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

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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.

Full Text

Preamble

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. Understanding the interaction mechanisms between water erosion and wind erosion is key to advancing our knowledge of this complex process. Therefore, in-depth investigation of how water erosion influences wind erosion is needed. This research employed a wind tunnel and two rainfall simulators to examine the effects of water erosion on subsequent wind erosion. Wind erosion measurements before and after water erosion were conducted 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 subsequent wind erosion. At the same slope, the restraining effects decreased as rainfall intensity increased, declining from 70.63% to 50.20% as rainfall intensity rose from 30 to 75 mm/h. Rills formed by water erosion could weaken these restraining effects at wind speeds exceeding 15 m/s, primarily by cutting through the fine grain layer and exposing the underlying sand layer, which is prone to wind erosion, to airflow. Additionally, the restraining effects varied considerably among different soil types. The restraining effects of rainfall on subsequent wind erosion depend on the formation of a coarsening layer with a crust and a compact fine grain layer after rainfall. These findings can deepen understanding of complex erosion and provide a 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 during dry seasons and water erosion during wet seasons often occur alternately and interact, producing a soil erosion process distinct from either wind or water erosion alone. 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 at 23.7×10 km^2, or approximately 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, where fragile ecological conditions and erratic weather produce soil erosion intensity far exceeding China' s average (Zou et al., 2003; Wang et al., 2011; Ta et al., 2014). Enhanced research on complex erosion could provide insights for evaluating soil erosion status and promoting soil and water conservation in this region.

Previous studies have primarily investigated wind and water erosion separately. For instance, increased soil moisture content can reduce soil erodibility and shorten the duration of wind erosion. Chepil (1956) found that as soil moisture content increased, soil erodibility first decreased slowly, then rapidly, and finally stabilized at a point where soil particles could no longer be transported. However, the moisture threshold at which particles become immobile varied widely among soil types (Ravi et al., 2006). Physical crusts formed after rainfall and natural air-drying can increase the wind speed threshold by up to 250%, thereby restraining subsequent wind erosion (Chepil, 1953, 1958; Gillette et al., 1982; Zobeck, 1991; Rice et al., 1996; Argaman et al., 2006).

Microrelief created by wind erosion can be reshaped by subsequent water erosion, forming both random and oriented roughness. Specifically, splash pits (random roughness) formed by raindrops can increase surface randomness, acting as shelters that prevent particle ejection (Zobeck and Popham, 2001; Jester and Klik, 2005), ultimately reducing subsequent wind erosion. Rills (oriented roughness) intersecting airflow at high angles can trap and deposit wind-blown materials in their leeward areas, decreasing wind erosion. However, rills parallel to airflow can significantly enhance wind speed and turbulence through a funneling effect (Burgess et al., 1989; Bañuelos-Ruedas et al., 2010), increasing wind erosion. Additionally, airflow carrying fine particles supplied by previous water erosion in rills can form sand-driving wind, which can increase wind erosion capacity by up to an order of magnitude (Zou et al., 1994).

In recent years, scholars have attempted to explore interactions between water and wind erosion during alternating erosion events. Song et al. (2007) found that rainfall following wind erosion formed a compact crust on sandy loess soil during natural air-drying, strengthening soil resistance to wind erosion and reducing subsequent wind erosion rates by up to 81.08%. Zhang et al. (2016) showed that water erosion could reshape bed surface micro-topography (e.g., rills), and wind erosion sediment yields were positively related to rill width and density within certain ranges. Tuo et al. (2016) investigated combined effects of wind and water erosion on topsoil particle size distribution and sediment yield.

Currently, few comprehensive and systematic studies examine how water erosion at different rainfall intensities influences subsequent wind erosion rates on air-dried beds at various wind speeds. These gaps hinder comprehensive understanding of the mechanisms and processes by which water erosion influences subsequent wind erosion, and impede accurate estimation of wind erosion rates in arid and semi-arid regions. To investigate interactions between wind and water erosion, we conducted experiments with a sequence of alternating wind and water erosion (i.e., 1st wind erosion–1st water erosion–2nd wind erosion–2nd water erosion), analyzing wind erosion influences on water erosion rates through two rounds of "wind erosion-water erosion" tests (Yang et al., 2017). This study aims to analyze how water erosion influences subsequent wind erosion based on wind erosion measurements before and after water erosion (i.e., 1st water erosion–2nd wind erosion), and to provide scientific basis for accurate wind erosion estimation and soil and water conservation in arid and semi-arid regions.

2.1 Soil and Equipment

The complex erosion experiment was conducted at the Fangshan Comprehensive Experimental Research Station of the State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, China. The test soil was typical semi-fixed aeolian sandy soil collected from Zhenglan Banner (Inner Mongolia Autonomous Region, China) in the agricultural-pastoral ecotone of northern China. The soil sample contained 0.08% clay (0.01–2.00 µm), 2.46% silt (2.00–20.00 µm), 15.41% fine sand (20.00–200.00 µm), and 82.05% coarse sand (200.00 µm). Disturbed soil was used to prepare experimental beds. This study utilized a blow-type wind tunnel and two rainfall simulators to simulate wind erosion and rainfall, respectively. A high-precision electronic scale (KCC150) measured soil box weights before and after wind erosion. A three-dimensional laser scanner (GX-DR200+3D) and a Malvern particle size analyzer (MS2000) measured bed surface elevation and topsoil particle size distribution before and after wind or water erosion. Technical specifications for these instruments are detailed in Yang et al. (2017).

2.2 Experimental Design and Process

In the agricultural-pastoral ecotone of northern China, wind erosion in spring, water erosion in summer, and wind erosion in winter occur alternately within a year, causing more severe soil erosion than either wind or water erosion alone (Zou et al., 2003; Wang et al., 2008). Based on a simulated sequence of alternating wind-water erosion corresponding to field conditions, this study analyzed water erosion influences on subsequent wind erosion through wind erosion experiments conducted before and after water erosion. Specifically, wind erosion before water erosion represents spring wind erosion in the field, "water erosion" represents summer water erosion, and "wind erosion after water erosion" represents winter or subsequent spring wind erosion on air-dried beds that experienced summer and autumn water erosion.

The experiments employed six wind speeds (0, 9, 11, 13, 15, and 20 m/s) and five rainfall intensities (0, 30, 45, 60, and 75 mm/h) at three slopes (5°, 10°, and 15°). Wind speeds after water erosion matched those before water erosion, though longer wind erosion durations were set for naturally air-dried beds that experienced rainfall at wind speeds of 11 and 13 m/s to make wind-sculpted micro-topography visible. Water erosion experiments were conducted on 5°, 10°, and 15° slopes at different rainfall intensities. However, limited by the 1.0 m height of the wind tunnel working section, soil boxes were placed at the most stable position 10 m downwind of the working section without slope variations, on the same horizontal plane as the working section floor (Fig. 1 [Figure 1: see original paper]). In water erosion experiments, rainfall lasted 48 minutes on all beds after runoff initiation. Given the obvious lateral abrasion of rills by wind-sand flow when rills align with airflow direction, we simulated wind erosion with airflow parallel to water erosion runoff direction. Complex erosion tests were conducted on bare sandy soil beds without vegetation.

The experimental procedures included: soil pre-treatment, soil bed preparation, wind erosion before water erosion, subsequent water erosion, and subsequent wind erosion on air-dried beds that experienced water erosion. The experimental process is detailed in Yang et al. (2017). Measured indices primarily included bed weight, bed surface elevation, and topsoil particle size before and after wind or water erosion.

2.3 Methods

The restraining effect (Q (%)) quantifies the degree to which water erosion influences subsequent wind erosion rates, calculated using the following equation:

$$\Delta Q = \frac{Q_{nrt} - Q_{wt}}{Q_{nrt}} \times 100\%$$

where Q_{nrt} is the wind erosion rate (soil erosion amount per unit time per unit area; $g/(m^2 \cdot min)$) for beds without rainfall exposure, and Q_{wt} is the average wind erosion rate ($g/(m^2 \cdot min)$) for air-dried beds that experienced water erosion.

Surface micro-topographic fluctuations are generally expressed by surface roughness (RR), quantified as the standard deviation of point elevations (Allmaras et al., 1966), calculated as:

$$RR = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(H_{xi} - \bar{H}_x)^2}$$

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

Independent t-tests examined differences in restraining effects between beds with and without rills, and also tested differences in restraining effects among slopes at wind speeds of 9, 11, 13, 15, and 20 m/s. All statistical analyses were performed using SPSS 18.0 software.

3.1 Influences of Water Erosion on Wind Erosion Rate

Table 1 presents average wind erosion rates for air-dried beds experiencing water erosion (Q_{wt}) and beds without water erosion exposure (Q_{nrt}). Under the same slope, Q_{wt} gradually increased with rainfall intensity but remained consistently smaller than Q_{nrt}. Therefore, water erosion restrained subsequent wind erosion, with restraining effects (Q) ranging from 50.20% to 70.63% across the three slopes. The primary mechanism was the increase in threshold wind speed from 9 to 11 m/s (based on observations and measurements) due to formation of a coarsening layer with a crust and a hard fine grain layer after water erosion and natural air-drying. As wind speed increased, these upper layers were gradually destroyed (first the coarsening layer, then the fine grain layer), weakening their restraining effects on wind erosion.

Under the same slope, restraining effects generally decreased with increasing rainfall intensity. At the same rainfall intensity, restraining effects decreased with increasing slope at rainfall intensities of 30–45 and 60–75 mm/h. The restraining effects first increased then decreased with increasing slope, reaching maximum values at 10° slope. We speculate that these variations in restraining effects relate to both the depth of the coarsening layer and the number and size of rills created by rainfall.

3.2 Roughness Changes Caused by Water Erosion

Water erosion reshaped micro-topography formed by previous wind erosion. For beds without rainfall exposure after wind erosion (e.g., at 15 m/s), blowouts formed at the front end of the bed surface (Fig. 2a [Figure 2: see original paper]) and sand ripples developed at the tail (Fig. 2b). In contrast, for beds experiencing rainfall (e.g., 60 mm/h, 10° slope) after the first wind erosion (e.g., 15 m/s), raindrop impact compacted the topsoil, water erosion generated rills, and rill depth and width increased downslope.

Under the combined influence of wind erosion and subsequent water erosion, bed micro-topography exhibited raindrop pits on blowouts created by previous wind erosion at the front end, and rills at the tail along the slope. The micro-topography previously formed by wind erosion was reshaped by water erosion. Subsequent wind erosion (i.e., the second wind erosion) also flattened inter-rill micro-topography (or beds without rills) by scraping the fine grain and coarsening layers (Figs. 2c and d). For beds with rills, the rills could cut through the fine grain layer and expose the underlying sand layer to airflow. Strong lateral abrasion by sand-laden airflow intensified within the rills, causing rill wall suspension and collapse, thereby accelerating rill development (Fig. 2d). Consequently, micro-topography formed by wind erosion following water erosion differed from that formed by wind or water erosion alone.

Water erosion altered surface random roughness by reshaping micro-topography from previous wind erosion. Roughness changes are shown in Table 2 . At the same rainfall intensity, water erosion increased roughness on most beds at 15° slope, where roughness increases from rills exceeded decreases from raindrop impact. Conversely, water erosion decreased roughness on most beds at 5° and 10° slopes, primarily by smoothing micro-topography. Note that we calculated only random roughness rather than oriented roughness, which would require additional parameters such as sand ripple and rill size and direction.

3.3 Topsoil Transect Changes Caused by Water Erosion

Rainfall substantially altered topsoil transect characteristics. Fine grains moved downward and accumulated in different soil layers due to rainfall infiltration, transforming the original uniform topsoil into three distinct layers from surface to bottom: a coarsening layer with a thin crust, a fine grain layer (at 1.0–2.5 cm depth) with certain hardness, and a sand layer. However, we observed no obvious differences between treatments. Average particle sizes of the coarsening layer (453.88 µm) and fine grain layer (363.29 µm) were 17.71% larger and 5.79% smaller than the control (385.60 µm), respectively (Fig. 3 [Figure 3: see original paper]). Compared to the control, coarse sand, fine sand, and silt proportions were 11.12% larger, 8.60% smaller, and 2.43% smaller in the coarsening layer; 2.25% smaller, 8.60% larger, and 1.31% smaller in the fine grain layer; and 1.44% larger, 0.05% smaller, and 0.72% smaller in the sand layer (Fig. 3).

4.1 Influence of Rills on the Restraining Effects

Water erosion restrained subsequent wind erosion, while rills affected these restraining effects. Independent t-tests for restraining effects between beds with and without rills showed that rills had an extremely significant influence on restraining effects at 15 m/s and 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 subsequent wind erosion (Rice et al., 1996; Argaman et al., 2006). However, wind erosion characteristics in rills differed from those in inter-rill areas or beds without rills, primarily manifesting as headward abrasion and lateral wall erosion (Zhang et al., 2016; Yang et al., 2017).

In our experiments, rills weakened restraining effects regardless of wind speed, with significant effects when wind speed exceeded 15 m/s (Fig. 4 [Figure 4: see original paper]), indicating that rills could reduce restraining effects at higher wind speeds. The main reasons for this weakening include: (1) rills can cut through the hard fine grain layer and expose the underlying sand layer to airflow (Chepil, 1951; Eldridge and Leys, 2003), resulting in higher wind erosion rates compared to inter-rill areas; (2) water erosion materials remaining in rills can serve as erodible substances for subsequent wind erosion; and (3) rills altered micro-topography and enhanced wind speed and turbulence of subsequent wind erosion through a funneling effect (Bowen and Lindley, 1977).

4.2 Influence of Soil Types on the Restraining Effects

The restraining effect of water erosion on subsequent wind erosion varied considerably among soil types. This effect was closely related to crust formation and fine grain downward movement caused by rainfall, characteristics that vary greatly among soil types (Chepil, 1953, 1958; Zobeck, 1991). Chepil (1953, 1958) estimated that crust restraining effects ranged from 60% to 96% at 15 m/s wind speed. Zobeck (1991) found that crusts formed on mineral and organic soils could be much more effective at reducing total soil erosion, with restraining effects of 90.20%-99.98% and 80.00%, respectively. In our experiments, water erosion restrained subsequent wind erosion of aeolian sandy soil by 55.42%-61.91% at 15 m/s wind speed. This result is consistent with Chepil (1953, 1958) but smaller than Zobeck (1991). Additionally, for semi-fixed aeolian sandy soil in our experiments and chestnut soil in pre-experiments at approximately 20 m/s wind speed, the former’ s restraining effect (60.53%) was smaller than the latter’ s (99.24%), while sandy loess soil showed an intermediate restraining effect (81.08%) (Song et al., 2007).

4.3 Applications and Implications

These results may be applicable to complex erosion on slopes in other arid and semi-arid regions, though water erosion influences on wind erosion vary among soil types. Our simulation results may not extend to other ecosystem types, but the trends may be suitable for regions with complex erosion in the farming-pastoral ecotone of northern China and similar areas.

Our study has potential for pairing measurements and extrapolations of wind-water erosion under similar conditions in arid and semi-arid regions. Wind and water erosion amounts can be influenced by factors present in both laboratory experiments and field research, such as driving factors (e.g., rainfall intensity 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 similarity between simulation and field conditions, we conducted wind erosion simulations on bed surfaces with random roughness and rill channels created by simulated rainfall, rather than artificial rill channels. Compared to beds with surfaces wetted by spray bottles, topsoil on rainfall-experienced beds was more compacted and its particle size distribution more closely resembled natural conditions. Furthermore, most existing research investigated restraining effects at single wind speeds, whereas our experiments used a sequence of wind speeds. Therefore, our results more appropriately represent water erosion influences on wind erosion. Additionally, restraining effects were higher at low rainfall intensities than at high intensities, indicating that rainfall-created rills could weaken restraining effects. However, due to the small soil bed size, soil erosion from upslope runoff was less obvious compared to natural conditions. Thus, field monitoring and larger-scale soil bed experiments are needed to further explore interactions between water and wind erosion.

5 Conclusions

Water erosion restrained subsequent wind erosion on air-dried beds by altering topsoil transect characteristics and micro-topography. The restraining effects across the three slopes showed a downward trend ranging from 70.63% to 50.20%. At the same slope, restraining effects decreased with increasing rainfall intensity. Rills created by water erosion could significantly weaken restraining effects when wind speeds exceeded 15 m/s. Furthermore, restraining effects varied considerably among soil types.

Our findings may deepen scientific understanding of complex wind-water erosion, help improve estimation accuracy of wind erosion amounts in areas experiencing complex erosion, and provide scientific references for regional soil and water conservation. However, restraining effects vary substantially among soil types, preventing broad inferences across different ecosystems and limiting direct application of our findings. This study investigated water erosion influences on subsequent wind erosion and its mechanisms from an integrative perspective. However, to fully understand interactions between wind and water erosion, scholars must simulate sequences of alternating wind and water erosion under conditions where runoff intersects airflow at various angles.

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