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An experimental study on the influences of water erosion on wind erosion in arid and semi-arid regions

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Abstract: Complex erosion by wind and water causes serious harm in arid and semi-arid regions. The interaction mechanisms between water erosion and wind erosion is the key to further our understanding of the complex erosion. Therefore, in-depth understandings of the influences of water erosion on wind erosion is needed. This research used a wind tunnel and two rainfall simulators to investigate the influences of water erosion on succeeding wind erosion. The wind erosion measurements before and after water erosion were run on semi-fixed aeolian sandy soil configured with three slopes (5°, 10° and 15°), six wind speeds (0, 9, 11, 13, 15 and 20 m/s), and five rainfall intensities (0, 30, 45, 60 and 75 mm/h). Results showed that water erosion generally restrained the succeeding wind erosion. At a same slope, the restraining effects decreased as rainfall intensity increased, which decreased from 70.63% to 50.20% with rainfall intensity increased from 30 to 75 mm/h. Rills shaped by water erosion could weaken the restraining effects at wind speed exceeding 15 m/s mainly by cutting through the fine grain layer, exposing the sand layer prone to wind erosion to airflow. In addition, the restraining effects varied greatly among different soil types. The restraining effects of rainfall on the succeeding wind erosion depend on the formation of a coarsening layer with a crust and a compact fine grain layer after rainfall. The findings can deepen the understanding of the complex erosion and provide scientific basis for regional soil and water conservation in arid and semi-arid regions.

Keywords: wind erosion; water erosion; sandy soil; particle size; surface roughness; wind-water erosion; agricultural-pastoral ecotone

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1 Introduction

In arid and semi-arid regions, wind erosion in dry seasons and water erosion in wet seasons often occur alternately and interact with each other, leading to a soil erosion process different from wind erosion or water erosion separately. This phenomenon is known as complex erosion by wind and water (Bullard and Livingstone, 2002; Bullard and McTainsh, 2003; Song et al., 2006). The total area of drylands affected by complex erosion is estimated to be 23.7×10^6 km^2 or approximately

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17.5% of the global land area (Bullard and McTainsh, 2003; Belnap et al., 2011). Complex erosion occurs frequently in the agricultural-pastoral ecotone of northern China and leads to soil erosion intensity far more than China's average due to its fragile ecological environment and erratic weather conditions (Zou et al., 2003; Wang et al., 2011; Ta et al., 2014). Enhancing research on complex erosion could provide insights into evaluating the soil erosion status and promote the soil and water conservation in this region.

In previous studies, the influences of water erosion on wind erosion were mostly investigated in wind erosion separately. For example, an increased soil moisture content can reduce the soil erodibility (wind erosion) and shorten the duration of wind erosion. Chepil (1956) found that, with the increase of soil moisture content, soil erodibility (wind erosion) first decreased slowly, then decreased rapidly, and finally stabilized at a value point where soil particles could no longer be blown away. However, the value of soil moisture content at which soil particles cannot be blown away varied widely among soil types (Ravi et al., 2006). Physical crusts, formed after soil experiencing rainfall and natural-air drying, can increase the wind speed threshold by as much as 250% and therefore restrain the succeeding wind erosion (Chepil, 1953, 1958; Gillette et al., 1982; Zobeck, 1991; Rice et al., 1996; Argaman et al., 2006).

The microrelief by wind erosion can be reshaped by the succeeding water erosion and form random roughness and oriented roughness. Specifically, splash pits (random roughness) formed by raindrops can increase the random roughness, serving as a shelter, to prevent particles from jumping out (Zobeck and Popham, 2001; Jester and Klik, 2005), and finally decrease the succeeding wind erosion amount. However, rills (oriented roughness) intersecting with airflow at a high angle can hold up and deposit wind-blown materials in the leeward area of the rills, and decrease the wind erosion amount. However, rills parallel to airflow can significantly enhance both wind speed and turbulence through the funneling effect (Burgess et al., 1989; Bañuelos-Ruedas et al., 2010), leading to an increased wind erosion amount. In addition, airflow carrying fine particles supplied by previous water erosion in rills can form sand-driving wind, which can increase the capability of wind erosion up to a dozen times (Zou et al., 1994).

In recent years, some scholars attempted to explore the interactions between water erosion and wind erosion in the process of alternating wind and water erosion. Song et al. (2007) found that rainfall after wind erosion formed a compact crust on the surface of a sandy loess soil in the process of natural-air drying, and the crust strengthened the resistance of soil to wind erosion, decreased the succeeding wind erosion rate up to 81.08%. The results by Zhang et al. (2016) indicated that water erosion could reshape micro-topography of bed surface (e.g., rills), and the sediment yields of wind erosion presented a positive relation with the rill width and density during the certain range. Tuo et al. (2016) investigated the combined effects of wind erosion and water erosion on the changes of topsoil particle size distribution and sediment yield.

Currently there is few comprehensive and systematic studies on how water erosion at different rainfall intensities influences the succeeding wind erosion rate on air-dried beds at different wind speeds. These problems hinder a comprehensive understanding of the mechanism and process of how water erosion influences the succeeding wind erosion, and impede the estimation accuracy of wind erosion rate in arid and semi-arid regions. To investigate the interaction between wind erosion and water erosion, we conducted experiments of a sequence of alternating wind and water erosion (i.e., 1st wind erosion–1st water erosion–2nd wind erosion–2nd water erosion), and analysed the influences of wind erosion on water erosion rate via two rounds of "wind erosion-water erosion" tests (Yang et al., 2017). In this study, the objective was to analyse the influences of water erosion on the succeeding wind erosion according to wind erosion before and after water erosion (i.e., 1st water erosion–2nd wind erosion); and to provide scientific basis for the accurate estimation of wind erosion amount and soil and water conservation in arid and semi-arid regions.

2 Materials and methods

2.1 Soil and equipment

The experiment of complex erosion was carried out at the Fangshan Comprehensive Experimental

Research Station of the State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, China. The tested soil was a typical semi-fixed aeolian sandy soil collected from Zhenglan Banner (Inner Mongolia Autonomous Region, China) in the agricultural-pastoral ecotone of northern China. The proportions of clay (0.01–2.00 μm), silt (2.00–20.00 μm), fine sand (20.00–200.00 μm), and coarse sand (≥200.00 μm) in the soil samples were 0.08%, 2.46%, 15.41% and 82.05%, respectively. The disturbed soil collected was used to prepare soil beds. In this study, a blow-type wind tunnel and two rainfall simulators were used to simulate wind erosion and rainfall, respectively. A high-precision electronic scale (KCC150) was used to weigh soil boxes before and after wind erosion. A three-dimensional laser scanner (GX-DR200+3D) and a Malvern particle size analyzer (MS2000) were employed to measure bed surface elevation and particle size distribution of topsoil sample before and after wind erosion or water erosion, respectively. The technical specifications of these instruments above were detailed in Yang et al. (2017).

2.2 Experimental design and process

In the agricultural-pastoral ecotone of northern China, within a year, wind erosion in spring, water erosion in summer and wind erosion in winter occur alternately, which lead to more serious soil erosion than single wind erosion or water erosion (Zou et al., 2003; Wang et al., 2008). Based on a simulated sequence of alternating wind-water erosion corresponding to the field situation, this study analysed the influences of water erosion on the succeeding wind erosion according to wind erosion experiments before and after water erosion. In specific, wind erosion before water erosion corresponds to wind erosion in spring on field. "Water erosion" refers to water erosion in summer and "wind erosion after water erosion" means wind erosion in winter or the following spring on the air-dried beds experiencing water erosion in summer and autumn. In the experiments, six wind speeds (i.e., 0, 9, 11, 13, 15 and 20 m/s) and five rainfall intensities (i.e., 0, 30, 45, 60 and 75 mm/h) at three slopes (i.e., 5°, 10° and 15°) were used. Wind speeds after water erosion were the same as that before water erosion, while longer wind erosion durations were set for natural-air dried beds experiencing rainfall at wind speeds of 11 and 13 m/s to make the wind-sculpted micro-topography visible.

Water erosion experiments were carried out on the slopes of 5°, 10° and 15° at different rainfall intensities. However, limited by the height (1.0 m) of the working section of the wind tunnel, soil boxes were placed on the most stable position at 10 m downwind of the working section without slope variations in the same horizontal plane as the floor of the working section (Fig. 1). In the water erosion experiments, rainfall lasted for 48 min on all beds after runoff occurred. In view of the obvious lateral abrasion of rills by wind-sand flow in the situation of rills with the same direction of airflow, we simulated wind erosion with airflow in the same direction of runoff in water erosion. Complex erosion tests were conducted on bare sandy soil bed without vegetation.

Fig. 1 Position of the bed in the wind tunnel

The experimental procedures were as follows: soil pre-treatments, soil bed preparation, wind erosion before water erosion, the succeeding water erosion, and the succeeding wind erosion on the air-dried beds experiencing water erosion. The experimental process was detailed in Yang et al. (2017). In the experimental process, measured indices mainly included the weight, bed surface elevation, topsoil particle size of the bed before and after wind erosion or water erosion.

2.3 Methods

The restraining effect (ΔQ (%)) is used to indicate the degree of water erosion influencing on the succeeding wind erosion rate. It is calculated using the following equation.

$$\Delta Q = \frac{|Q_{\mathrm{wt}} - Q_{\mathrm{nrt}}|}{Q_{\mathrm{nrt}}} \times 100\% , \tag{1}$$

where, Q_{nrt} is the wind erosion rate (soil erosion amount per unit time per unit area; g/(m^2·min)) of the beds without experiencing rainfall; and Q_{wt} is the average wind erosion rate (g/(m^2·min)) of the air-dried beds experiencing water erosion.

Generally, micro-topographic fluctuations of soil surface is expressed by surface roughness (RR), which was quantified by the standard deviation of point elevations (Allmaras et al., 1966). It is calculated as:

$$\mathrm{RR} = \left\{ \frac{1}{n-1} \sum_{i=1}^{n} \left[H_{x_i} - \overline{H} \right]^2 \right\}^{\frac{1}{2}} , \tag{2}$$

where RR is the surface roughness (mm); n is the number of observed points; H_{x_i} is the elevation (mm) of point (x_i); and $\overline{H}$ is the average elevation of all points $\{x_i\}$.

An independent t-test was used to examine differences in the restraining effects between beds with and without rills, and also was used to test the differences in the restraining effects among slopes at wind speeds at 9, 11, 13, 15 and 20 m/s. All statistical analyses were performed using SPSS 18.0 software.

3 Results

3.1 Influences of water erosion on wind erosion rate

Table 1 shows the average wind erosion rate of the air-dried beds experiencing water erosion (Q_{wt}) and the beds (Q_{nrt}) without experiencing water erosion. It can be seen that, under the same slope, with the increase of rainfall intensity, Q_{wt} gradually increased but were always smaller than Q_{nrt}. Therefore, the water erosion restrained the succeeding wind erosion, and the restraining effect (ΔQ) varied from 50.20% to 70.63% at three slopes. The main reasons were that the threshold wind speed increased from 9 to 11 m/s (according to observations and measurements) due to the

Table 1 Effects of water erosion on wind erosion rate under different rainfall intensities

Slope (°)	Wind erosion rate and its change	Rainfall intensity (mm/h)			
		30	45	60	75
5	Q_{nrt} (g/(m^2·min))	4.16	4.16	4.16	4.16
	Q_{wt} (g/(m^2·min))	1.22	1.40	1.75	2.07
	ΔQ (%)	–70.63	–66.35	–57.82	–50.20
10	Q_{nrt} (g/(m^2·min))	4.16	4.16	4.16	4.16
	Q_{wt} (g/(m^2·min))	1.40	1.59	1.51	1.53
	ΔQ (%)	–66.30	–61.86	–63.59	–63.32
15	Q_{nrt} (g/(m^2·min))	4.16	4.16	4.16	4.16
	Q_{wt} (g/(m^2·min))	1.36	1.68	1.70	1.80
	ΔQ (%)	–67.36	–59.64	–59.04	–56.61

Note: The slope refers to the slope of the bed in water erosion experiments, while the beds were in the same horizontal plane in wind erosion tests as the floor of the wind tunnel without slope variations.

coarsening layer with a crust and the hard fine grain layer formed after water erosion and natural-air drying. With increasing wind speed, the upper layers were gradually destroyed (first the coarsening layer then the fine grain layer), and their restraining effects on wind erosion weakened.

Under the same slope, the restraining effects generally decreased with the increase of rainfall intensity. At the same rainfall intensity, the restraining effects decreased with increasing slope at rainfall intensities of 30–45 and 60–75 mm/h, the restraining effects first increased and then decreased with increasing slope, and achieved the highest value at 10° slope. We speculated that the variations of restraining effects were related to the depth of the coarsening layer but the number and size of a rill were created by rainfall.

3.2 Roughness changes caused by water erosion

Water erosion reshaped micro-topography formed by wind erosion. For beds without experiencing rainfall after the wind erosion (e.g., 15 m/s), blowouts were formed at the front end of the bed surface (Fig. 2a) and sand ripples at the tail (Fig. 2b). In contrast, for beds experiencing rainfall (e.g., 60 mm/h, 10° slope) after the 1st wind erosion (e.g., 15 m/s), raindrop striking compacted topsoil, water erosion generated rills, and the depth and width of rills increased along the slope. Under the influences of wind erosion and the succeeding water erosion, micro-topography of the bed presented raindrop pits on blowouts by previous wind erosion at the front end of the bed surface and rills at the tail of the bed along the slope. The micro-topography previously formed by wind erosion was reshaped by water erosion. The succeeding wind erosion (i.e., the 2nd wind erosion) also flattened the inter-rill (or the beds with no rills) micro-topography by scraping the fine grain layer and coarsening layer (Figs. 2c and d). For the beds with rills, the rills can cut through the fine grain layer and expose the sand layer under the fine grain layer to airflow. The strong lateral abrasion of sand-laden airflow intensified in the rills, resulting in the suspension and collapse of rill walls, and therefore accelerated the development of rills (Fig. 2d). Therefore, micro-topography formed by wind erosion following water erosion was not the same as that solely formed by wind erosion or water erosion.

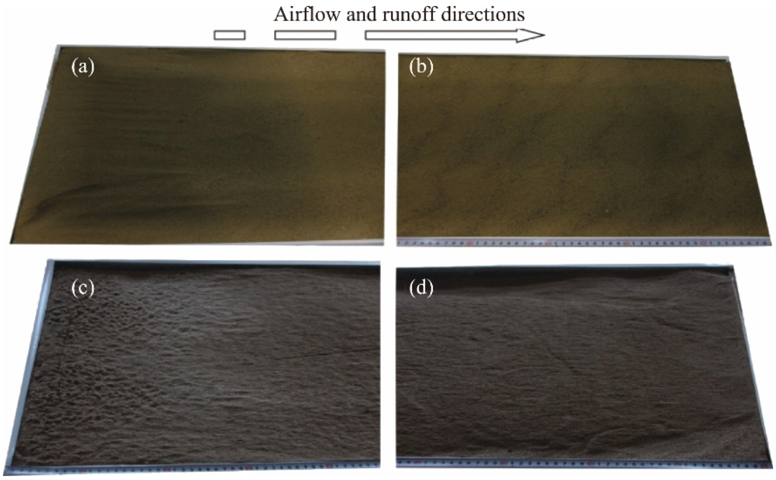

Fig. 2 Micro-topography formed by wind erosion and water erosion. Photos of beds after wind erosion, blowouts are in the front end of the bed (a) and sand ripples are in the tail of the bed (b). Photos of the front (c) and the tail (d) of the bed experiencing the process of "wind erosion (15 m/s)–rainfall (60 mm/h, 10° slope)–wind erosion (15 m/s)".

Water erosion changed surface random roughness via reshaping micro-topography formed by the previous wind erosion. The roughness changes are shown in Table 2. With the same rainfall intensity, water erosion increased the roughness of most beds on 15° slope where the roughness increase caused by the rills exceeded the roughness decrease by the raindrop striking. In contrast, water erosion decreased the roughness of most beds at the slopes of 5° and 10° mainly by scraping micro-topography. It should be noted that we only calculated random roughness rather than oriented roughness, which needed other parameters, such as the size and direction of sand ripples and rills.

Table 2 Bed roughness at the slopes of 5°, 10° and 15° before and after water erosion

Slope (°)	Roughness and its change	Rainfall intensity (mm/h)			
		30	45	60	75
5	R_{w12}	3.15	2.90	3.19	3.60
	R_{wr}	2.96	2.71	3.05	3.64
	ΔR	0.94	0.93	0.95	1.01
10	R_{w12}	3.32	3.71	4.20	3.95
	R_{wr}	3.21	3.07	3.33	3.42
	ΔR	0.97	0.83	0.79	0.87
15	R_{w12}	3.00	3.86	3.32	3.33
	R_{wr}	3.60	3.78	4.11	7.28
	ΔR	1.20	0.98	1.24	2.18

Note: R_{w12}, the average roughness of the control; R_{wr}, the average roughness of the beds after water erosion; ΔR, the roughness change caused by water erosion, $\Delta R=R_{wr}/R_{w12}$.

3.3 Topsoil transect changes caused by water erosion

Rainfall greatly changed topsoil transect characteristics of the beds. Fine grains moved downward and accumulated in different soil layers due to the effects of rainfall infiltration. This modified the original beds from uniform topsoil to three layers from the surface to the bottom, including a coarsening layer with a thin crust, a fine grain layer (at the depth of 1.0–2.5 cm) with certain hardness and a sand layer. However, we did not observe the obvious differences between different treatments. Average particle sizes of the coarsening layer (453.88 μm) and the fine grain layer (363.29 μm) were 17.71% larger and 5.79% smaller than that of the control (385.60 μm), respectively (Fig. 3). Besides, compared to those of the control, the proportions of coarse sand, fine sand and silt sand were 11.12% larger, 8.60% smaller and 2.43% smaller for the coarsening layer; 2.25% smaller, 8.60% larger and 1.31% smaller for the fine grain layer; 1.44% larger, 0.05% smaller and 0.72% smaller for the sand layer (Fig. 3).

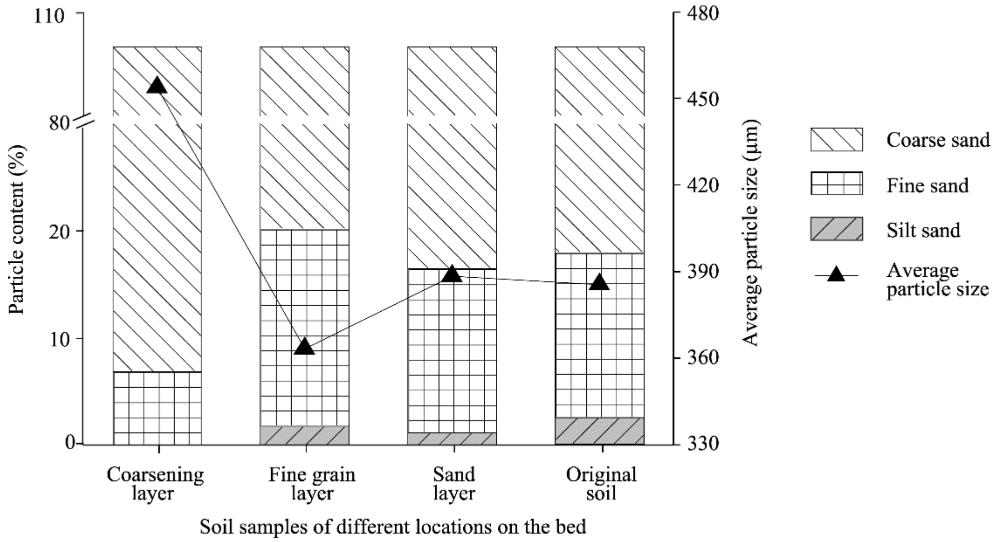

Fig. 3 Particle content and average particle size of soil samples of different locations on the bed

4 Discussion

4.1 Influence of rills on the restraining effects

Water erosion restrained the succeeding wind erosion, while rills affected the restraining effects.

Independent *t*-test for the restraining effects of beds with and without rills showed that rills had an extremely significant influence on the restraining effects at 15 m/s and had a significant influence at 20 m/s. Rainfall compacted and coarsened the topsoil and a hard fine grain layer formed after air-drying, which restrained the succeeding wind erosion (Rice et al., 1996; Argaman et al., 2006). However, wind erosion features of the rills were different from those of the inter-rill or the beds without rills, and mainly presented abrasion of rill head and lateral erosion of rill walls (Zhang et al., 2016; Yang et al., 2017). In our experiments, the rills weakened the restraining effects regardless of the wind speed, and the effects were significant when the wind speed exceeded 15 m/s (Fig. 4), indicating that the rills could weaken the restraining effects at higher wind speeds. The main reasons for rills weakening the restraining effects included: (1) the rills can cut through the hard fine grain layer and expose the sand layer below to airflow (Chepil, 1951; Eldridge and Leys, 2003), resulting in a higher wind erosion rate compared with the inter-rill; (2) water erosion materials remaining in the rills can serve as erodible substances for the succeeding wind erosion; and (3) the rills changed the micro-topography and enhanced the wind speed and turbulence of the succeeding wind erosion through the funnelling effect (Bowen and Lindley, 1977).

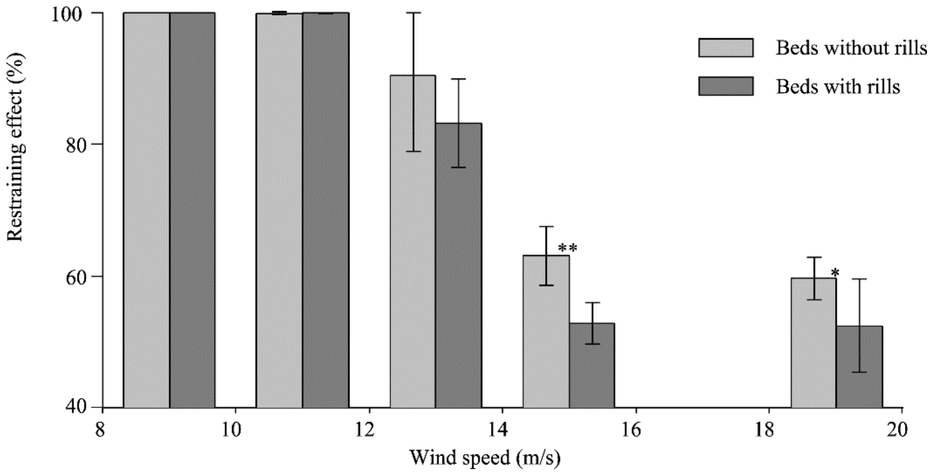

Fig. 4 Influence of rills on the restraining effects (mean±SD) at wind speed of 9–20 m/s. Bars indicate standard deviation. *, significant difference; **, extremely significant difference.

4.2 Influence of soil types on the restraining effects

The restraining effect of water erosion on the succeeding wind erosion varied greatly among soil types. The restraining effect was closely related to crusts and the downward movement of fine grains caused by rainfall, while these characteristics varied greatly among soil types (Chepil, 1953, 1958; Zobeck, 1991). Chepil (1953, 1958) estimated that the restraining effects of crusts varied from 60% to 96% at a wind speed of 15 m/s. Zobeck (1991) found that some crusts formed on mineral soils and organic soils can be much more effective at reducing total soil erosion and the restraining effects were 90.20%–99.98% and 80.00%, respectively. In our experiments, water erosion restrained the succeeding wind erosion of the aeolian sandy soil by 55.42%–61.91% at a wind speed of 15 m/s. This result is consistent with that reported by Chepil (1953, 1958) but is smaller than that by Zobeck (1991). In addition, for semi-fixed aeolian sandy soil in experiments and chestnut soil in pre-experiments, at wind speed of around 20 m/s, the restraining effect of the former (60.53%) was smaller than the later (99.24%), while the restraining effect of sandy loess soil (81.08%) (Song et al., 2007) was observed between the two soils above.

4.3 Applications and implications

The results may be applicable to complex erosion on slopes in other arid and semi-arid regions, but the influences of water erosion on wind erosion vary among different soil types. Our simulation results may not be extended to other types of ecosystems. However, the trends may be suitable for the regions with complex erosions in the farming-pastoral ecotone of northern China as well as the regions under the similar situation.

Our study has the potential ability to pair measurements and extrapolations of wind-water erosion under similar conditions in arid and semi-arid regions. The amount of wind and water erosion can be influenced by factors existing in both laboratory experiments and field research, such as some driving factors (e.g., the intensity of rainfall and wind speed), disturbance factors (e.g., random roughness and oriented roughness (i.e., rills)), and soil erodibility factors (e.g., topsoil particle size distribution and soil moisture content) (Chepil, 1953; Zou et al., 2014). To improve the similarity between simulation and field conditions, we conducted wind erosion simulations on the bed surface with random roughness and rill channels created by simulated rainfall, instead of artificial rill channels. Compared with beds with soil surfaces wetted by spray bottle, topsoil of the beds experiencing simulated rainfall was more compacted and its particle size distribution was closer to topsoil under natural conditions. Besides, most existing research investigated the restraining effects at a certain wind speed, rather than a sequence of wind speeds in our experiments. Therefore, the results based on the experiments more appropriately presented the influences of water erosion on wind erosion. Furthermore, the restraining effects at low rainfall intensities were higher than those at high rainfall intensities, indicating that the rills created by rainfall could weaken the restraining effects. Additionally, due to limitation of small size of the soil bed, soil erosion from upslope runoff was not obvious when compared with that occurred under the natural conditions. Thus, field monitoring and experiments on larger-scale soil bed are needed to further explore the interaction between water erosion and wind erosion.

5 Conclusions

Water erosion restrained the succeeding wind erosion of the air-dried beds through changing topsoil transect characteristics and micro-topography. This restraining effects of the three slopes showed a downward trend with a range from 70.63% to 50.20%. At the same slope, the restraining effects decreased with increasing rainfall intensity. The rills created by water erosion could obviously weaken the restraining effects when wind speeds exceeding 15 m/s. Furthermore, the restraining effects varied greatly among soil types.

Our findings may deepen the scientific understanding of complex erosion by wind and water, help to improve the estimation accuracy of wind erosion amount in the areas with complex erosion, and provide scientific references to regional soil and water conservation. However, the restraining effects vary considerably among soil types, which prevent broad inferences across different types of ecosystems and limits the direct inferences of our findings. This study investigated the influences of water erosion on the succeeding wind erosion and its influencing mechanism in an integrative view. However, to fully understand the interactions between wind erosion and water erosion, scholars still need to simulate a sequence of alternating wind and water erosion under the situations where runoff intersecting with airflow at an angle.

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