, 1958, 1964, 1965 and 1966). The third set, including five soil conservation plots (SCP) and one cultivated cropland plot, was also established by SISWC

Fig. 3. Short slope plots (SSP) with a dimension of 2 m wide and 7 m long at slope angles of 5°, 10°, 15°, 20°, 25°, and 30°.

Table 1
Characteristics of soil conservation and cultivated cropland plots.

Plot	Slope gradients (°)	Slope length (m)	Plot area (m^2)	Slope aspects	Observation period
Woodland	31	23.1	200	NE	1957–1965
Alfalfa	30	20	100	NE	1957–1965
Grassland	37	Varied	399	NW	1959–1964
Terrace	0–1	15	75	NE	1957–1958 and 1960–1966
Earth bank	24	N/A	288–1453	NE	1959–1965
Croplands	10–30	Varied	200–1855	NE	1957–1968

and the characteristics of those plots are summarized in Table 1. The five soil conservation measures are woodland, grasses, alfalfa, contour earth banks, and terraces. Soil and water loss from those plots were monitored by SISWC over a various length of time (6–12 years) out of 1957–1968 (Table 1). The monitoring equipment and sampling methods for the second and third sets of plots are described in detail elsewhere (SISWC, 1982; Zhu, 2013). All the soil and water loss data collected from the second and third set of plots were compiled by SISWC (SISWC, 1982).

3. Results and discussion

3.1. Rainfall characteristics

The mean annual rainfall over the 17-year of three study periods was 547.4 mm, ranging from 243.3 mm in 1965 and 756.3 mm in 1964. This was about 10% higher than the long-term mean annual precipitation, 496.7 mm, recorded by SISWC. The annual precipitation had a coefficient of variation of 0.24 and a skewness of −0.51. An average of 432.9 mm, or 78.6% of the total yearly precipitation, fell in the rainy season from May to September (Supplementary Table 1). It is noted that almost all the runoff generation storms occurred in the rainy season in this region (Zhu et al., 1997). Over the SSP, LSP, and SCP monitoring periods, the mean annual precipitation was 522 mm, 524 mm, and 565 mm; the mean rainfall amount in the rainy season was 405 mm, 413.4 mm and 449.5 mm, which accounted for 77.6%, 78.9% and 79.5% of total annual precipitation, respectively (Fig. 4).

Supplementary Table 1 related to this article can be found, in the online version, at doi:10.1016/j.ejrh.2014.08.006.

In this study, if a storm generated flows on any of those monitoring plots, it was referred to as a runoff generation event. Flows may be present on some plots but absent on other plots in a small runoff generation rainfall event due to the difference in soil infiltration. There were 22, 25, and 59

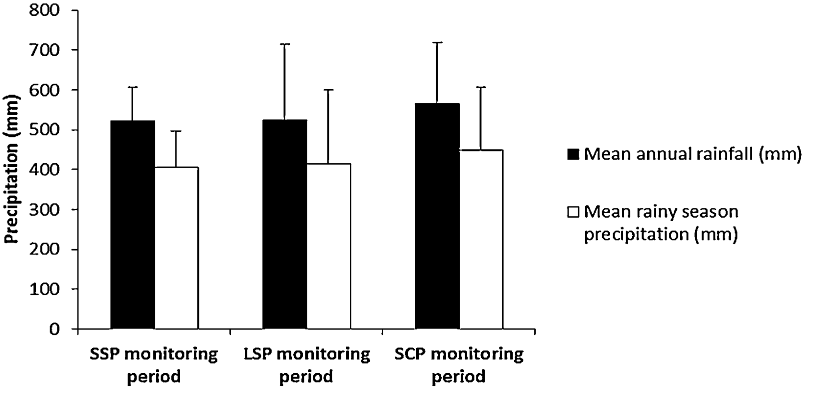

Fig. 4. Mean annual precipitation and rainy season (May to September) precipitation and standard deviation error bars for Short Slope (SSP), Long Slope (LSP), and Soil Conservation (SCP) plots for monitoring periods of SSP (1985, 1987–1989, 2000, 2001, 2003), LSP (1957, 1958, 1964–1966), and SCP (1957–1966).

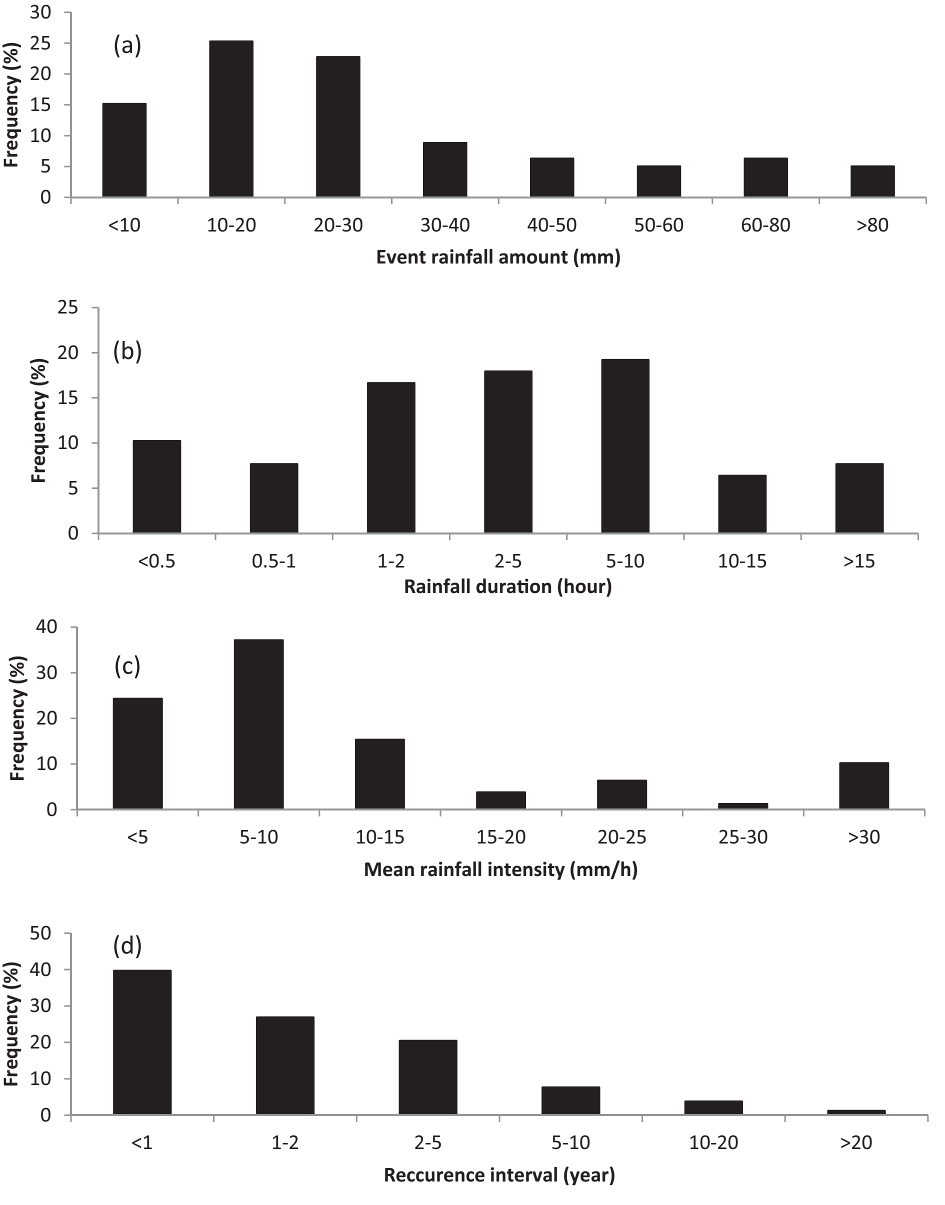

Fig. 5. Frequency of runoff generation storms (a) event rainfall amount; (b) rainfall duration; (c) mean event rainfall intensity; and (d) recurrence intervals.

runoff generation storm events in the SSP, LSP, and SCP monitoring periods. It is noted that the LSP monitoring period was within the SCP monitoring period. Overall, all those runoff generation storm events ranged from 3.6 to 110 mm in event rainfall amount, 0.25–26.1 h in rainfall duration, and 1.03–62.4 mm/h in mean event intensity (Fig. 5).

To determine the recurrence intervals of runoff generation storms, an empirical equation was used in this study (Eq. (1)). The equation was developed by Shanxi Bureau of Meteorology based on the long-term continuous data collected at the weather stations across the Shanxi Province. The coefficients (*A*,

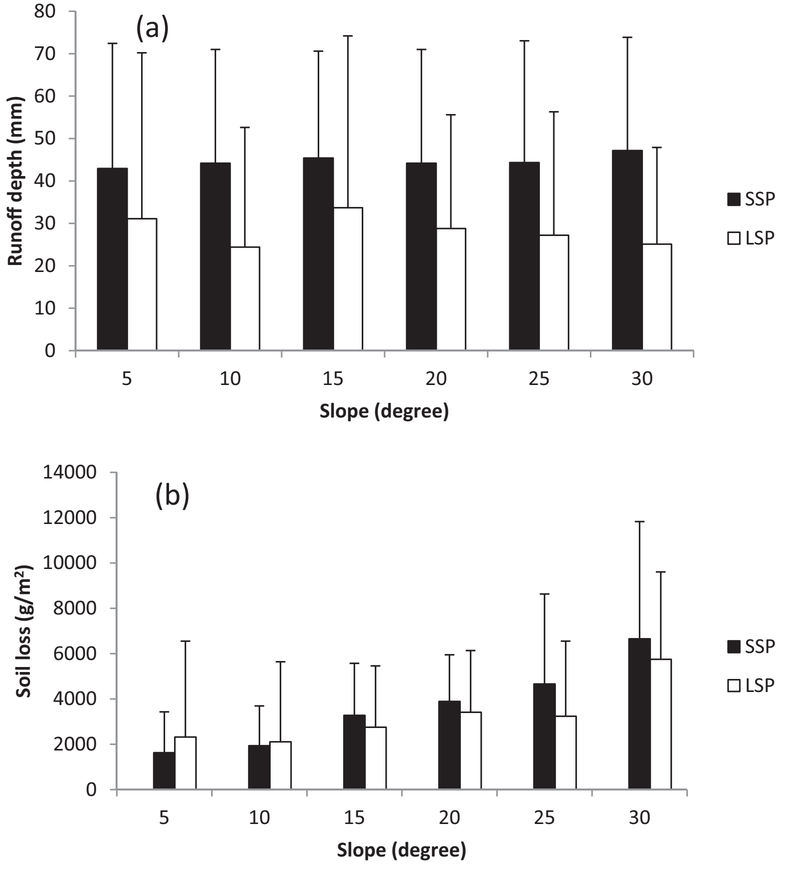

Fig. 6. Mean annual runoff and soil loss on Short Slope (SSP) and Long Slope (LSP) plots and their standard deviation error bars: (a) runoff and (b) soil loss.

B, *n*) in the equation were calibrated using the rainfall data in each region and they are varied from region to region.

$$\log N = \frac{I \times t^n}{B24^{n-1}} \tag{1}$$

Where *N* is recurrence interval (year); *t* is rainfall duration (h); *I* is mean rainfall intensity (mm/h); *A*, *B* and *n* are coefficients ($A = 40$, $B = 65$, and $n = 0.7$). The recurrence intervals of all the runoff generation storms over the study periods are shown in Fig. 5d.

3.2. Effects of slope steepness on water and soil loss

3.2.1. Annual runoff and soil loss

At slope angles of 5°, 10°, 15°, 20°, 25°, and 30°, the mean annual runoff per unit area was 42.9, 44.2, 45.4, 44.2, 44.3 and 47.2 mm on SSP, in comparison of 31.1, 24.3, 33.7, 28.8, 27.2, and 25.1 mm on LSP. Overall, the variation in runoff per unit area with slope angles was fairly limited on SSP (Fig. 6a). The highest mean annual runoff, occurring at 30°, was only 9.1% more than the lowest, occurring at 5°. On LSP, the highest mean annual runoff, occurring at 15°, was 27.8% more than the lowest, occurring at 10°. The relationship between runoff and slope angles was inconsistent between SSP and LSP. On SSP, the mean annual runoff per unit area generally showed a slight increase with slope angles.

However, on LSP, the mean annual runoff reached a maximum at 15° and then decreased with slope angles. The inconsistent and complex relationship between runoff and slope angles might be ascribed to the effects of several factors on soil infiltrability. Field infiltration experiments at micro-plot scale (0.5 m × 0.5 m) indicated that the average steady infiltration rate decreases with slope gradient in this region (Li et al., 1995). However, the loess soil is very susceptible to soil crust (Luk and Cai, 1990). The development of soil crust can significantly decrease infiltration rates (Römkens et al., 1990a). Luk and Cai (1990) observed that multiple cycles of soil crust development and destruction occur in the rainfall processes. Zhang and Cai (1992) found that soil crustability of loess is varied with slope gradients. The rainfall intensity also affected surface crust development (Römkens et al., 1990b). In addition, rill development is very active on the sloping lands in this region and the threshold of rill formation is varied with slope gradients and rainfall intensity (Wang and Zhang, 1992). Infiltration between inter-rill and rill areas may be different due to the destruction of crusts in rill areas. The combined effect of the above individual factors on runoff generation was highly complicated and difficult to separate.

At slope angles of 5°, 10°, 15°, 20°, 25°, and 30°, the mean annual soil loss per unit area was 1633.5, 1941.1, 3278.5, 3896.3, 4663.8, and 6658.2 g/m^2 on SSP, in comparison of 2320.3, 2109.2, 2752.4, 3417.4, 3238.1, and 5878.8 g/m^2 on LSP. Soil loss per unit area increased with slope steepness in both SSP and LSP (Fig. 6b). Although LSP generated 36.4% less annual runoff per unit area than SSP, ranging from 25.7% at 15° to 46.7% at 30°, they produced an average of only 3.6% less annual soil loss per unit area than SSP. In addition to the difference in rainfall between the two periods, this may also imply that the runoff infiltration and detention on long slope was higher than that on short slope, and that the concentrated flows on long slope had greater flow velocities and thereby erosion power than runoff generating from short slope (Wischmeier, 1972; Lal, 1982).

The annual runoff and soil loss per unit area showed wide variations among years of observation on both SSP and LSP (Supplementary Table 2). The coefficient of variation ranged from 0.59 to 0.73 in runoff and 0.56–1.18 in soil loss on SSP, in comparison of 0.91–1.26 in runoff and 0.67–1.83 in soil loss on LSP. This reflected the great variation in precipitation among years. As an extreme, there was no runoff and soil loss on LSP in 1965. The year had the lowest annual precipitation of 243.3 mm, among which 126.9 mm fell in the rainy season but none of it generated runoff. However, annual soil loss did not increase linearly with yearly precipitation either. The greatest yearly precipitation in 1964 did not produce the highest soil loss on LSP. The highest annual soil loss occurred on SSP in 2000. That year had a total of precipitation of 487.2 mm, which was even considerably below the mean annual precipitation of 522 mm over the7-year SSP monitoring period. This clearly indicates that annual rainfall is not a reliable rainfall index to predict runoff generation and soil loss in semi-arid environments. Wei et al. (2000) even found that the highest runoff ratio and erosion rates occurred not in wet years, but in dry years in the loess region, which is ascribed to the high fluctuations and variabilities of temporal rainfall in semi-arid climates (Hogarth et al., 2004; Nearing et al., 2005). Therefore, runoff and soil loss must be further examined on a storm event basis.

Supplementary Table 2 related to this article can be found, in the online version, at doi:10.1016/j.ejrh.2014.08.006.

3.2.2. Event runoff and soil loss

The event runoff and soil loss from SSP and LSP were listed in Supplementary Table 3. The average event runoff per unit area was 11.1, 11.5, 11.8, 12.2, 12.4, and 12.9 mm on SSP, in comparison of 6.2, 4.9, 6.8, 5.8, 5.4, 5.0 mm on LSP at 5°, 10°, 15°, 20°, 25° and 30°, respectively. The higher runoff per event on SSP than on LSP was partly ascribed to the greater average event rainfall amount (33.7 mm) over the SSP monitoring period than that (25.3 mm) over the LSP monitoring period. Correspondingly, the mean event runoff coefficient was higher on SSP than on LSP at all the slope angles, with 33.1, 34, 35, 36.4, 36.9, 38.2% on SSP, comparing 24.6, 19.2,26.6,22.8,21.5, 19.8% on LSP at 5°, 10°, 15°, 20°, 25°, 30°, respectively. This was partly because the proportion of rainfall lost to the initial infiltration and ponding prior to runoff initiation was inversely related to the event rainfall amount.

Supplementary Table 3 related to this article can be found, in the online version, at doi:10.1016/j.ejrh.2014.08.006.

At 5°, 10°, 15°, 20°, 25° and 30°, the mean event soil loss was 423.5, 503.3, 850, 1010.2, 1305.9, and 1815.9 g/m^2 on SSP, in comparison of 464.1, 421.8, 550.4, 683.5, 647.6 and 1150.1 g/m^2 on LSP.

Event soil loss per unit area was higher on SSP than LSP at all the slope angles except 5°. However, the soil loss: runoff ratio was higher on LSP than on SSP, with 38.2, 43.8, 72.0, 82.8, 105.3, 140.8 on SSP, in comparison of 74.8, 86.1, 80.9, 117.8, 119.9, and 230 on LSP at 5°, 10°, 15°, 20°, 25° and 30°, respectively. This again suggests that the concentrated water runoff on long slopes had greater erosive power and transport capacity than the runoff originating from short slopes. Both runoff and soil loss were greatly varied and skewed among storm events, and soil loss had overall greater variations than runoff on both SSP and LSP (Supplementary Table 3).

To relate rainfall to event runoff and soil loss, we chose event rainfall amount and storm recurrence interval as rainfall indices and correlated each of them with soil loss and runoff separately using power, linear, polynomial, and exponential functions. It was found that recurrence interval was better than event rainfall amount as a rainfall index (Supplementary Table 4). Zhu et al. (1997) indicated that only rainfall amount with an intensity of over 0.2 mm per minute during a storm is effective in runoff generation. This threshold of rainfall intensity is comparable to the minimum infiltrability on the crusted loess surface in the region. The correlation between soil loss and recurrence interval was best fitted by linear function on SSP and by polynomial function on LSP. Also, a higher correlation coefficient between rainfall recurrence interval and soil loss exists on SSP than on LSP. The correlation between rainfall and runoff follows the same pattern as the one between rainfall and soil loss, though the former generally had higher correlation coefficients than the latter. Fu et al. (2011) summarized the studies on the relationship between soil loss and slope gradients into three categories: power functions (e.g., Zingg, 1940; Musgrave, 1947); linear functions (e.g. McCool et al., 1987; Liu et al., 1994); and polynomial functions (e.g. Wischmeier and Smith, 1978). Nevertheless, all of these studies have been limited to relatively gentle slopes.

Supplementary Table 4 related to this article can be found, in the online version, at doi:10.1016/j.ejrh.2014.08.006.

To assess the relative contributions of storms with various recurrence intervals to total soil and water loss, we divided recurrence intervals into five categories: less than 1, 1–2, 2–5, 5–10 and greater than 10 years. Supplementary Table 5 listed the contributions of each category of storms to total soil and water loss at different slope angles. On SSP, rainstorms with recurrence intervals less than 1 year contributed to an average of 9.6% of total runoff and 12.4% of total soil loss; storms with recurrence intervals greater than 2 years were responsible for 68.6% of total runoff and 69.2% of total soil loss; the single largest rainstorm with a recurrence interval of 21.5 years contributed to 19.6% of total runoff and 31.5% of total soil loss. On LSP, storms with recurrence intervals less than one year contributed to an average 25.4% of total runoff and 24.8% of total soil loss; storms with recurrence intervals greater than 2 years were responsible for 66% of total runoff and 66. 1% of total soil loss; the single largest storm with a recurrence interval of 10 years produced 23.3% of total runoff and 32% of total soil loss. It is interesting to notice that the contributions of storms with recurrence intervals greater than 2 years to total runoff and soil loss were comparable between SSP and LSP.

Supplementary Table 5 related to this article can be found, in the online version, at doi:10.1016/j.ejrh.2014.08.006.

3.3. *S factor calculation for USLE and RUSLE models*

The slope factor used in the USLE was calculated in Eq. (2) (Wischmeier and Smith, 1978):

$$S = 65.4\sin^2\theta + 4.56\sin\theta + 0.0654 \tag{2}$$

The above equation was modified in RUSLE as following (McCool et al., 1987):

$$S = 10.8\sin\theta + 0.03, \quad \text{for} \quad q < 9\% \tag{3}$$

$$\text{Or}\, S = 16.8\sin\theta - 0.50 \quad \text{for} \quad q > 9\% \tag{4}$$

Where S is slope factor and θ is slope angle in per cent. The S values calculated using the equations in USLE and RUSLE were compared with the scaled ratio based on the measured annual soil loss data on both SSP and LSP (Fig. 7). It can be seen that the S values calculated from the equations were much higher than the measured ones, which suggests that the slope factor equations must be modified when

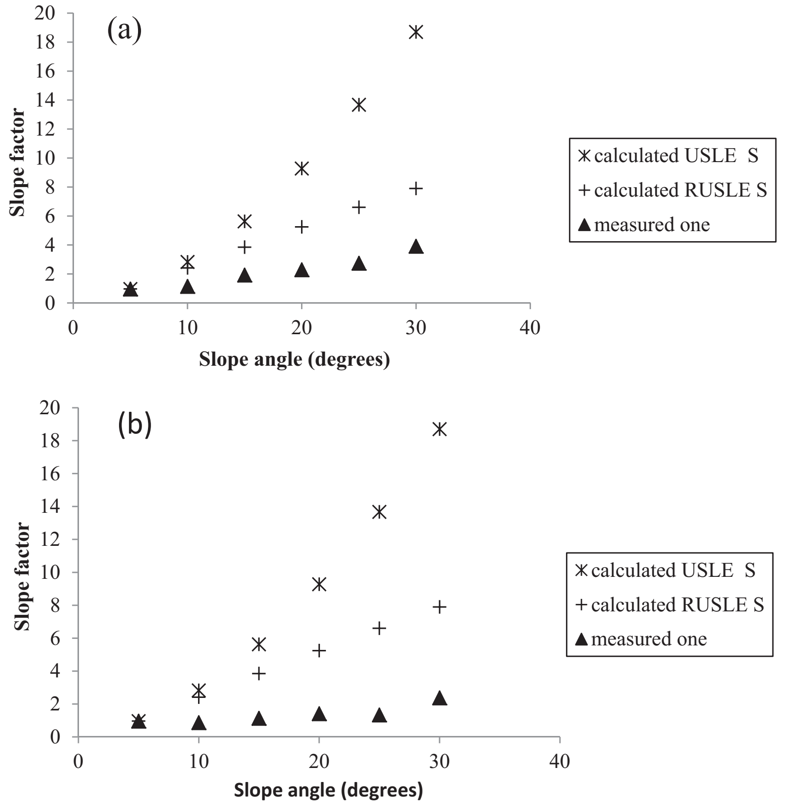

Fig. 7. Comparison of calculated *S* factors and measured ones (a) Short Slope (SSP) and (b) Long Slope (LSP) plots.

applying USLE or RUSLE models to this region. As the slope length of LSP was 20 m, quite close to the standard length of the USLE plots, we used the annual soil loss measured from LSP to develop the *S* factor equation for this region as following:

$$S = 6.8533 \sin\theta + 0.1222 \quad R^2 = 0.9448 \tag{5}$$

3.4. Effectiveness of soil and water conservation measures

The mean annual runoff and soil loss per unit area from five conservation plots, including woodland, grasses, alfalfa, contour earth banks and terraces, as well as cropland were shown in Fig. 8. The effectiveness of the soil conservation practices in controlling runoff was mixed. The mean annual runoff per unit area was 20.4 mm on earth bank, 19.5 mm on woodland, 18.2 mm on alfalfa plot, 5.0 mm on terrace and 2.5 mm on grassland, representing 123.8%, 118.9%, 111.0%, 30.3% and 15.2% of the runoff detected from cropland, 16.4 mm. In contrast, all five conservation practices were effective in reducing soil loss. The mean annual soil loss per unit area was 3073.1 g/m^2 on earth bank, 1575 g/m^2 on alfalfa land, 667.7 g/m^2 on woodland, 489.2 g/m^2 on grassland, and 452.4 g/m^2 on terraces, representing 48.9%, 25.1%, 10.6%, 6.9%, and 6.4% of the soil loss detected from cropland, 6279.3 g/m^2 on cropland.

While annual soil loss was, on average, much lower on all the soil conservation plots than on the cultivated cropland, it was varied among the years of observation (Supplementary Table 6). Soil loss from the three biological plots in the first year (1957) was even higher than that from the cultivated cropland, with 3690 g/m^2 on woodland, 3903.9 g/m^2 on grassland, and 2900 g/m^2 on alfalfa, in comparison of 2517.6 g/m^2 on cropland. This can be explained by the disturbance of surface soil during

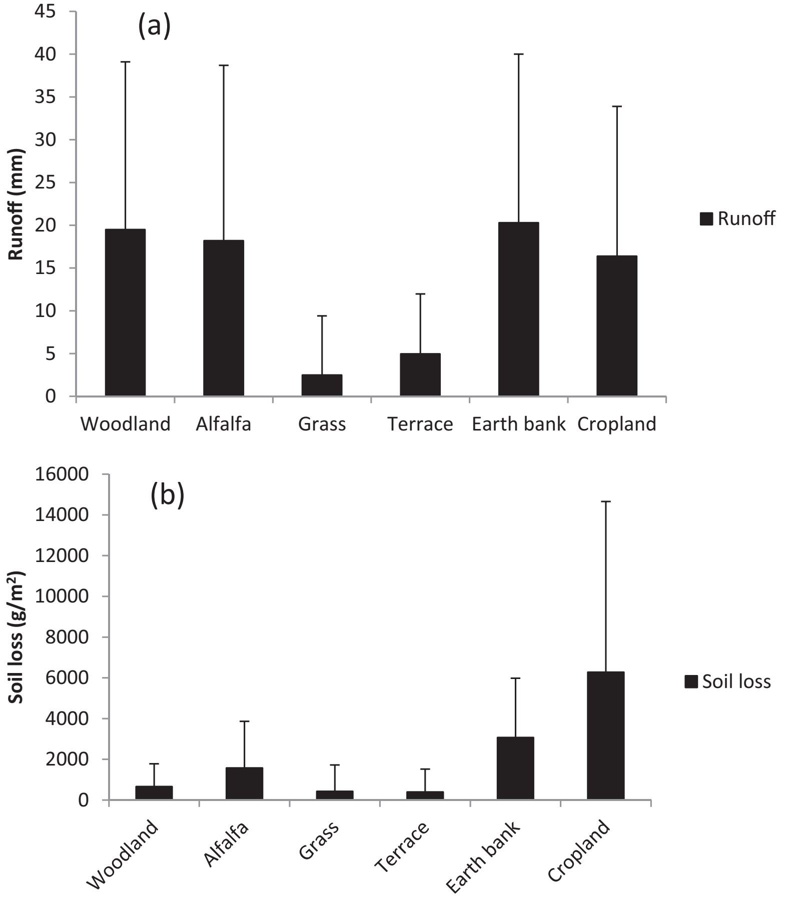

Fig. 8. Mean annual runoff and soil loss from conservation and cropland plots and their standard deviation error bars: (a) runoff and (b) soil loss.

the stage of planting and the low vegetation cover during the stage of establishment, which was also reported elsewhere (Garcia-Estringana et al., 2013). Since the second year, there had been almost no soil loss on grassland and very little erosion on woodland; soil loss on alfalfa had been also significantly lower than the cultivated cropland except in 1962. Runoff per unit area in the first 3 years (1957, 1958, 1959) was higher in woodland than in cultivated cropland. After then, runoff had been lower in dry years (1960, 1961, 1962, 1965) but higher in wet years (1963 and 1964) than that in cultivated cropland. Terrace was very effective in reducing runoff and soil loss in all years but the last year (1966). This might be related to the deterioration of sediment detention capability as terraces were getting old. Earth banks had lowest effectiveness in reducing soil loss among all the five conservation practices, even with higher annual soil loss than cultivated cropland in 1962 and 1963.

Supplementary Table 6 related to this article can be found, in the online version, at doi:10.1016/j.ejrh.2014.08.006.

We further examined soil loss on conservation practices and cropland plots in different frequency storms (Fig. 9 and Supplementary Table 7). It is especially important to assess how effective of those conservation practices in controlling soil loss in storms greater than 2-year recurrence intervals, since those storms contributed to more than two thirds of the total soil loss in the cultivated slope lands, as indicated before. The mean event soil loss in those large storms was 530 g/m^2 on woodland, 922.9 g/m^2 on alfalfa land, 477.2 g/m^2 on grassland, 228.5 g/m^2 on terraceland, and 1690 g/m^2 on earth bank,

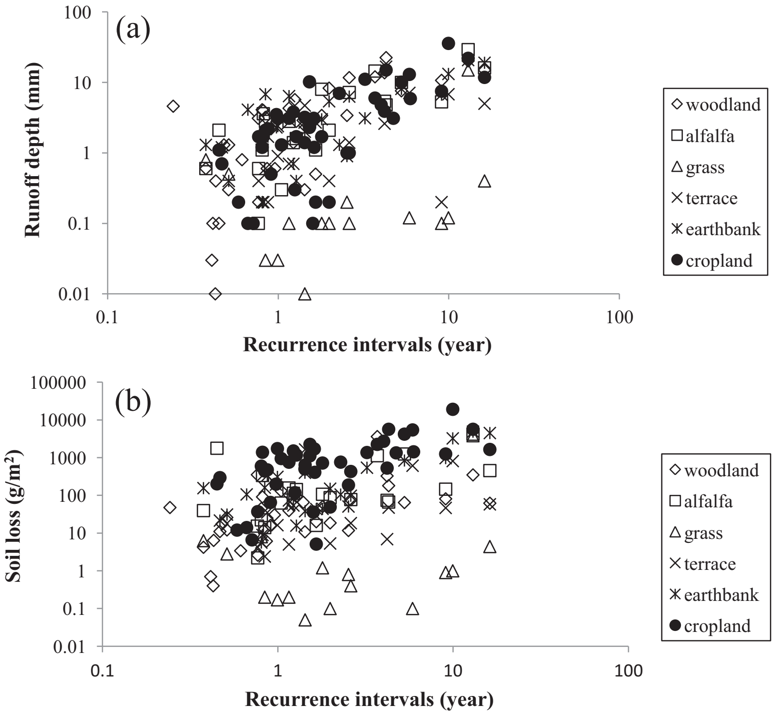

Fig. 9. Soil and water loss from conservation and cropland plots in storms of different recurrence intervals and their standard deviation bars: (a) runoff and (b) soil loss.

representing 15.7%, 27.4%, 14.1%, 6% and 50.1% of the soil loss detected from the cropland, 3373 g/m^2. Of those large storms, there were three extreme storms with recurrence intervals greater than 10 years, in which the mean event soil loss was 205.5 g/m^2 on woodland, 2322.1 g/m^2 on alfalfa land, 1271.8 g/m^2 on grassland, 434.9 g/m^2 on terraceland, and 4203.3 g/m^2 on earth banks, representing 2.3%, 26%, 14.4%, 4.9% and 47.7% of the soil loss detected from cropland, 8809.3 g/m^2. With respective of runoff reduction, it is important to know how effective of those practices in reducing runoff in extreme large storms which may cause flooding. The mean event runoff for storms with recurrence intervals of greater than 10 years was 17.6 mm on woodland, 22.7 mm on alfalfa land, 5.2 mm on grassland, 5.9 mm on terraces, and 17.7 mm on earth banks, representing 75.9%, 97.8%, 22.4%, 25.4% and 76.3% of runoff generating from cropland, 23.2 mm on cropland.

Supplementary Table 7 related to this article can be found, in the online version, at doi:10.1016/j.ejrh.2014.08.006.

Finally, soil loss by the maximum annual erosion event was compared to annual total soil loss on the cropland plot (Fig. 10). It can be seen that erosion rate by the maximum annual erosion event was widely varied among years, ranging from 409 to 19,127 g/m^2, which contributed to a mean value of 64% of the annual total soil loss, ranging from 22.2 to 90.6%. The rainfall amount of the maximum annual erosion event accounted for a mean value of 9.1% of annual precipitation, ranging from 3.4 to 15.7%. In other words, a fraction of annual precipitation was often responsible for majority of annual total erosion in this semi-arid region. However, it is noted that the maximum annual erosion event was not necessarily the maximum annual rainfall event. For example, in 1958, the largest storm event with rainfall amount of 78.8 mm merely generated soil loss of 529 g/m^2, in comparison of the largest erosion event of 5651 g/m^2 caused by a storm of 50.9 mm in rainfall amount. This indicated the significance of other rainfall characteristics (e.g. intensity, pattern, duration, and antecedent rainfall) besides event rainfall amount in determining rainfall erosivity.

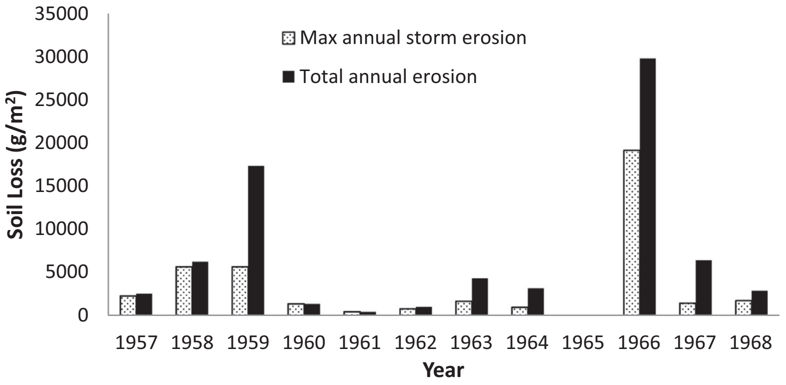

Fig. 10. Soil loss in the maximum annual erosion event and annual total soil loss on the cropland plot.

4. Conclusions

The hilly loess region in China is dissected by dense gullies and the individual households farm the narrow and often steep lands in inter-gully areas. This justifies the purpose of the present study on soil and water loss on the slope plots with relatively short lengths and a wide range of slope angles up to 30°. This study combines three sets of plot data to assess soil and water loss from cultivated slopelands and to evaluate the effectiveness of different conservation practices in controlling erosion and runoff. Each set of data contains multiple-year observations of soil and runoff loss under widely varied rainstorms, which are typical to semi-arid climates.

With an increase of slope angles, runoff per unit area slightly increased on SSP, but it decreased after reaching a maximum at 15° on LSP, which may be related to the complicated effect of several factors (e.g. crusting, rill development, rainfall conditions) on soil infiltrability. Soil loss per unit area increased with slope angles on both SSP and LSP. There were 36.4% less runoff but only 3.6% less soil loss per unit area produced on LSP than on SSP, which was likely ascribed to more runoff infiltration and greater flow velocity on long slope as a comparison of short slope.

Event recurrence interval is a better rainfall index than event rainfall amount in correlating rainfall to soil loss and runoff. The correlation between soil loss and recurrence interval can be best fitted with a linear equation on SSP and a polynomial equation on LSP. Storms with recurrence intervals greater than 2 years contributed to about two thirds of the total runoff and soil loss. The slope equations in USLE/RUSLE overestimated the *S* factor in this region.

On the steep cropland, a fraction of annual precipitation was often responsible for majority of annual total erosion in this semi-arid region. In general, the soil conservation practices were more effective in reducing soil loss than in reducing runoff on steep cultivated croplands. The five conservation practices (earth banks, woodland, alfalfa, terrace and grassland) generated 123.8%, 118.9%, 111.0%, 30.3% and 15.2% of the mean annual runoff on cropland, and correspondingly yielded 48.9%, 25.1%, 10.6%, 6.9%, and 6.4% of mean soil loss on cropland. The effectiveness of soil erosion control in storms greater than 2 years in recurrence intervals decreased in the order of terraces > grasses > woodland > alfalfa > earth bank, while the effectiveness in reducing runoff caused by storms greater than 10 years in recurrence intervals decreased in the order of grasses > terraces > woodland > earth banks > alfalfa.

Acknowledgements

We gratefully acknowledge that the following people at Shanxi Institute of Soil and Water Conservation have been involved in field monitoring and data compiling in the different periods: Wang, X.P., Liu, S.P., Zeng, B.Q., Jia, Z.J., Fu,J.S., Zhang, Z.G. This project was funded by the Graduate School at University of Minnesota (Grant No. 22166). The manuscript also benefits from the comments and suggestions of Dr. Batelaan and two anonymous reviewers.

References

Chen, Y.Z., Luk, S.H.,1989. Sediment sources and recent changes in the sediment load of the Yellow River, China, vol. 1. In: Proceedings 5th International Soil Conservation Conference, Bangkok, Thailand. Department of Land Development, Bangkok, pp. 313–323.

Fox, D.M., Bryan, R.B., 1999. The relationship of soil loss by interrill erosion to slope gradient. Catena 38, 211–222.

Fu., S., Liu, B., Liu, H., Li, X., 2011. The effect of slope on interrill erosion at short slopes. Catena 84, 29–34.

Garcia-Estringana, P., Alonso-Blázquez, N., Marques, M.J., Bienes, R., González-Andrés, F., Alegre, J., 2013. Use of Mediterranean legume shrubs to control soil erosion and runoff in central Spain. A large-plot assessment under natural rainfall conducted during the stages of shrub establishment and subsequent colonization. Catena 102, 3–12.

Hogarth, W.L., Parlange, J.Y., Rose, C.W., 2004. Soil erosion due to rainfall impact with inflow: an analytical solution with spatial and temporal effects. J. Hydrol. 295, 140–148.

Hoyos, N., 2005. Spatial modeling of soil erosion potential in a tropical watershed of the Colombian Andes. Catena 63, 85–108.

International Soil Conservation Organization (ISCO), 2002. 12th ISCO Congress Conference, May 26–31 , Beijing, China.

Kinnell, P.I.A., 2010. Event soil loss, runoff and the universal soil loss equation family of models: a review. J. Hydrol. 385, 384–397.

Laflen, J.M., Baker, J.L., Hartwig, R.O., Buehelle, W.F., Johnson, H.P., 1978. Soil and water loss from conservation tillage system. Trans. ASAE 21, 881–886.

Lal, L.R., 1982. Effects of slope length and terracing on runoff and erosion on a tropical soil. IAHS Publ. 137, 23–31.

Lal, R., 1998. Soil erosion impact on agronomic productivity and environment quality. Crit. Rev. Plant Sci. 17, 319–464.

Larson, W.E., Lindstrom, M.J., Schumacher, T.E., 1997. The role of severe storms in soil erosion: a problem needing consideration. J. Soil Water Conserv. 52, 90–95, March–April.

Li, G., Luk, S.H., Cai, Q.G., 1995. Topographic zonation of infiltration in the hilly loess region, North China. Hydrol. Process. 9, 227–235.

Liu, B.Y., Nearing, M.A., Risse, L.M., 1994. Slope gradient effects on soil loss from steep slopes. Trans. ASAE 37 (6), 1835–1840.

Liu, B.Y., Nearing, M.A., Shi, P.J., Jia, Z.W., 2000. Slope length effects on soil loss for steep slopes. Soil Sci. Soc. Am. J. 64, 1759–1763.

Liu, D.S., 1964. Loess Deposits in the Middle Reaches of Yellow River. Science Press, Beijing, pp. 234.

Lu, X.X., Higgitt, D.L., 2001. Sediment delivery to the three gorges: 2: local response. Geomorphology 47, 157–169.

Luk, S.H., Cai, Q.G., 1990. Laboratory experiments on crust development and rainsplash erosion of loess soils, China. Catena 17 (3), 261–276.

Mannaerts, C.M., Gabriels, D., 2000. A probabilistic approach for predicting rainfall soil erosion losses in semiarid areas. Catena 40, 403–420.

McCool, D.K., Brown, L.C., Foster, G.R., Mute Hler, C.K., Meyer, L.D., 1987. Revised slope steepness factor for the universal soil loss equation. Trans. ASAE 30, 1005–1013.

Mugagga, F., Kakembo, V., Buyinza, M., 2012. Land use changes on the slopes of Mount Elgon and the implications for the occurrence of landslides. Catena 90, 39–46.

Musgrave, G.W., 1947. The quantitative evaluation of factors in water erosion – a first approximation. J. Soil Water Conserv. 2, 133–138.

Nearing, M.A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M., Nunes, J.P., Renschler, C.S., Souchère, V., van Oost, K., 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61, 131L 154.

Podwojewski, P., Orange, D., Jouquet, P., Valentin, C., Nguen, Van Thiet, Janeau, J.L., Toan, T.D., 2008. Land-use impacts on surface runoff and soil detachment within agricultural sloping lands in Northern Vietnam. Catena 74, 109–118.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). In: USDA Agriculture Handbook., pp. 703.

Römkens, M.J.M., Prasad, S.N., Whisler, F.D., 1990a. Surface sealing and infiltration. In: Anderson, M.G., Burt, T.P. (Eds.), Process Studies in Hillslope Hydrology. Wiley, West Sussex, England, pp. 127–172, Chapter 5.

Römkens, M.J.M., Prasad, S.N., Parlange, J.Y., 1990b. Surface seal development in relation to rainstorm intensity. Catena Suppl. 17, 1–11.

Rumpel, C., Chaplot, V., Planchon, O., Bernadou, J., Valentin, C., Mariotti, A., 2006. Preferential erosion of black carbon on steep slopes with slash and burn agriculture. Catena 65, 30–40.

Shanxi Institute of Soil and Water Conservation (SISWC), 1982. Rainfall, Runoff and Sediment Data (1955–1981) (unpublished in Chinese).

Turkelboom, F., Poesen, J., Ohler, I., Van Keer, K., Ongprasert, S., Vlassak, K., 1997. Assessment of tillage erosion rates on steep slopes in northern Thailand. Catena 29, 29–44.

Wang, G.P., Zhang, Z.G., 1992. Rill initiation and erosion on the loess soils. In: Soil Erosion Management and Application of Geographical Information System in the Loess Plateau region, Western Shanxi. Science Press, Beijing, pp. 257 (in Chinese).

Wei, W., Chen, L.D., Fu, B.J., Chen, J., 2000. Water erosion response to rainfall and land use in different drought level years in the loess hilly area of China. Catena 81, 24–43.

Wischmeier, W.H., 1972. Upslope erosion analysis. In: Environmental Impact on Rivers. Water Resources Publication, Fort Collins, CO, USA.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion loss. A guide to conservation planning. In: USDA Agriculture Handbook no. 537, Washington, DC.

Zhang, G.Y., Cai, C.F., 1992. Process of formation, destruction and micormorphology of crust on loess soil. In: Soil Erosion Management and Application of Geographical Information System in the Loess Plateau region, Western Shanxi. Science Press, Beijing, pp. 257 (in Chinese).

Zhu, A., Wang, P., Zhu, T.X., Chen, L.J., Cai, Q.G., Liu, H.P., 2013. Modeling runoff and soil erosion in the Three-Gorge Reservoir drainage area of China using limited plot data. J. Hydrol. 492, 163–175.

Zhu, T.X., Cai, Q.G., Zeng, B.Q., 1997. Runoff generation on a semi-arid agricultural catchment: field and experimental studies. J. Hydrol. 196, 99–118.

Zhu, T.X., 2003. Tunnel development over a 12 year period in a semi-arid catchment of the Loess Plateau, China. Earth Surf. Process. Landf. 28, 507–525.
Zhu, T.X., 2013. Spatial variation and interaction of runoff generation and erosion within a semi-arid, complex terrain catchment: a hierarchical approach. J. Soils Sediments 13, 1770–1783.
Zingg, A.W., 1940. Degree and length of land slope as it affects soil loss in runoff. Agric. Eng. 21 (2), 59–64.