Responses of water erosion to rainfall extremes and vegetation types in a loess semiarid hilly area, NW China

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Abstract:

Rainfall extremes (RE) become more variable and stochastic in the context of climate change, increasing uncertainties and risks of water erosion in the real world. Vegetation also plays a key role in soil erosion dynamics. Responses of water erosion to RE and vegetation, however, remain unclear. In this article, on the basis of the data measured on 15 plots (area: 10 m × 10 m and 10 m × 5 m) and the definition of World Meteorological Organization (WMO) on rainfall extremes, 158 natural rainfall events from 1986 to 2005 were analysed, and rain depth and maximal 30-min intensity (MI₃₀) were used to define RE. Then, water erosion process under RE and five vegetation types (spring wheat, alfalfa, sea buckthorn, Chinese pine, and wheatgrass) were studied in a key loess semiarid hilly area, NW China. The following findings were made: (1) The minimal thresholds of depth and MI₃₀ for defining RE were determined as 40.11 mm and 0.55 mm/min, respectively. Among the studied rainfall events, there were four events with both the variables exceeding the thresholds (REI), five events with depths exceeding 40.11 mm (REII), and four events with MI₃₀ exceeding 0.55 mm/min (REIII). Therefore, not only extreme rainstorm, but also events with lower intensities and long durations were considered as RE. Moreover, RE occurred mostly in July and August, with a probability of 46 and 31%, respectively. (2) Extreme events, especially REI, in general caused severer soil-water loss. Mean extreme runoff and erosion rates were 2.68 and 53.15 times of mean ordinary rates, respectively. The effect of each event on water erosion, however, becomes uncertain as a result of the variations of RE and vegetation. (3) The buffering capacities of vegetation on RE were generally in the order of sea buckthorn > wheatgrass > Chinese pine > alfalfa > spring wheat. In particular, sea buckthorn reduced runoff and erosion effectively after 3–4 years of plantation. Therefore, to fight against water erosion shrubs like sea buckthorn are strongly recommended as pioneer species in such areas. On the contrary, steep cultivation (spring wheat on slopes), however, should be avoided, because of its high sensitivities to RE. Copyright © 2009 John Wiley & Sons, Ltd.

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INTRODUCTION

Water erosion in the Chinese loess hilly area is still very severe, challenging the sustainability of social and environmental security in the locality (Fu, 1989; Kang *et al.*, 2001; Wei *et al.*, 2006a; Chen *et al.*, 2007a). Special meteorological status and intensified human activity, coupled with harsh natural conditions and fragile ecosystems, are considered as the major trigger and driver of water erosion in this semiarid environment (Shi and Shao, 2000; Wang *et al.*, 2006; Xu *et al.*, 2007).

Among these factors, precipitation extremes, in particular, play important roles in inducing severer water erosion in the semiarid ecosystems than in the temperate areas. For example, studies show that the temporal distribution of heavy rainstorms is especially necessary for assessing runoff amount and erosion rate (Klik and

Truman, 2003; Apaydin *et al.*, 2006). The severity, frequency, extent, and impact of soil erosion processes are likely to be altered by the high degree of fluctuation and variation of rainfall depth, intensity and frequencies (Gregory *et al.*, 1999; Sivakumar, 2007). The number, timing and magnitude of storms also greatly impact hydrological processes (Weltzin *et al.*, 2003). Soil erosion, landslides, mass movements, and debris flows have been monitored and found to be more severe when large-scale heavy rainstorms occur (Cheng *et al.*, 2002). The annual nutrient loss due to water erosion, under extremely heavy rainfall, exceeds 50% of the total amount (Gao *et al.*, 2005). Mannaerts and Gabriels (2000) also found that the dominant seasonal concentration of water erosion was limited to a few major storms only.

More notably, the episodes of rainfall extremes (RE) in nature have been monitored to be more capricious, stochastic, and unpredictable during the past several decades (Weltzin *et al.*, 2003). The intensity, frequency, and regimen of extreme precipitation events, which have already increased globally, are predicted to increase

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further (Easterling *et al.*, 2000; IPCC Working Group I, 2001). This variability will probably increase the complexity and uncertainty of water erosion process (Gregory *et al.*, 1999; Zhang and Liu, 2005a). For example, studies found that changeable precipitation is the main factor in runoff and sediment alteration (Guo, *et al.*, 2002; Jake *et al.*, 2003; Chen *et al.*, 2007b). Recently, a new prediction declares that rain erosivity, which is the major driving force of water erosion, will increase 8–35% on the Chinese Loess Plateau in the next 10 decades (Zhang and Liu, 2005a). Another study also found high levels of seasonal and annual runoff fluctuations in this region during the past several decades, mainly owing to the varied precipitation patterns (Xu *et al.*, 2007). High degree of variations and occurrences of RE coupled with fragile earth surface can cause severer consequences of soil erosion and land degradation.

The type, cover, structure, and age of vegetation, on the other hand, are another key factor, besides RE, influencing water erosion processes (Cerdà, 1998; Zhou *et al.*, 2006; Pizarro *et al.*, 2006). Studies found that various hydrological responses occur under different vegetation communities (Fu, 1989; Chen *et al.*, 2003; Zhang *et al.*, 2005b; Zhao *et al.*, 2006). Vegetation plays a key role in intercepting rainfall, increasing water infiltration, fixing soil by roots, providing mechanical protection by reducing raindrop energy and ‘splash’ effects, and trapping sediment (Gyssels and Poesen, 2003; Rey *et al.*, 2004; Bochet *et al.*, 2006). Water erosion will decrease, if adapted vegetation restoration is applied. In particular, proper plant selection and management (mulching and land closure) can increase surface cover and root energy, improve soil property, and therefore reduce soil erosion (Hou *et al.*, 1996; Cheng *et al.*, 2002; Li *et al.*, 2004; Adekalu *et al.*, 2006). Vegetation destruction (steep cultivation and bare zones caused by deforestation,) or improper species use, on the contrary, may deteriorate soil features and induce severe soil loss as well as land degradation on larger scales (Wang *et al.*, 2003; Pimentel *et al.*, 2004; Li *et al.*, 2007). For example, sloping farmlands converted from forests and grasslands in the loess hilly area have suffered from severe erosion, and water and nutrient loss for a long time (Zheng *et al.*, 2004; Zheng, 2006). Decrease or even disappearance of vegetative cover plays negative role in modifying the processes of rainfall interception and overland flow, which affect the dynamics of surface water cycle and deposition of sediment yields (Kang *et al.*, 2001; Pan and Shuangguan, 2006; Rulli and Rosso, 2007).

However, responses of water erosion to RE remain unclear, and this is especially true under different vegetation types. Studying RE and their erosion responses among vegetation types is thus significant for understanding the comprehensive mechanisms and dynamics of hydrological and erosion processes. Furthermore, consecutive measurements from plot scales for long periods have been confirmed to be of crucial importance for reliable water erosion analysis and prediction on larger scales (Zhang *et al.*, 1996; Licznar and Nearing, 2003). In this

study, 158 natural rainfall events producing runoff were used for RE selection. These data sets were based on field measurement and collection extending from 1986 to 2005 (data in 2000 and 2001 missing). The main purpose of this article is to highlight and discuss the responses of water erosion processes to RE and vegetation types in a key loess semiarid hilly area, NW China. Three specific sub-objectives are expected to be achieved: (1) to study the role of RE on water erosion processes; (2) to analyse the buffering capacities of different vegetation types on extreme rates of runoff and erosion; (3) to discuss the combined effect of RE and vegetation types on water erosion processes.

MATERIALS AND METHODS

Study area

The study area and experimental plots are located at the field station (Figure 1) of Dingxi Soil and Water Conservation Institute (1895m a.s.l., 35°33'N, 104°35'E) in Anjiagou catchment, a typical loess hilly area in Gansu, NW China. This region is dominated by a semiarid continental temperate climate, with two distinct seasons, cold-dry winters and warm-wet summers (Xu *et al.*, 2007). The mean annual precipitation has been about 426.6mm over the past five decades, over 80% of which has fallen in the rainy season from May to September (Wang *et al.*, 2003), with an annual variability of 26%. The maximum and minimum precipitations have been 721.8 mm, in 1967 and 245.7 mm, in 1982 (Huang *et al.*, 2005a). However, the potential annual evaporation can reach 1510 mm. The mean monthly temperature ranges from −7.6 to 27.5 °C, with an average annual temperature of 6.3 °C. Annually, about 141 days are frost-free.

Local soil is developed from the wind-accumulated loess parent material, which is about 40–60 m deep. The dominant soil is calcic Cambisol (FAO-UNESCO, 1974) with clay content of 33.12–42.17%, organic matter of 3.7–13.4 g/kg, and soil bulk density of 1.09–1.36 g/cm³ within 2-m depth. Meanwhile, the topography in the study area is fragmentized and complex (Table I), with a mean slope of 14.3° and a gully density of 3.14 km/km². This type of soil and landform is easy to suffer from serious water erosion (Fu and Gulinck, 1994; Wei *et al.*, 2006 b).

After hundreds of years of cultivation and other strong human disturbances, most of the natural vegetation in this area has been converted into farmland, causing loss of ground cover protection. The majority of the remainder consists of natural secondary grass species [wheatgrass (*Agropyron cristatum* L. Gaertn), needle-grass (*Stipa capillata* Linn.), etc.] and planted vegetation types such as sea buckthorn (*Hippophae rhamnoides* L.), pea tree (*Caragana Korshinskii* Kom), poplar (*Populus* spp), Chinese arborvitae (*Platycladus orientalis* L.), Chinese pine (*Pinus tabulaeformis* Carr), and apricot (*Prunus armeniaca* L.). The main crop species are spring wheat (*Triticum aestivum* L. cv Leguan), alfalfa (*Medicago*

Figure 1. Location of the study area and experimental design

Table I. Topography and gradient features of the study area

Index	Slope gradient						Landform			
	<5°	5°–10°	10°–15°	15°–20°	20°–25°	>25°	Hilltop	Hill slope	Terrace	Gully slope
Ratio (%)	11.7	14.1	38.9	15.1	9.3	11.2	0.9	74.6	10.8	13.7

sativa L.), potatoes (*Solanum tuberosum* L.), and maize (*Zea mays* L.). Because of severe drought and poor soil conditions *in situ*, most of the artificial plants can not grow well and the productivity remains relatively low.

Experimental manipulation

In 1986, 15 plots were collocated on a north-facing hill-slope, about 100 m from the meteorological station of Dingxi Soil and Water Conservation Institute. Before constructing the plots, former cultivated rain-fed crops, such as wheat, potatoes, beans, and millet in this area were cleared off. To reduce the effects of position and topography, all the runoff plots were established on the same slope. They were oriented parallel to the slope and adjacent to one another.

The following five vegetation types with three replications have been investigated on the 15 experimental plots (slope degree: 10°, 15 and 20°), which were installed in the same year (1986): (1) Spring wheat (*T. aestivum* L. cv Leguan): field management was similar to that used by local farmers, and the seeds of spring wheat were sown in April each year and harvested manually in late July or early August. Because of bad climate and severe drought, spring wheat remained low in productivity during the periods of measurement. (2) Alfalfa (*M. sativa* L.): the seeds were sown by drilling or broadcasting in April, 1986 and harvested in late July of the

same year. Alfalfa was replanted annually from 1993 to 1999, because of low productivity. (3) Sea buckthorn (*H. rhamnoides* L.): saplings were planted at 1.0 m by 1.0 m spacing in March, 1986. Litter remained on the plots without clearance. A few artificial disturbances, due to high density and prickly branches, existed in this plant community. (4) Chinese pine (*P. tabulaeformis* Carr.): Chinese pine saplings were planted in 3.0-m rows and 1.5-m columns in March 1986, without artificial pruning and irrigation. (5) Wheatgrass (*A. cristatum* L. Gaertn): This natural species was left to grow without any human disturbance since 1986, when the cropland was abandoned, and wheatgrass has now become the dominant species in the patches. It is well known as a good grass species growing in cold arid regions. Meanwhile, the mean annual coverage rate of each vegetation type from 1986 to 2005 was measured (Figure 2).

Plots used for sea buckthorn and Chinese pine were 10m × 10m, while plots used for spring wheat, alfalfa, and wheatgrass were 10m × 5m. On each plot, cement ridges (about 30 cm above ground) were constructed at the borders to isolate plot runoff and sediment yield. A discharge ditch was created at the top of each plot to control runoff and sediment yield from the upper slope. At the base of each plot, a marked H-flume and two volumetric tanks were built at the outlet of each plot for surface runoff and sediment collection.

Figure 2. Average annual coverage of vegetation types from 1986 to 2005 (*Measurement*: The coverage of alfalfa and wheatgrass was estimated in the maximal growth period by 5 quadrates of $1\text{ m} \times 1\text{ m}$ within each plot; the coverage of sea buckthorn and pine was measured by means of values of canopy width; the coverage of spring wheat was estimated by the row spacing. The mean coverage rate of three replications was used for each vegetation type.)

Data measurement

Daily rainfall during the rainy seasons was measured and recorded by a SM₁ pluviometer and a SJ₁ auto-siphon udometer in the study area. A rainfall event would be separated into two parts and defined as two independent events, if an interval exceeding 6 h existed during the event. According to the basic information provided by the data logger, several key rainfall variables including depth, duration, average intensity, and maximum 30-min intensity (MI_{30}) were all calculated and recorded. Runoff volume from each plot in each rainfall event was recorded simultaneously. Sediments from the 15 plots were first sampled using 250-ml bottles, and then deposited, separated from the water, and dried at 105°C in a forced air oven to a constant weight. The monitored data were then used to calculate the related hydrological indices representing the degrees of soil erosion and water loss.

Definition of RE

In this study, RE are defined on the basis of the criterion of the World Meteorological Organization (WMO), i.e. when the difference between the specific rainfall variables and corresponding mean values of 30-year measurements exceeds the double variance of each variable, the rainfall events are defined as RE (CCCIN, 2002). Moreover, depth and MI_{30} are used to determine RE in this article. The corresponding calculated equation is as follows:

$$\chi - \varpi > 2\theta \quad (1)$$

where χ represents rainfall variable such as depth or intensity, ϖ is the mean value of this variable in 30 years, and θ is the variance of the related variable.

On the basis of the definition mentioned above, two specific sub-criteria for determining RE were carried out as follows: (1) Rainfall depth exceeds its mean annual value (calculated as 18.87 mm in this study), and MI_{30} exceeds the summation of its double variance and annual

value. (2) If MI_{30} can not reach the WMO criterion, rainfall depth must exceed the corresponding criterion. Rainfall events agreeing with one or both of the two criteria will be regarded as an extreme rainfall event.

Clustering and statistical methodology

In this study, hierarchical clustering method was used to analyse and classify different styles of RE. This method is a fundamental and important tool for statistical analysis, widely used in such diverse scientific fields as psychology, zoology, biology, hydrology, botany, sociology, meteorology, physiognomy, etc. (Yu and He, 2003). It aims to group objects on the basis of their similarities, and the number of clusters is obtained by automatic statistical analysis (Hong, 2003). Two types of hierarchical clustering methods are included, i.e. R type and Q type (Yu and He, 2003). R type clustering is used for variable classification, and Q type clustering for different cases. In this article, R type clustering procedure is used.

Meanwhile, to open out more specific features of the defined RE, the descriptive statistical method was used for analyzing three key rainfall variables (i.e. rain depth, duration, and MI_{30}) shown in Figure 3 and Table II. Furthermore, in order to calculate and analyse the relationships between RE, runoff, erosion, and vegetation types clearly, two indicators including REr (r = runoff) and REe (e = erosion), which respectively represent the ratio of extreme runoff coefficient to the mean runoff coefficient and the ratio of extreme erosion modulus to mean erosion modulus, are established in this study and can be determined by the following two mathematical equations:

$$REr = MERC/MRC = (ESR/EPD)/(SR/PD) \quad (2)$$

where MERC, MRC, ESR, EPD, SR and PD refer to mean extreme runoff coefficient (%), mean runoff coefficient (%), extreme surface runoff, extreme precipitation

Figure 3. Characteristics of rainfall variables of extreme events. *Note:* RD, rainfall depth (unit: mm); D, duration (unit: min); MI₃₀, maximal intensity in 30 min (unit: mm/min)

Table II. Descriptive Statistics of rainfall variables

Variable	Range	Minimum	Maximum	Sum	Mean	SD	CV
RD (mm)	44-60	22.00	66.60	519.00	39.92	12.22	0.31
D (min)	1407.0	22.0	1435.0	8354.0	642.6	501.9	0.78
MI ₃₀ (mm/min)	0.84	0.11	0.95	—	0.51	0.27	0.53

RD, D, MI₃₀, SD and CV separately refer to rainfall depth, duration and maximal intensity in 30 min, standard deviation and coefficient of variation.

depth, surface runoff and precipitation depth, respectively.

$$REe = MEEM/MEM = (ESL/PA)/(SL/PA) \quad (3)$$

where MEEM, MEM, ESL, SL and PA refer to mean extreme erosion modulus (t/km^2), mean erosion modulus (t/km^2), soil loss under extreme rainfall events, soil loss under ordinary rainfall events, and area of experimental plot, respectively.

All the calculations were processed under SPSS 13.0 for windows.

RESULTS

Defined RE

According to the consecutive data sets and WMO criterion, the thresholds of depth and MI_{30} of RE in the study area are firstly determined, i.e. 40.11 mm and 0.55 mm/min, respectively. Meanwhile, the mean depth for the ordinary events is calculated as 18.87 mm. To be an extreme event, each of the two variables should separately exceed the threshold of 40.11 mm or 0.55 mm/min. According to this criterion, 13 extreme events were finally screened out from a total of 158 rainfall events from 1986 to 2005 (2000 and 2001 are excluded). All the remaining 145 rainfall events belonged to ordinary events, and are not to be involved in this article.

From the results shown in Figure 3, we can see that extreme events appeared almost every year during the past two decades. More importantly, this kind of events experienced clear variation among different months. During this period, RE occurred six times in July with a probability of 46%, four times in August with a probability of 31%, and three times in May with 24% probability. No events of RE however, were captured in June and September during the past 20 years. From this point of view, the most important time for paying special attention is July, followed by August, and May.

Meanwhile, it can be seen that the selected rainfall variables experienced high fluctuations among different extreme events during the years from 1986 to 2005 (Table II). The rainfall depths of extreme events ranged from 22.00 to 66.60 mm with a mean value of

39.92 mm, and this value is far higher than the mean depth (18.87 mm) of ordinary rainfall events. The duration varied from 22 to 1435 min with a high coefficient of variation of 0.78. The maximal intensity in 30 min, however, experienced a highest value of 0.95 mm/min and a lowest value of 0.11 mm/min. These quantitative results indicate that not only extremely heavy storms, but also some events with lower intensities and long durations are here considered as RE.

Furthermore, the captured 13 extreme events have been classified into three categories on the basis of their similarities under the procedure of hierarchical clustering method. This is used for analyzing the common features of different types of RE and then discussing their erosive role (Figure 4).

The first category (REI) has such features as depth and MI_{30} , all above the relevant threshold. This kind of events holds a total percentage of 30.77%. The second category (REII) is the aggregation of RE with depth exceeding the related threshold (40.11 mm), but the value of MI_{30} does not reach the corresponding standard (0.55 mm/min). Herein, five extreme events were captured, holding a total percentage of 38.46%. Although the MI_{30} of this kind of events is relatively low, it has higher rainfall depths due to longer durations. The third category (REIII) of RE has such features as MI_{30} exceeding the threshold of 0.55 mm/min and the depths in the ranges of 18.87–40.11 mm.

This result also revealed that secondary classifications existed in the last two categories (the lightest broken line shown in Figure 4). Two sub-levels appeared in RE II and RE III. In RE II, for example, two extreme rainfall events belonged to the same sub-category, and the other three extreme events pertain to the other sub-category. The main reason for this can be attributed to the difference of MI_{30} . For category III, however, the MI_{30} once reached

Figure 4. Hierarchical clustering of RE

Figure 5. The degrees of water loss under vegetation types and RE

Figure 6. The degrees of soil loss under vegetation types and RE

0.95 mm/min, which was the highest maximal intensity of the monitored years, its depth, however, was only 26.5 mm. This event is obviously known from other events in this category.

Runoff under RE and vegetation types

It is found that the ratios of extreme runoff coefficients to mean runoff coefficients (REr) under different vegetation types and RE are relatively complex and differ from each other (Figure 5). Firstly, in most cases, the runoff coefficients of extreme rainfall events were far higher than those of ordinary rainfall events. For example, the highest value of REr was 9.50 on 26 July 1989 (Figure 5), which appeared for Chinese pine. Secondly, the results show that the ratios of runoff coefficients of different vegetation types under the same extreme event differed greatly. For example, the values of REr of spring wheat and alfalfa on 8 July 1993 were respectively monitored as 4.08 and 4.76, whereas the related REr values of sea buckthorn, Chinese pine, and wheatgrass were only 0.50, 0.61, and 0.59. Thirdly, surface runoff for the same vegetation type has different consequences regarding water

loss under different extreme rainfall features. For example, the value of REr on 28 July 1996 under sea buckthorn was only 0.38, whereas the value on 1 July 1986 reached 7.13 (Figure 5). Lastly, sea buckthorn was found to have high runoff coefficients under the first two extreme rainfall events (occurred on 19 May and 1 July, both in 1986), and then became very low and relatively stable in the following years.

Erosion under RE and vegetation types

From Figure 6, we can see that the degree and dynamics of soil loss rate caused by water erosion under the interaction of vegetation types and RE differ from each other. Generally, the ratio of extreme erosion modulus to the mean erosion modulus (REe) is very high under the impact of most of the events. The highest values of REe in the five vegetation types are in the order of spring wheat (368.53) > alfalfa (353.60) > sea buckthorn (345.18) > Chinese pine (222.46) > wheatgrass (90.45). The peak value under each vegetation type however, did not always appear in the same rainfall event. For example, the highest erosion modulus under sea buckthorn was

observed on 19 May 1986, whereas all the related highest moduli under other four vegetation types appeared on 26 July 1989. Meanwhile, results also showed that the degree of extreme erosion was different among different vegetation types, even under the same extreme rainfall event.

DISCUSSION

Responses of water erosion process to RE

According to the results, soil erosion and water loss are severer under RE than under ordinary rainfall events in most cases (Figures 5 and 6). Generally, mean extreme runoff coefficient (MERC) and mean extreme erosion modulus (MEEM) are respectively 14.74% and 1.43×10^5 t/km², which are 2.68 times and 53.15 times of those under ordinary rainfall events (Table III). The results therefore, re-confirmed the destructive role of RE on water erosion processes reported in other studies (Wang *et al.*, 1996; Gao *et al.*, 2005). Meanwhile, as elaborated previously (Figure 3), the key periods for extreme events to occur are July, August and May, with percentages of 46.15, 30.77 and 23.08, respectively. Therefore, in order to minimize the destructive role of these kinds of events on surface soil and water, much attention should be paid to the most vital and sensitive periods when soil erosion potentials are highest, i.e. July and August. Furthermore, in order to control severe soil erosion caused by RE more successfully, other countermeasures such as straw mulch, plastic film mulch, and land closure should be taken into account. Such measures are highly valuable in improving soil character and reducing severe water erosion (Li *et al.*, 2004; Huang *et al.*, 2005b; Adekalu *et al.*, 2006).

In this study, extreme rainfall events are grouped into three major categories based on the thresholds of depth and MI₃₀ (Figure 4). Results indicate that the sensitivity of runoff and erosion to different extreme events differs. In general, surface water loss and soil erosion, are more sensitive to the first category of extreme events (REI) than those of other two categories (RE II and RE III), whose

depth and MI₃₀ both exceed the thresholds of 40.11mm and 0.55mm/min (Figures 3 and 4). For example, the values of REr and REe under rainfall events which occurred on 26 July 1989 are higher than those under the majority of other extreme events, although some variances may appear among different vegetation types. Therefore, from the point of view of rainfall features, RE with high intensity and large amount play a vital role in causing severe soil erosion and water loss in most cases. REII, which is the aggregation of extreme rainfall events with long duration but low intensity, also causes high sensitivity and variation regarding water erosion rates. This important finding indicates that extreme runoff and erosion are not always caused by heavy rainstorms with strong intensities only. Events with long durations but relatively low intensities also play important roles in inducing severe water erosion. This result highlights the characteristics of RE in the key loess semiarid hilly area, mainly because previous studies only considered rainstorms with extremely strong intensities as extreme events (Wang *et al.*, 1984; Wang *et al.*, 1996; Gao *et al.*, 2005). The effect of RE III on runoff and soil erosion, moreover, is also significant, although it has shorter duration and lower depth than the other two RE types. The frequency, intensity and duration of extreme events, which are more consequential to water erosion than the mean values, are stressed in this study. Moreover, according to our results, the specific amount and degree of runoff and erosion under these three extreme rainfall categories are complicated, and it is mainly because the factors which influence water erosion rates and risks are too complex to predict in the real world (Fu, 1989; He *et al.*, 2004; Wang *et al.*, 2006; Chen *et al.*, 2007b).

Responses of extreme water erosion to vegetation types

In this study, the extreme rates of runoff and soil loss in the five vegetation types mentioned have been investigated (Table IV). Results show that the types and ages of vegetation play a key role in controlling extreme hydraulic destruction, and this conclusion is very similar to those in other studies (Rey *et al.*, 2004; Bochet *et al.*, 2006). Herein, to understand their specific responses to RE, the five xeric vegetations and their effects on water erosion are separately addressed in detail.

The first one is Chinese pine (*P. tabulaeformis* Carr.). This plant is a traditional pine species in China. Its ability for holding soil water and preventing surface runoff, however, remains controversial. For example, the

Table III. Mean runoff and soil erosion under extreme events and ordinary events

Index	MERC (%)	MRC (%)	REr	MEEM (t/km ² /a ¹)	MEM (t/km ² /a ¹)	REe
Value	14.74	5.51	2.68	1.43×10^5	2683	53.15

Table IV. Extreme runoff and erosion features in each vegetation type

Index	Spring wheat	Alfalfa	Sea buckthorn	Chinese pine	Wheatgrass
MERC (%)	23.02	19.98	4.31	15.83	10.56
MRC (%)	8.40	7.16	2.61	5.46	3.91
MERC/MRC	2.74	2.79	1.65	2.90	2.70
MEEM (t/km ² /a ¹)	4.87×10^5	1.87×10^5	1.86×10^3	2.32×10^4	1.39×10^4
MEM (t/km ² /a ¹)	8612	3321	135	600	427
MEEM/MEM	56.55	56.31	13.78	38.67	32.55

Table V. Features of surface cover and soil hydrological indexes

Index	Spring wheat	Alfalfa	Sea buckthorn	Chinese pine	Wheatgrass
MCC (%)	48	54	92	74	90
SBD (g/cm ³)	1.23	1.21	1.17	1.26	1.20
WHC (%)	14.3	14.1	14.8	13.4	14.6
LD (mm)	—	—	30	19	20
SOM (%)	1.23	1.65	1.96	1.32	1.88

MCC, mean canopy cover; SBD, soil buck density; WHC, water holding capacity; LD, litter depth; SOM, soil organic matter.

ratio of MERC and MRC (REr) under Chinese pine is the highest according to our research (Table IV). This implies that it was more sensitive to extreme runoff than the other four vegetation types. Two major reasons are possibly responsible for this phenomenon. First, it could be the long term effects of growing Chinese pine on the physicochemical characteristics of the surface soil. Huang *et al.* (2005b) found that the surface soil under Chinese pine gradually hardened with time, which decreased water infiltration and increased surface runoff. Second, more grease was observed in the litter of Chinese pine than in other plant litters, which eventually decreased the water holding capacity of the litter and created more surface runoff (Liu *et al.*, 2002).

Alfalfa (*M. sativa* L.), an excellent fodder for livestock, is planted in large scale in the loess area of China. In this study however, alfalfa was found very sensitive to RE, sometimes even more than spring wheat (Table III). There may be three major reasons for this. First, it was reported that the survival and growth of alfalfa are at the cost of soil water exhaustion (Li *et al.*, 2007), which deteriorates the soil status *in situ* and thus increases soil erosion, especially under extreme rainfall conditions (Wang *et al.*, 2003). For example, a study in a similar semiarid area found that 1100 l of water are required to produce 1 kg biomass of alfalfa (Pimentel *et al.*, 2004). Second, alfalfa always grows from July to late August. This time happens to be the sensitive season for soil and water loss, mostly because of high rainstorm frequencies and extreme events. Because of its high quality as forage for animal use, local farmers reap alfalfa, disturb the soil, and finally seriously decrease or even uncover the surface layer. In this situation, the risk of runoff and soil erosion dominated by heavy and frequent downpours sharply increases. Thirdly, we found that alfalfa grows well in flat areas (terrace, dam-land, etc.) where soil is fertile and humid, while it grows poorly in sloping areas because of water and nutrient shortages (Unpublished material). Because of these limitations, large-scale plantation of alfalfa with the major purpose of soil and water conservation should be carefully re-examined (Li *et al.*, 2007), and detailed measures and approaches such as land selection for alfalfa growth should also be of concern.

Sea buckthorn (*H. rhamnoides* L.), famous for its high drought resistance and as an excellent drug raw-material, is the most powerful species at fighting against

extreme hydrological events among the five types of vegetation (Table IV). The possible reasons are as follows. First, sea buckthorn grows well and has a higher canopy density and coverage, especially after 3–4 years succession (Figure 2, Table IV). Effective vegetative coverage however, is proved to have a markedly negative correlation with erosion rates (Hou *et al.*, 1996; Pizarro *et al.*, 2006). Second, soil under sea buckthorn is more improved than that under the other vegetation types. After about 20 years of succession, the soil buck density of sea buckthorn becomes the lowest of the five vegetation types, at only 1.17 g/cm³ (Table IV). Its water holding capacity and organic matter content in the soil surface are also higher than those of others. Higher water holding capacity and organic matter content, however, have been found to play key roles in increasing water infiltration and surface roughness (Bissonnais *et al.*, 2005), and they, therefore, increase the runoff threshold and decrease the potential erosion risk. Third, the litter under sea buckthorn was the highest found in a local study in September, 2005 (Table V). Plant litter plays an effective role in weakening raindrop energy, improving soil physiochemical condition, increasing surface roughness and slowing runoff velocities (Hou *et al.*, 1996; Neave and Rayburg, 2007). Meanwhile, thick layer of plant litter may improve soil organic matter (SOM), and SOM may improve water infiltration rate by as much as 150%, thus decreasing runoff amount and velocity (Pimentel *et al.*, 2004). Fourth, the effective root network may help to increase slope stability and anti-splash erosion capability (Cheng *et al.*, 2002).

Spring wheat (*T. aestivum* L. cv Leguan) was found to play the poorest role in reducing water erosion rates amongst the five vegetation types (Table IV; Figures 5 and 6). The reasons could be attributed to several aspects such as poor density and coverage, bad soil properties, and strong human disturbance (Li *et al.*, 2004; Huang *et al.*, 2005b). For example, low density and poor coverage of spring wheat play ineffectual role in intercepting rainfall and reducing raindrop energy (Robichaud *et al.*, 2006). Meanwhile, as one of the major crop species in this area, the effect of spring wheat on runoff and soil erosion is different from that of the other vegetation types. For instance, the roots of spring wheat are proved to be less powerful in protecting and fixing soil than those of grasses, shrubs or arbors (Zheng *et al.*, 2004). Furthermore, our study indicates that spring wheat is harvested in late July or early August each year, leaving

the soil to be bare until the next year. This will certainly increase the risks and rates of water erosion. All these factors contribute a lot to the different roles of spring wheat and other four vegetation types in reducing water erosion rates.

Wheatgrass (*A. cristatum* L. Gaertn), an excellent native grass in fighting against drought and cold weather, always grows well on abandoned farmlands in the loess plateau. Studies indicate that wheatgrass has a powerful ability on controlling extreme water erosion rates, weaker than that of sea buckthorn but higher than those of the other three vegetation types (Table III). Two major factors possibly account for this. One, soil conditions such as soil buck density (SBD), SOM, and water holding capacity (WHC) are all improved after nearly 20 years of succession (Table V). However, lower SBD, and higher SOM and WHC are proved to reduce runoff and soil loss effectively, even under extreme rainfall events (Adekalu *et al.*, 2006). Second, the canopy coverage of wheatgrass however, was lower than that of sea buckthorn but higher than those of the other three vegetation types, according to field investigation (Figure 2). Other studies also drew similar conclusions. For example, because of poor rainfall interception and redistribution, grass communities like wheatgrass were found to play less effective roles in controlling soil erosion in the steep slopes than dense shrubs (Zhang *et al.*, 2005b; Zhao *et al.*, 2006).

Responses of water erosion to the interaction of vegetation types and RE

Results indicate that processes of surface water flow and sediment transportation become complicated and dubious under the co-functions of RE and vegetation types (Figures 5 and 6). The following hypothesis could be proposed to explain our results. First, the features and time-series of RE play key roles in the specific dynamics of water erosion (Figure 3 and Table II). Rainfall variables, which influence the regimes and dynamics of runoff and erosion, are considerably complicated and instantaneous (Gregory *et al.*, 1999; Cheng *et al.*, 2002; Weltzin *et al.*, 2003; Apaydin *et al.*, 2006; Sivakumar, 2007). Second, the effects of vegetation types and growing conditions on soil erosion are also indicated. In general, our study highly emphasizes the combined roles of hydrological and erosional processes under vegetation types and RE. On the one hand, vegetation conditions such as coverage and density change highly with different vegetation ages (Figure 2), which eventually alter the regimes of surface water loss and soil erosion over space and time (Cerdà, 1998; Xu, 2006). This has also been confirmed by other studies. For example, Li *et al.* (2006) found that the improvement of vegetation coverage rate at landslide reached 89.69% after over 6 years of natural succession. On the other hand, the amounts/depths, intensities and distributions of extreme events also experienced high temporal variations (Table II and Figure 3). The coupled role of these two factors on water erosion thus became non-linear and difficult to determine in many cases. Although the mean values of runoff and

erosion under extreme events are generally higher than those under common events, our study also indicates that there is no exact mathematical relationship between a specific extreme event and the consequent extreme hydrological response. Both previous and recent studies have achieved similar results. For example, many studies have confirmed that the largest rainfall events do not necessarily produce the maximum soil erosion and related extreme fluvial discharge (Romero *et al.*, 1999; Nunes *et al.*, 2005; José *et al.*, 2007). Because of this, the relation between erosion process and extreme rainfall in the semiarid Mediterranean region is still hard to assess and uncover (Michael *et al.*, 2005; José *et al.*, 2007).

Meanwhile, our results also indicate that the stages of vegetation development play a key role in controlling and altering water erosion processes, resulting in the hydrological response becoming increasingly more insensitive to RE. For example, sea buckthorn was very sensitive to RE at initial stages after plantation, exhibiting the highest RER for extreme events that occurred on 19 May 1986, 1 July 1986 and 3 August 1988, and also REe on 19 May 1986 (Figures 5 and 6). After three to four successive years, however, water erosion in sea buckthorn became less sensitive to RE, and thus little soil and water loss was created. Therefore, to fight against severe water erosion caused by RE in larger scales, more special attention should be paid not only to the spatial re-adjustment of vegetation types, but also to the different stages of growth of the vegetation.

CONCLUSIONS

In this study, on the basis of field measured hydrological data and the definition of WMO on extreme events, two rainfall variables including depth and MI_{30} were used to determine and classify RE. The following results were obtained: First, the thresholds of depth and MI_{30} for RE are separately calculated as 40.11 mm and 0.55 mm/min, with the mean depth of ordinary events being 18.87 mm. Results indicate that not only extremely heavy rainstorms, but also some rainfall events with lower intensities and long durations should be considered as RE. Secondly, extreme events cause severer hydrological destruction in most cases, especially for the events whose depth and MI_{30} all above the thresholds (REI). The specific erosion consequence, however, becomes complex and uncertain due to the differences of rainfall variables, timing, frequency, vegetation types, etc. Thirdly, as a result of the influence of vegetation types and their ages, responses of water erosion to different extreme events differ. The buffering capacity of the five vegetation types on RE was generally in the order of sea buckthorn > wheatgrass > Chinese pine > alfalfa > spring wheat. Perennial plants such as sea buckthorn were monitored to be sensitive to RE in the first 3–4 years after plantation. However, with the vegetative succession going on, the role of sea buckthorn in reducing water erosion rates enhanced significantly.

These findings have important implications for controlling water erosion caused by RE in the semiarid environments. For example, although RE may generally cause severe water erosion and soil loss, the highest erosion rate are not necessarily caused by the severest extreme event. Therefore, to fight against water erosion more effectively special attention should be paid to the characteristics of RE and vegetation types. Other measures such as mulching and land closure are encouraged for protecting the surface soil from severe erosion. Meanwhile, land use readjustment and vegetation restoration are strongly needed. The shrub, sea buckthorn was intensely recommended to be pioneer species because of its high quality in fighting extreme hydrological events, especially after 3–4 years of plantation. Slope cultivation (spring wheat planted on deep slopes), however, should be avoided in most possible cases, because of its higher sensitivity to extreme rainfall events.

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