J Soils Sediments (2016) 16:105–114
DOI 10.1007/s11368-015-1171-x

SOILS, SEC 2 • GLOBAL CHANGE, ENVIRON RISK ASSESS, SUSTAINABLE LAND USE • RESEARCH ARTICLE

# Changed surface roughness by wind erosion accelerates water erosion

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Received: 5 March 2015 / Accepted: 27 May 2015 / Published online: 12 June 2015


**Abstract**
*Purpose* Wind and water erosion are two dominant types of erosion that lead to losses of soil and water; understanding their interactions is important for estimating soil quality and environmental impacts in regions where both types of erosion occur. This study was devoted to investigate the characteristics of the surface roughness, runoff, and erosion rates under a one-way wind erosion-rain erosion sequence.
*Materials and methods* The experimental setup included a wind tunnel and a rain simulator. Soil samples were collected from a sloped wasteland in Wuqi County, northern Shaanxi province, China. This experiment was conducted with wind erosion firstly and water erosion thereafter, with three wind speeds (0 [control], 11, and 14 m $s^{-1}$) and rain intensities (60, 80, and 100 mm $h^{-1}$). The physical properties of top soil samples (0–1 cm) were analyzed after each wind erosion test. The soil surface roughness (mm), runoff (mm $h^{-1}$), and erosion (g $m^{-2}$ $h^{-1}$) rates were calculated after wind and water erosion. Linear regression analysis was used to estimate the relationships between surface roughness, runoff rate, erosion rate, and erosion factors.
*Results and discussion* Wind erosion increased the sand content in the top 1 cm of soil in simulation area by 6.51–6.74 % and decreased clay and silt contents by 7.65–9.15 and 17.94–18.15 %, respectively, relative to the original surface soil. Compared with the control, the wind erosion treatments increased the surface roughness, runoff, and erosion rates by 8.12–78.06, 4.5–21.69, and 7.25–38.97 %, respectively, at wind speeds of 11 and 14 m $s^{-1}$. The relationship between runoff and rain duration under different rain intensities after wind erosion were described well by a logarithmic function, whereas a large degree of variation was observed in erosion rate. The increased values of runoff and erosion rates in the different treatments, however, became weaker with increasing rain intensity, probably due to the much higher energy of the rain at the highest intensity, which decreased the proportional influence of wind erosion on the microtopography of the soil. Linear regression showed that surface roughness, runoff, and erosion rates were positively associated with wind speed and rain intensity ($P<0.01$).
*Conclusions* Wind erosion clearly has the capacity to intensify water erosion. Results demonstrate the need for controlling of wind erosion to reduce water erosion in regions where both types of erosion occur. Moreover, a consideration of the impact of wind erosion on water erosion is required for effective erosion prediction in these regions.

**Keywords** Erosion rate · Runoff · Surface roughness · Water erosion · Wind erosion

Responsible editor: Fanghua Hao

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## 1 Introduction

Wind and water erosion are two common types of erosion in arid and semiarid regions and are generally studied as distinct processes (Bullard and Livingstone 2002). Pulses of wind and

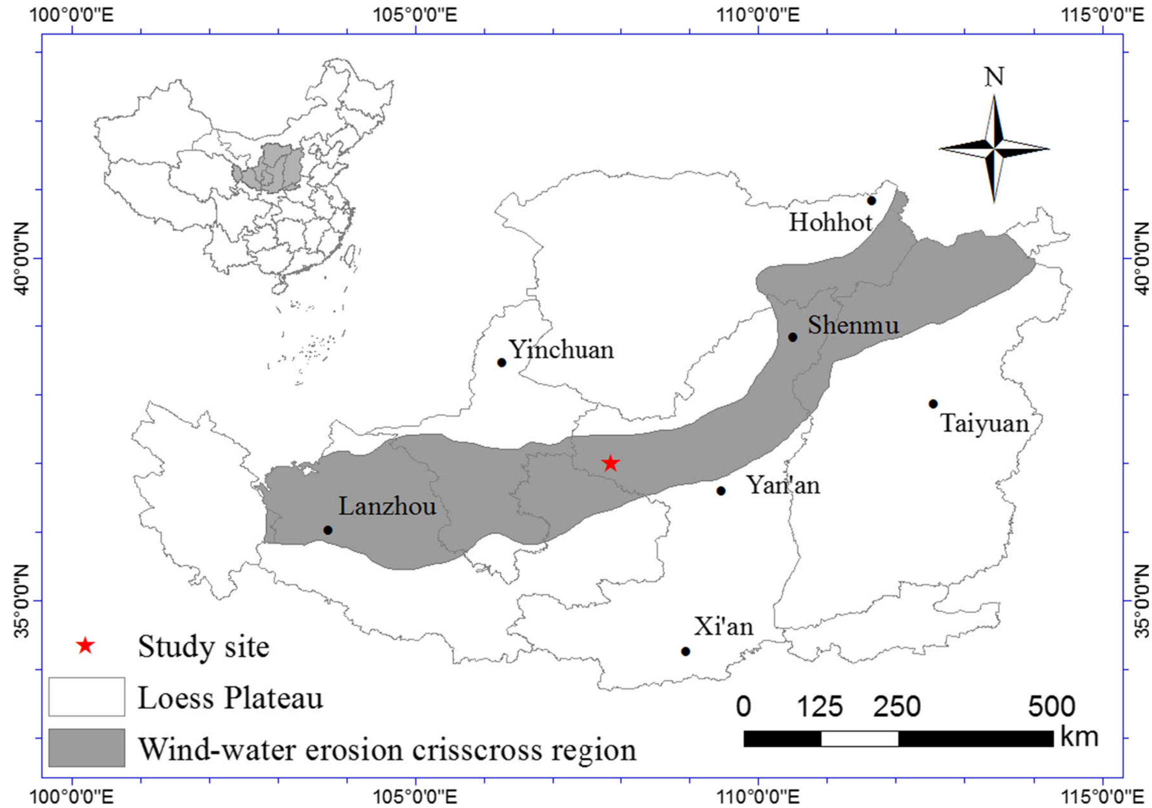


**Fig. 1** Location of the study site in wind-water erosion crisscross region on Loess Plateau

water erosion may alternate in the same area (Song et al. 2006). One region suffering alternating wind-water erosion is located in north China, especially along the marginal zones of the desert in northwest China and of the mountains in north China (103° 33′–113° 53′ E, 35° 20′–40° 10′ N) (Zou et al. 2003). This region encompasses an area of more than $17.8 \times 10^4$ $km^2$ (Tang 2000). In this region, wind erosion mainly occurs during winter and spring and rain falls during summer and autumn (Zhang et al. 2011). The ecological environments in these areas are quite variable and fragile, and the amount of soil that has been eroded is much more than that of the average in China (Zou et al. 2003).

Wind erosion may have a direct influence on water erosion in regions where both types of erosion occur. Wind erosion is a dynamic process that spatially reconfigures the loose ground surface material (Lv and Dong 2006), providing the conditions upon which water erosion can act more easily than without preceding wind erosion (Song et al. 2006). Wind erosion can also destroy the soil structure (Lowery et al. 1995; Larney et al. 1998; Lopez 1998; Song et al. 2005), increase the soil surface roughness (Ferreira et al. 2011), and modify the fluvial features (Farouk et al. 2000; Bullard and Livingstone 2002), thereby impact water erosion followed. Soil structure is an important index for evaluating the resistance of soil to scouring (Zhu et al. 2010) and is an important factor in water erosion. Under a specific set of circumstances, linear roughness oriented from upslope to downslope; nonlinear features or rills oriented on contour. Linear rough surfaces may yield more runoff and soil losses than nonlinear rough surfaces (Romkens et al. 2001; Gomez and Nearing 2005). The flow of water becomes more concentrated into drainage pathways (e.g., rills) on linear rough surfaces, so the potential for scouring is higher (Helming et al. 1998; Dunkerley and Brown 1999).

Previous studies on the wind and water erosion have focused on the simultaneous occurrence of rain and wind (Sweeney and Loope 2001; Visser et al. 2004), especially on wind-driven rain (WDR) (Blocken et al. 2006). WDR is rain

**Fig. 2** Diagram of wind tunnel structure

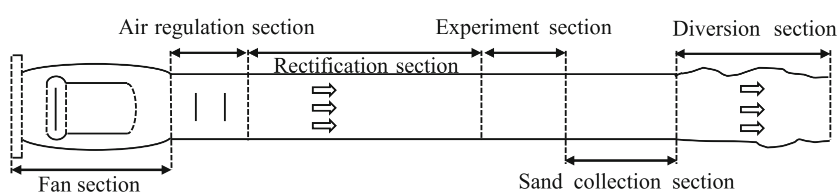

**Table 1** The effect of wind erosion on the particle-size composition of the topsoil (0–1 cm)

| Soil particle (%) | Particle size (%) | | | Increase compared to control (%) | |
|---|---|---|---|---|---|
| | Control | 11 m s$^{-1}$ | 14 m s$^{-1}$ | 11 m s$^{-1}$ | 14 m s$^{-1}$ |
| Clay (<0.002 mm) | 12.68±0.40 a | 11.71±0.18 b | 11.52±0.07 b | −7.65 | −9.15 |
| Silt (0.002–0.02 mm) | 19.12±0.28 a | 15.65±0.29 b | 15.69±0.10 b | −18.15 | −17.94 |
| Sand (0.02–2 mm) | 68.20±0.52 a | 72.64±0.40 b | 72.80±0.11 b | 6.51 | 6.74 |

Different lowercase letters indicate significant differences between wind speeds at the same particle

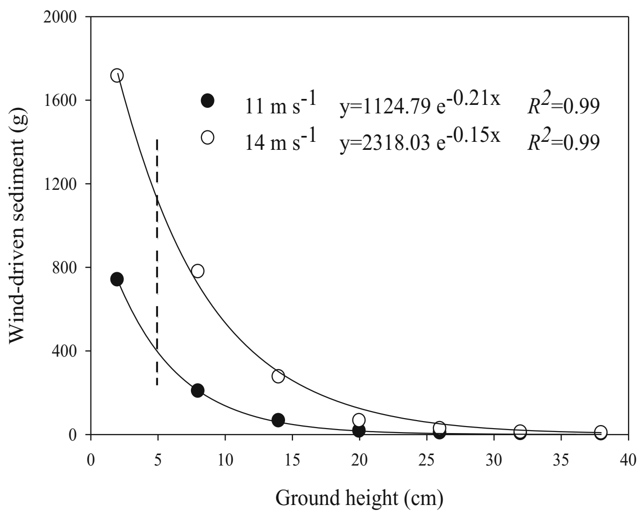


**Fig. 3** Wind-driven sediment at various ground heights

that is given a horizontal velocity component by the wind and that falls obliquely (Blocken and Carmeliet 2004). Erpul et al. (2002) showed that soil particles disturbed by raindrops and driven by wind travel farther than typical saltating sand grains. The previous studies, however, restrict the study of interactions between wind and water erosion. First, studies on the mode and degree of influence and the process of one erosion type following the other erosion type are inadequate. Second, most studies focus on a qualitative rather than a quantitative analysis of the effects of wind erosion on water erosion and the relationship between them (Li et al. 2010). Third, the measurements of and the comparisons between wind and water erosion are inaccurate when the two processes alternate in nature. These problems hinder the recognition of the consequences induced by alternating erosion of wind and water and the evaluation of the state of soil erosion in regions where both types of erosion occur (Zha et al. 1997).

To bridge these gaps, a simulation experiment combining an artificial wind with a simulated rain was conducted, and the runoff and erosion rates of water erosion following wind erosion were analyzed. The purposes of this study were to understand the response of surface microtopography to water erosion and wind erosion, explore the erosion process of water erosion following wind erosion, and to quantitatively evaluate the impact of wind erosion on runoff and water erosion rates.

## 2 Material and methods

### 2.1 Soil and equipment

This study was conducted in the Simulation Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau at the Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources in China. The soil used in the experiment was sandy loam collected from the top 20 cm from Wuqi County in Shaanxi Province, China. This soil was obtained from a sloped wasteland that is the primary site of soil erosion in the area (Fig. 1). The *d*50 was 0.026 mm, with 12.68 % clay content, 19.12 % silt content, and 68.20 % sand content.

The experimental setup included a wind tunnel and a rain simulator. The wind tunnel measured 24×1.2×1 m (length×

**Table 2** Soil surface roughness at various wind speeds and rain intensities

| Rain intensity (mm h$^{-1}$) | Soil surface roughness (mm) at the wind speeds | | | Increase compared to control (%) | |
|---|---|---|---|---|---|
| | Control | 11 m s$^{-1}$ | 14 m s$^{-1}$ | 11 m s$^{-1}$ | 14 m s$^{-1}$ |
| 60 | 1.91±0.04 a | 2.05±0.04 a | 2.75±0.17 b | 7.33 | 43.98 |
| 80 | 2.21±0.06 a | 1.80±0.06 a | 2.93±0.38 b | −18.55 | 32.58 |
| 100 | 2.36±0.43 a | 3.20±0.51 a | 6.08±2.10 b | 35.59 | 157.63 |
| Average | 2.16±0.23 a | 2.35±0.75 a | 3.92±1.87 b | 8.12 | 78.06 |

Different lowercase letters indicate significant differences between wind speeds at the same rain intensity width × height) and included a fan section (4 m), sections for wind regulation (1.5 m) and rectification (10 m), an experimental section (1.28 m), and sections for sand collection (3.02 m) and diversion (4.2 m) (Fig. 2). The regulation section could produce an airflow with a stable field free of turbulence. The uniformity of airflow velocity was >99 %, and the gradient of axial static pressure was <0.005. Wind speed could continuously vary from 0 to 15 m $s^{-1}$ using a coordinated inverter in the fan section (Wang et al. 2014). A vane anemometer, installed 0.2 m from the experimental section and 0.2 m above the tunnel floor, accurately (±0.2 m $s^{-1}$) adjusted the wind speed. The diversion section evacuated the airflow to maintain a clean laboratory environment.

The height of the rain simulator nozzle was 16 m. The drop size distribution range from 0.6 to 3.0 mm, and the rain heterogeneity was greater than 85 % (Lv et al. 2014). The rain intensity was precisely adjusted (±2.7 mm $h^{-1}$) by controlling the aperture of the nozzle and the water pressure. Experimental box for wind and water erosion were constructed with a dual-function movable steel tank measuring 1.1 × 0.7 × 0.35 m (length × width × depth).

### 2.2 Experimental design

This experiment was designed with three levels of wind speed (0 [control], 11, and 14 m $s^{-1}$) and rain intensity (60, 80, and 100 mm $h^{-1}$). The wind speed of 14 m $s^{-1}$ approaches the maximum monthly average wind speed in the study region. These rainfall intensities were representative of low-, medium-, and high-intensity erosion events in the study area (Tang 1990). Wind erosion was first simulated followed by water erosion to mimic real field conditions where wind and water erosion occur alternately throughout the year. All the treatments were performed in triplicate.

### 2.3 Experimental process

The soil sample was passed through a 5-mm sieve after the removal of root fragments and was then air-dried to a moisture content of approximately 1.3 %. The experimental box was filled with soil in 5-cm layers to a depth of 35 cm at a bulk density of 1.30 g $cm^{-3}$. Each layer was roughened by a small rake to minimize the discontinuity between layers. Once the box was prepared, it was pushed into the wind tunnel and the soil surface was aligned exactly paralleled to the experimental section's floor. Wind erosion was simulated for 20 min, after which the experimental box was moved to the rain hall where rain was immediately simulated at a slope gradient of 15° for the rain angle. Water erosion was simulated for 60 min. Plastic runoff collection buckets at the box outlet were changed every 6 min. After the rain, the runoff in each bucket was weighed and then allowed to stand to separate the sediment from the supernatant. The supernatant was discarded, and the sediment

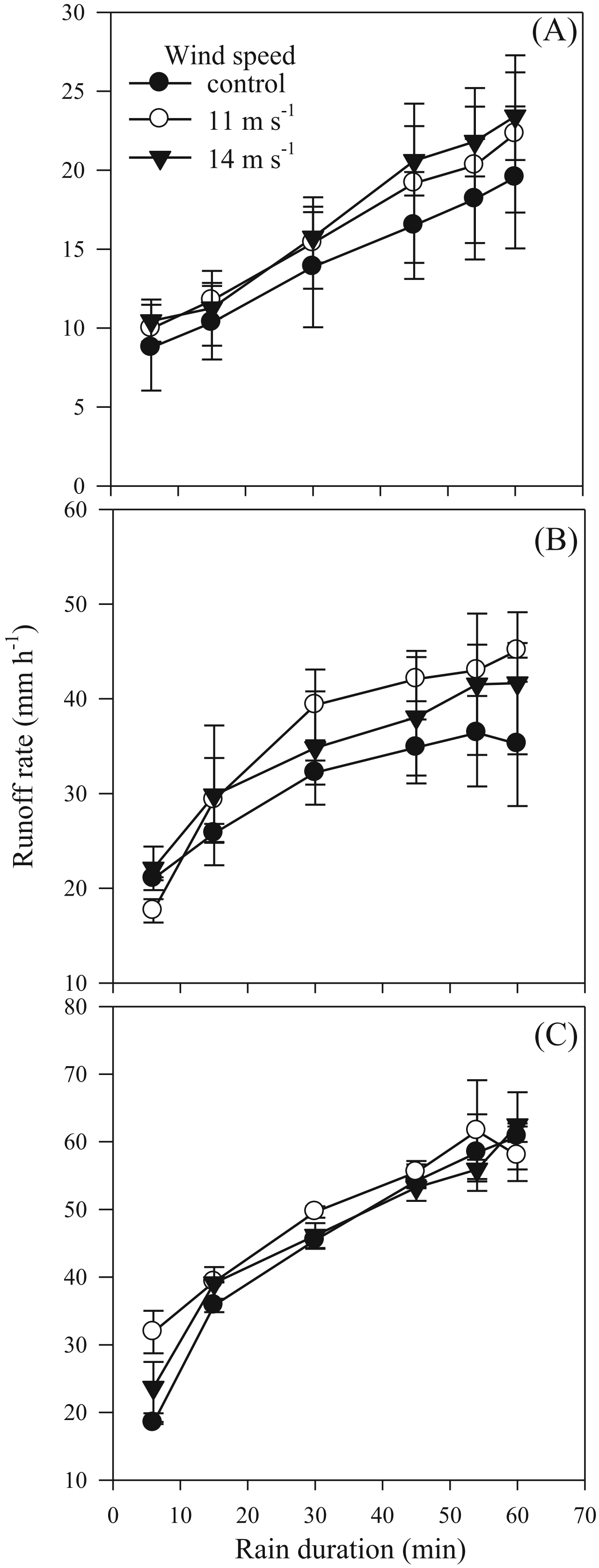


**Fig. 4** Runoff rates for the wind speeds at rain intensities of **a** 60 mm $h^{-1}$, **b** 80 mm $h^{-1}$, and **c** 100 mm $h^{-1}$

was dried and weighed. The runoff (mm $h^{-1}$) and erosion (g $m^{-2}$ $h^{-1}$) rates were then calculated.

### 2.4 Measurements

Surface soil sampling, using a sharp knife, was collected along the length from 1-cm layers before each water erosion test at the three points (each point spacing 45 cm, with an area of 1 $cm^2$) and mixed to effectively form one soil sample. The particle composition was measured by a Mastersizer 2000 laser diffraction device. The soil surface random roughness (surface microtopography) was measured by pin roughness meter after each water erosion test (Cremers et al. 1996). The pin meter was constructed using 52 pins set 0.5 cm apart. It was placed on the soil surface and a photograph was taken. The photograph was then digitized with a hand scanner and analyzed using a photograph editor program (Profile meter program, Wagner 1992; Cremers et al. 1996). The program automatically calculates the standard deviation of each pin's height, based on the control standard height (Liu et al. 2003). The standard deviation was served as a value of soil surface roughness. Ten replicates were calculated at soil surface for the directions perpendicular and parallel to the slope. The error of test was about 0.2 mm.

### 2.5 Data analyses

One-way ANOVA was used to analyze the effects of wind erosion on surface roughness, runoff, and erosion rates under water erosion. When significant treatment effects were identified ($P$<0.05), the LSD test was used to compare the treatments (Tables 2, 3, and 4). Two-way ANOVA was used to examine the interactions between wind speed and rain intensity and their impact on surface roughness, runoff, and erosion rates (Table 5). Linear regression analysis was used to estimate the relationships between surface roughness, runoff rate, erosion rate, and erosion factors. All statistical analyses were performed using SPSS 18.0.

## 3 Results

### 3.1 Response of soil physical properties and sediment to wind erosion

The simulated winds are sufficiently strong to move soil particles (Ekhtesasi and Sepehr 2009). Our results showed that wind erosion increased the sand content in the top 1 cm of soil in our simulation area by 6.51–6.74 % and decreased clay and silt contents by 7.65–9.15 and 17.94–18.15 %, respectively, relative to the original surface soil (Table 1). Reliable prediction of the height profile of the wind-eroded sediment flux is crucial for the estimation of transport rates (Dong and Qian 2007). The total sediment transport was well correlated with the height above ground and could be described by a natural exponential function for the wind speed of either 11 or 14 m $s^{-1}$ (Fig. 3).

### 3.2 Response of soil surface roughness to water erosion following wind erosion

Table 2 shows the soil surface roughness under the various wind treatments (0, 11, and 14 m $s^{-1}$) at the various rain intensities (60, 80, and 100 mm $h^{-1}$). After a simulated rain, soil surface roughness differed significantly between the control and wind erosion treatments at a wind speed of 14 m $s^{-1}$ but not at a wind speed of 11 m $s^{-1}$. Compared with the control, the surface roughness at a wind speed of 14 m $s^{-1}$ increased by 43.98 % at a rain intensity of 60 mm $h^{-1}$, by 32.58 % at an intensity of 80 mm $h^{-1}$ and by 157.63 % at an intensity of 100 mm $h^{-1}$. Higher wind speed and rain intensity produced higher surface roughness. The soil surface

**Table 3** Regression analysis of runoff rate with rain duration at different erosion intensities

| Wind speed (m $s^{-1}$) | Rain intensity (mm $h^{-1}$) | Regression analysis parameters | | | Runoff rate (mm $h^{-1}$) | Increase compared to control (%) |
|---|---|---|---|---|---|---|
| | | $a$ | $b$ | $R^2$ | | |
| Control | 60 | 6.349 | 7.567 | 0.946 | 12.11±1.33 a | – |
| 11 | | 7.212 | 8.571 | 0.938 | 14.73±2.80 b | 21.69 |
| 14 | | 7.961 | 8.482 | 0.900 | 14.72±0.36 b | 21.60 |
| Control | 80 | 9.060 | 20.99 | 0.947 | 27.82±0.51 a | – |
| 11 | | 15.734 | 18.832 | 0.966 | 33.11±1.74 b | 19.01 |
| 14 | | 11.430 | 22.133 | 0.963 | 31.37±0.31 b | 12.76 |
| Control | 100 | 24.287 | 18.886 | 0.996 | 39.97±1.48 a | – |
| 11 | | 16.976 | 30.699 | 0.946 | 43.33±1.77 b | 10.37 |
| 14 | | 20.901 | 23.845 | 0.995 | 41.77±2.00 ab | 4.50 |

Different lowercase letters indicate significant differences between runoff rates at the same rain intensity roughness was threefold higher at a wind speed of 14 m $s^{-1}$ and rain intensity of 100 mm $h^{-1}$ than at a wind speed of 11 m $s^{-1}$ and rain intensity of 60 mm $h^{-1}$.

Water erosion can be divided into three processes: splash, sheet, and gully erosion (Huo et al. 2008). Our tests showed that prior wind erosion caused the early appearance of sheet and rill erosion, compared to the control. For example, under the rain intensity of 100 mm $h^{-1}$, samples exposed to a wind speed of 14 m $s^{-1}$ produced sheet erosion faster than those exposed to 0 m $s^{-1}$. This result indicated that wind erosion could cause earlier water erosion.

### 3.3 Response of runoff to water erosion following wind erosion

Rain falling on a bare soil surface will first infiltrate into the soil, and runoff will occur when the rain intensity exceeds the infiltration capacity of the soil (Liu et al. 2013). In our study, the runoff rate increased rapidly during rain in all combinations of wind speed and rain intensity (Fig. 4). The amounts of runoff in the wind erosion treatments were all larger than those of the controls. Runoff rate differed significantly between both wind erosion treatments and the control ($P<0.05$) but not between the 11 and 14 m $s^{-1}$ wind speed treatments. Wind erosion increased the runoff from rain erosion by 4.5–21.69 % relative to the control. The relationship between runoff rate and rain duration at the various wind speeds and rain intensities was described well by a logarithmic function (Table 3):

$$Rr = a \times \ln t + b \quad (1)$$

where $Rr$ is the runoff rate (mm $h^{-1}$), $t$ is the rain duration (min), and $a$ and $b$ are constants.

The effect of wind erosion on the runoff, however, decreased as rain intensity increased. At a rain intensity of 60 mm $h^{-1}$, the runoff with wind erosion at wind speeds of 11 and 14 m $s^{-1}$ increased by 21.60–21.69 %. In contrast, under a rain intensity of 100 mm $h^{-1}$, the runoff with wind erosion increased by 4.50–10.37 % (Table 3).

### 3.4 Response of erosion rate to water erosion following wind erosion

Large variations in erosion rate were observed. Without wind erosion, the erosion rate decreased over time and then stabilized at the low rain intensity of 60 mm $h^{-1}$ but increased slightly for the last 15 min at the higher intensity of 100 mm $h^{-1}$ (Fig. 5). In contrast, the erosion rate with wind erosion increased as the rain proceeded after the first 15 min at all rain intensities. The increase in erosion rate was larger with than without wind erosion.

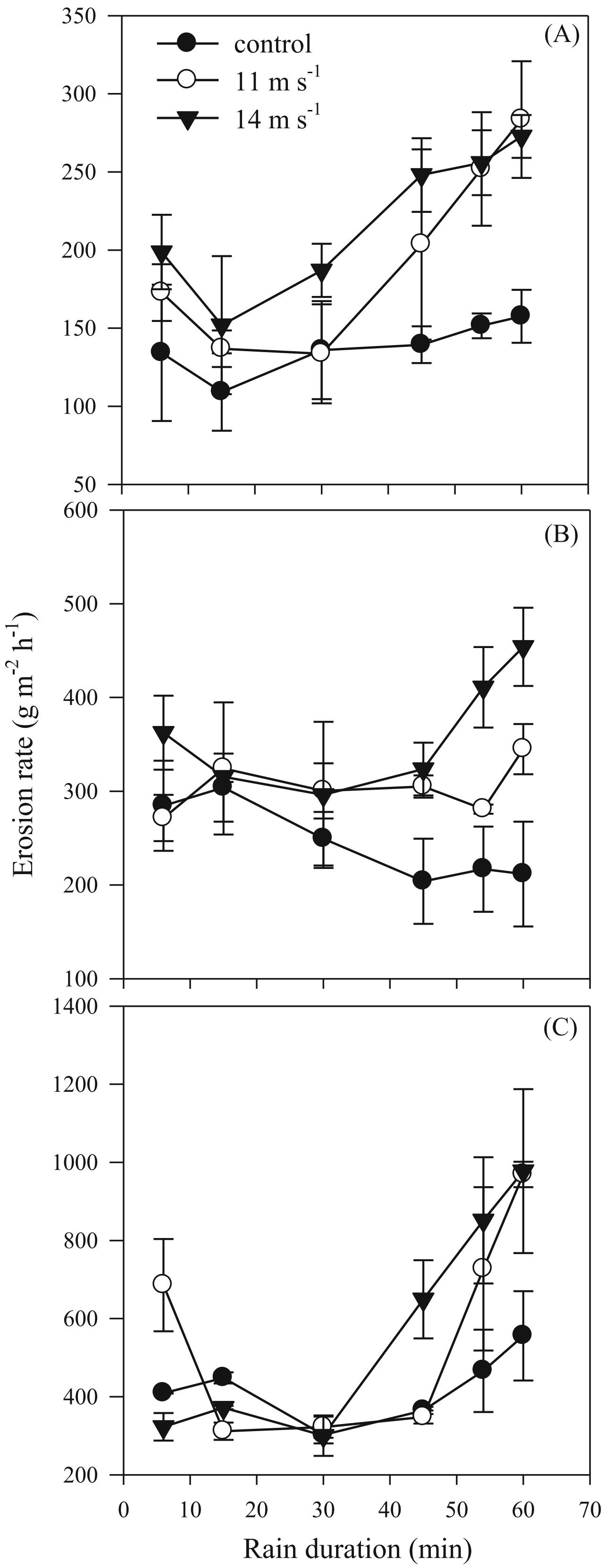


**Fig. 5** Erosion rates for the wind speeds at rain intensities of **a** 60 mm $h^{-1}$, **b** 80 mm $h^{-1}$, and **c** 100 mm $h^{-1}$

**Table 4** Erosion rates at various wind speeds and rain intensities

| Rain intensity (mm $h^{-1}$) | Erosion rate (g $m^{-2}$ $h^{-1}$) at the wind speeds | | | Increase compared to control (%) | |
|---|---|---|---|---|---|
| | Control | 11 m $s^{-1}$ | 14 m $s^{-1}$ | 11 m $s^{-1}$ | 14 m $s^{-1}$ |
| 60 | 141.87±9.49 a | 181.43±24.03 b | 197.15±13.64 b | 27.90 | 38.97 |
| 80 | 250.91±37.65 a | 297.99±18.89 b | 339.42±47.73 b | 18.77 | 35.27 |
| 100 | 393.38±17.10 a | 421.88±25.13 a | 484.61±19.68 b | 7.25 | 23.19 |

Different lowercase letters indicate significant differences between erosion rates at the same rain intensity

**Table 5** Significance levels of the correlations among wind speed, rain intensity, and their interaction on surface roughness, runoff, and erosion rates

| Variable | Wind speed (*WS*) | Rain intensity (*RI*) | Interaction (*WS*×*RI*) |
|---|---|---|---|
| Surface roughness (*Sr*) | 0.000* | 0.000* | 0.000* |
| Runoff rate (*Rr*) | 0.000* | 0.000* | 0.514 |
| Erosion rate (*Er*) | 0.000* | 0.000* | 0.470 |

*$P<0.01$, correlation is significant

At different rain intensities, erosion rates were higher with preceding wind erosion than without (Table 4). Compared with the control, the wind erosion treatments increased the erosion rate by 7.25–38.97 % at wind speeds of 11 and 14 m $s^{-1}$, and most of the increases were significant ($P<0.05$). The increased values of erosion rate in the different treatments, however, decreased with increasing rain intensity, consistent with the variation in runoff rate. At a rain intensity of 60 mm $h^{-1}$, the erosion rate with wind erosion increased by 27.9–38.97 %. In contrast, at an intensity of 100 mm $h^{-1}$, the erosion rate with wind erosion increased by 7.25–23.19 %.

### 3.5 Correlations among surface roughness, runoff, erosion rate, and erosion factors

Table 5 indicates that the effect of the interaction between wind speed and rain intensity on surface roughness was significant at $P<0.01$. The effects on the runoff and erosion rates were much weaker and not significant ($P>0.05$). Positive linear relationships were generally observed among surface roughness, runoff, and erosion rates associated with wind speed and rain intensity:

$$Sr = -1.283 + 0.096WS + 0.041RI \qquad \left(R^2 = 0.461, P < 0.01\right) \tag{2}$$

$$Rr = -29.166 + 0.244WS + 0.701RI \qquad \left(R^2 = 0.967, P < 0.01\right) \tag{3}$$

$$Er = -260.861 + 4.91WS + 6.509RI \qquad \left(R^2 = 0.944, P < 0.01\right) \tag{4}$$

where *Sr* is the surface roughness (mm), *Rr* is the runoff rate (mm $h^{-1}$), *Er* is the erosion rate (g $m^{-2}$ $h^{-1}$), and *WS* and *RI* are the wind speed (m $s^{-1}$) and rain intensity (mm $h^{-1}$), respectively.

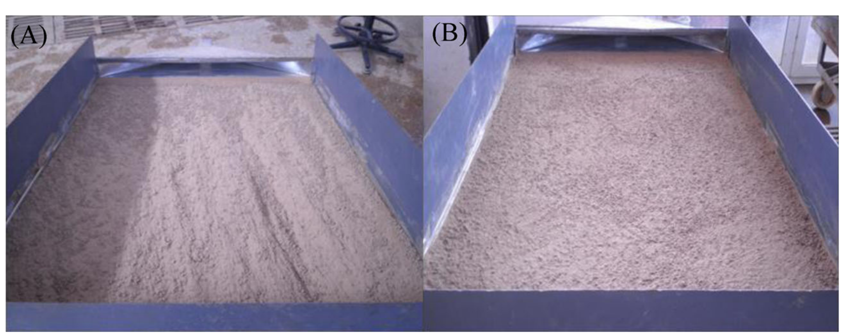


**Fig. 6** Change of surface microtopography at a wind speed of **a** 14 m $s^{-1}$ and **b** 0 m $s^{-1}$ (control)

## 4 Discussion

The roughness of the soil surface is the main index used to describe microtopography and is influenced by the type of erosion, strength of wind, and amount of rain (Zobeck and Onstad 1987; Helming et al. 1998). The study indicated that the soil surface roughness was increased by wind speed treatments, relative to no wind erosion. This result can be attributed to a combination of factor. Wind erosion can first lead to the loss of fine soil particles and thus the increase in soil coarseness (Su et al. 2002; Gomes et al. 2003; Zhao et al. 2006; Zhang et al. 2007a; Ekhtesasi and Sepehr 2009). The study identified a similar trend, that the sand content in the top 1 cm of soil increased by 6.51–6.74 % and clay and silt contents decreased by 7.65–9.15 and 17.94–18.15 %, respectively, relative to the original soil (Table 1). After wind erosion, linear fringes or rills also were created oriented from upslope to downslope (Fig. 6). Generally, soil surface roughness includes linear and two types of nonlinear. In our study, the simulated winds can only spatially reconfigure the linear surface roughness.

The generation of runoff from slopes is closely associated with the soil surface roughness (Cremers et al. 1996; Liu et al. 2003). By increasing the linear surface roughness, wind erosion could effectively altered runoff rate (Table 4). Generally, runoff was delayed on the rough surface, probably due to the greater infiltration rate of the soil with greater roughness (Moore and Singer 1990; Darboux and Huang 2005). However, this effect was temporary and suitable for the initial state, the influence of the detention storage on runoff disappeared quickly once all the depressions were filled and interconnected, and the trend reversed toward more runoff from the rough surface after that point in time (Gomez and Nearing 2005). Erosion and runoff transport occurred and evolved simultaneously and are thus closely related. Exponential relationship was observed between the erosion and runoff rates (Fig. 7). Erosion was greater on the rougher slope because greater runoff amounts were concentrated into more energetic flow pathways, while on the smoother surfaces flow was shallow and dispersed (Romkens et al. 2001; Gomez and Nearing 2005). In addition, erosion is affected by the resistance of soil to detachment by raindrop (Gomez and Nearing 2005; Song et al. 2005; Zhang et al. 2007b). The soils in the study used for water erosion were not original, since soil cohesion has been decreased by wind erosion (Ekhtesasi and Sepehr 2009). This may be another effect tends to cause greater erosion.

The runoff and erosion were closely related to wind erosion, meanwhile, were influenced by changed intensity of water erosion (Tables 3 and 4). The study indicated that the extent of the influence decreased with increasing rainfall intensities (Guo et al. 2010; Zhang et al. 2011). This difference may be ascribed to the much higher energy of the rain at the highest intensity, which decreased the proportional influence of wind

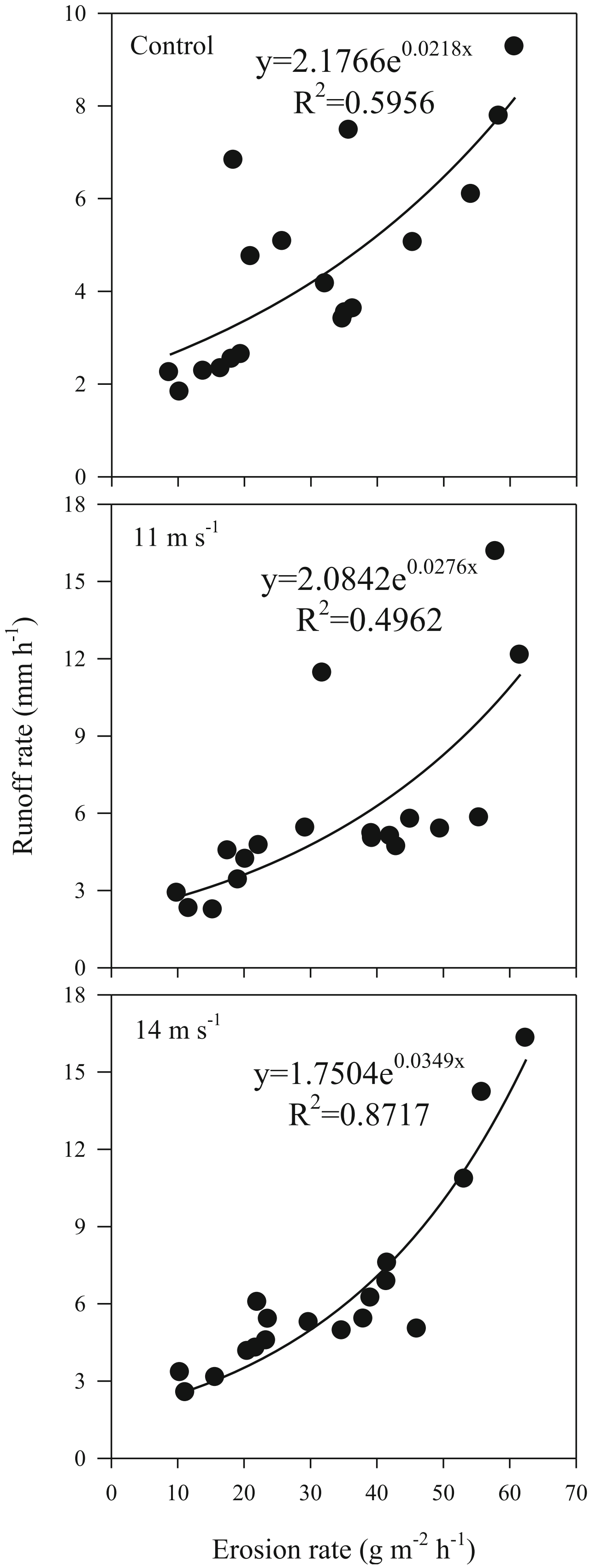


**Fig. 7** Relationship between runoff rate and erosion rate in the treatments

erosion on the physical properties and microtopography of the soil and thus reduced the effects of wind erosion on runoff and erosion rates. This finding implies that both water and wind erosion should be controlled to reduce the intensifying effects of alternating water and wind erosion.

The study also revealed that the erosion rate varied with wind speed and rain intensity. At rain intensities of 60 and 80 mm $h^{-1}$, the erosion rate without wind erosion tended to stabilize after 15 min, consistent with the findings of Guo et al. (2010). This phenomenon may be attributed to the formation of a physical sealing on the slope within 15 min that reduces the erosion of the soil. By contrast, the erosion rate first decreased to a minimum and then increased with the duration of the rain under the water and wind erosion treatment. This was attributed to sheet and rill erosion appeared earlier with than without wind erosion, thereby leading to a significant increase in the erosion rate. At the highest rain intensity of 100 mm $h^{-1}$, the erosion rate with wind erosion increased greatly. This increase was attributed to sheet erosion, which developed into rill erosion after 15 min of rain.

## 5 Conclusions

Wind erosion caused the early appearance of sheet and rill erosion, relative to no wind erosion. Wind erosion also effectively altered soil surface roughness, runoff, and erosion rates. Regression analysis showed the surface roughness, runoff, and erosion rates were positively correlated with wind speed and rain intensity. The results indicated that there exists an interaction under a one-way wind erosion-rain erosion sequence, the need for considering the impact of wind erosion on water erosion when predicting erosion where both types of erosion occur. Moreover, the findings reported in this study indicated that both water and wind erosion should be controlled to reduce the intensifying effects of alternating water and wind erosion; however, the controlling of wind erosion could significantly reduce water erosion. Further study is required to understand the effect of wind erosion on water erosion. Because we examined only bare soil at horizontal wind velocity, the land cover, wind direction, and other conditions remain unknown. More importantly, it is necessary to explore the erosional processes under two-way wind/water erosion sequence.

**Acknowledgments** This study was supported by the National Natural Science Foundation of China (Nos. 41171422 and 40971174), the Strategic Guide Special Branch Project of the Chinese Academy of Sciences (No. XDA05050504), and the Talent Cultivation Project: Light of the West of the Chinese Academy of Sciences. The authors thank Dr. Matthew Alan Bowker in Northern Arizona University for his significant comments.

## References

Blocken B, Carmeliet J (2004) A review of wind-driven rain research in building science. J Wind Eng Ind Aerodyn 92:1079–1130

Blocken B, Poesen J, Carmeliet J (2006) Impact of wind on the spatial distribution of rain over micro-scale topography-numerical modelling and experimental verification. Hydrol Process 20:345–368

Bullard JE, Livingstone L (2002) Interactions between aeolian and fluvial systems in dryland environments. Area 34:8–16

Cremers NHDT, Dijkvan PM, Roode APJ, Verzandvoort MA (1996) Spatial and temporal variability of soil surface roughness and the application in hydrological and soil erosion modeling. Hydrol Process 10:1035–1047

Darboux F, Huang CH (2005) Does soil surface roughness increase or decrease water and particle Transfers? Soil Sci Soc Am J 69: 748–756

Dong ZB, Qian GQ (2007) Characterizing the height profile of the flux of wind-eroded sediment. Environ Geol 51:835–845

Dunkerley DL, Brown KJ (1999) Banded vegetation near Broken Hill, Australia: significance of surface roughness and soil physical properties. Catena 37:75–88

Ekhtesasi MR, Sepehr A (2009) Investigation of wind erosion process for estimation, prevention, and control of DSS in Yazd-Ardakan plain. Environ Monit Assess 159:267–280

Erpul G, Norton LD, Gabriels D (2002) Raindrop-induced and wind-driven soil particle transport. Catena 47:227–243

Farouk EB, Maingue M, Robinson C (2000) Fluvio-aeolian dynamics in the north-eastern Sahara: the relationship between fluvial/aeolian systems and ground-water concentration. J Arid Environ 44:173–183

Ferreira AD, Farimani A, Sousa ACM (2011) Numerical and experimental analysis of wind erosion on a sinusoidal pile. Environ Fluid Mech 11:167–181

Gomes L, Arrue JL, Lopez MV, Sterk G, Richard D, Gracia R, Sabre JM, Gaudichet A, Frangi JP (2003) Wind erosion in a semiarid area of Spain: the welsons project. Catena 52:235–256

Gomez JA, Nearing MA (2005) Runoff and sediment losses from rough and smooth soil surfaces in a laboratory experiment. Catena 59:253–266

Guo CJ, An XQ, Wu M, Hong YL (2010) Simulation experiment of erosion and sediment yield of spoil ground. Soil Water Conserv China 3:29–31 (in Chinese)

Helming K, Romkens MJM, Prasad SN (1998) Surface roughness related processes of runoff and soil loss: a flume study. Soil Sci Soc Am J 62:243–250

Huo Z, Shao MA, Horton R (2008) Impact of gully on soil moisture of shrubland in wind-water erosion crisscross region of the Loess Plateau. Pedosphere 18:674–680

Larney FJ, Bullock MS, Janzen HH, Ellert BH, Olson ECS (1998) Wind erosion effects on nutrient redistribution and soil productivity. J Soil Water Conserv 53:133–140

Lopez MV (1998) Wind erosion in agricultural soil: an example of limited supply of particles available for erosion. Catena 33:17–28

Lowery B, Swan J, Schumacher T, Jones A (1995) Physical properties of selected soils by erosion class. J Soil Water Conserv 50:306–311

Li QY, Cai GQ, Fang HY (2010) Advances in complex erosion of wind and water and ecological restoration. Prog Geogr 29:65–72 (in Chinese)

Liu GB, Xu MX, Ritsema C (2003) A study of soil surface characteristics in a small watershed in the hilly, gullied area on the Chinese Loess Plateau. Catena 54:31–44

Liu JE, Wang ZL, Yang XM, Jiao N, Shen N, Ji PF (2013) The impact of natural polymer derivatives on sheet erosion on experimental loess hillslope. Soil Tillage Res 139:23–27

Lv P, Dong ZB (2006) Wind tunnel experiments on the turbulent transmission over the near surface layer of different surfaces. Environ Geol 50:983–988
Lv W, Li SQ, Lei TW, Li FH (2014) Effects of polyacrylamide application on rainfall runoff in composite slopes of loessial soil. Trans CSAE 30:71–79 (in Chinese)
Moore DC, Singer MJ (1990) Crust formation effects on erosion processes. Soil Sci Soc Am J 54:1117–1123
Romkens MJM, Helming K, Prasad SN (2001) Soil erosion under different rainfall intensities, surface roughness, and soil water regimes. Catena 46:103–123
Song Y, Liu LY, Yan P (2006) A review on complex erosion by wind and water research. J Geogr Sci 16:231–241
Song Y, Liu LY, Yan P, Cao T (2005) A review of soil erodibility in water and wind erosion reaserch. J Geogr Sci 15:167–176
Su YZ, Zhao HL, Zhang TH, Li YL (2002) Processes and characteristics of soil degradation in rainfed farmland in the Horqin sandy land. J Soil Water Conserv 16:25–28
Sweeney MR, Loope DB (2001) Holocene dunesourced alluvial fans in the Nebraska Sand Hills. Geomorphology 38:31–46
Tang KL (1990) Regional characteristics of soil erosion and its control approaches on Loess Plateau. Science Press, Beijing, pp 42–103 (in Chinese)
Tang KL (2000) Importance and urgency of harnessing the interlocked area with both water and wind erosion in the Loess Plateau. Soil Water Conserv China 11:11–12, 17 (in Chinese)
Visser SM, Sterk G, Ribolzi O (2004) Techniques for simultaneous quantification of wind and water erosion in semi-arid regions. J Arid Environ 59:699–717
Wagner LE (1992) PMP: Profile Meter Program, documentation manual. United States Department of Agriculture pp. 27–2.8
Wang L, Shi ZH, Wu GL, Fang NF (2014) Freeze/thaw and soil moisture effects on wind erosion. Geomorphology 207:141–148
Zha X, Tang KL, Zhang PC (1997) Monitoring and research methods on eco-environment evolution in the crisscross region of water-wind erosion. Bull Soil Water Conserv 17:6–9 (in Chinese)
Zhang CL, Zou XY, Yang P, Dong YX, Li S, Wei XH, Yang S, Pan XH (2007a) Wind tunnel test and $^{137}Cs$ tracing study on wind erosion of several soils in Tibet. Soil Tillage Res 94:269–282
Zhang GH, Liu GB, Wang GL, Wang YX (2011) Effects of vegetation cover and rainfall intensity on sediment-bound nutrient loss, size composition and volume fractal dimension of sediment particles. Pedosphere 21:676–684
Zhang GS, Chan KY, Oates A, Heenan DP, Huang GB (2007b) Relationship between soil structure and runoff/soil after 24 years of conservation tillage. Soil Tillage Res 92:122–128
Zhao HL, Yi XY, Zhou RL, Zhao XY, Zhang TH, Drake S (2006) Wind erosion and sand accumulation effects on soil properties in Horqin Sandy Farmland, Inner Mongolia. Catena 65:71–79
Zhu BB, Li ZB, Li P, Liu GB, Xue S (2010) Soil erodibility, microbial biomass, and physical-chemical property changes during long-term natural vegetation restoration: a case study in the Loess Plateau, China. Ecol Res 25:531–541
Zobeck TM, Onstad CA (1987) Tillage and rainfall effects on random roughness: a review. Soil Tillage Res 9:1–20
Zou YR, Zhang ZX, Wang CY, Zhao XL, Liu B (2003) Analysis on the distribution characteristics of the interleaving zones of water/wind erosion in China. Arid Zone Res 3:67–70 (in Chinese)