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Influence of wind erosion on dry aggregate size distribution and nutrients in three steppe soils in northern China

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ABSTRACT

Wind erosion is a key process that causes soil degradation in the semiarid steppe regions of northern China. However, few studies have quantitatively measured the changes in dry aggregate distribution and nutrients in steppe soils under continuously varying wind erosion intensity. The objectives of this study were as follows: (1) to explore the different responses of three steppe soils to natural windblown treatments and (2) to quantify the changes in soil dry aggregate distribution, particle size distribution and soil nutrient contents under various wind erosion intensities for three steppe soils. We obtained samples of the following soils subjected to varying wind intensity via a natural windblown treatment: meadow steppe (MS), typical steppe (TS) and desert steppe (DS). Then, the physical and chemical properties of all soil samples were measured. The results showed that dry aggregate fractions < 0.2 mm were selectively depleted by wind erosion and exhibited an exponential decrease in the residual soils with increasing wind erosion intensity. The organic carbon (OC), total nitrogen and available nitrogen in the three soils and the total phosphorous and available potassium in the TS and DS soils showed exponential decreases with increasing wind erosion intensity. The higher amounts of OC and nutrients were associated with fine dry aggregates (< 0.2 mm), and fine dry aggregates were preferentially depleted by wind erosion, providing a mechanism for nutrient depletion caused by wind erosion. Finally, we established a comprehensive conceptual model of fine soil aggregate/particle depletion by wind erosion and subsequent nutrient depletion due to anthropogenic disturbances in temperate steppe areas.

1. Introduction

Wind erosion is a common phenomenon in many arid and semiarid areas around the world and can influence soil texture and associated soil nutrient balances (Gillette and Hanson, 1989; Lawrence and Neff, 2009; Okin et al., 2004; Poortinga et al., 2011; Prospero et al., 2012; Shinoda et al., 2011; Yan et al., 2013, 2015). Several studies have revealed that wind erosion causes soil degradation by directly depleting fine particles and associated nutrients, especially in arid and semiarid areas (Li et al., 2007; Yan et al., 2013). Meadow steppe (MS), typical steppe (TS) and desert steppe (DS) are three types of grasslands distributed from east to west in Inner Mongolia based on the natural climate and vegetation conditions. In past decades, the degradation of the grassland area in Inner Mongolia has reached > 90% due to inappropriate overgrazing and cultivation (Yan et al., 2010). Moreover, the decrease in land surface coverage and the increase in disturbance of the surface soil has accelerated soil wind erosion. The feedback of wind erosion to grassland ecosystems is the main cause of land degradation in this area (Yan et al., 2010).

One of the main effects of wind erosion is soil particle coarsening, wherein nonerodible dry aggregates or individual coarse sand particles become more abundant at the soil surface (Chepil, 1953a; Wang et al., 2015). Previous studies have found that the soil dry aggregate size distribution is a main influence on wind erosion. The different dry aggregate size fractions can be divided into three groups according to their erodibility: < 0.42 mm, highly erodible fraction; 0.42–0.84 mm, semierodible fraction; and > 0.84 mm, nonerodible fraction (Chepil, 1953b). An important secondary factor influencing wind erosion is soil texture, which affects dry aggregate structure. In sandy soils, the < 0.125 mm particle fraction is most susceptible to depletion by wind erosion (Li et al., 2009; Yan et al., 2013). Although studies have described soil particle coarsening due to wind erosion, most have focused on either soil dry aggregate distribution or soil particle size distribution under certain wind erosion conditions. Few studies have conducted

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quantitative analyses of the changes in the distributions of both soil dry aggregates and particle sizes under a continuously increasing intensity of wind erosion (Li et al., 2007; Wang et al., 2015). This scarcity is mainly due to the difficulty of determining soil loss (as a measure of wind erosion intensity) due to wind erosion in the field, particularly when measuring wind erosion intensity as a continuous variable (Wang et al., 2015).

Another important influence of wind erosion on ecosystems is soil organic carbon (OC) and nutrient depletion. Compared with wind erosion in desert ecosystems, which primarily involves dust transport, wind erosion in agricultural or grassland ecosystems, which have more vegetation coverage, involves more organic-matter- and nutrient-associated dust transportation. Therefore, OC and nutrient transport by wind erosion in agricultural and grassland ecosystems are of particular concern because they can influence regional and even global OC and nutrient balance (Chappell et al., 2013; Goossens, 2004; Webb et al., 2012, 2013). The mechanism of OC and nutrient depletion involves the higher susceptibility of fine soil particles than of larger particles to depletion by wind erosion and the disproportionately greater amounts of OC and nutrients in fine soil particles (Li et al., 2007; Yan et al., 2013). Although studies have described the susceptibilities of different particle sizes and nutrients to loss by wind erosion, most have considered the influence of wind erosion with respect to either changes in soil texture or changes in nutrients. Relatively few studies have concurrently addressed the effects of wind erosion on the distributions of soil dry aggregates and particle sizes as well as on soil nutrients, especially under a continuously varying intensity of wind erosion.

In summary, the main aim of our study is to explore what remains and what is eroded by various windblown processes and, further, to explore the mechanism of grassland degradation driven by wind erosion. To this end, we conducted natural windblown treatments for unconsolidated soils sampled from three types of steppe. The specific objectives of this study were as follows: (1) to explore the responses of the three steppe soils to natural windblown treatments, (2) to quantify the change in the dry aggregate/particle size distribution under various wind erosion intensities for the three steppe soils, (3) to quantify the change in soil nutrient contents under various wind erosion intensities for the three steppe soils, and (4) to ultimately establish a conceptual model for the depletion of fine soil aggregate/particle and associated nutrients driven by both human activity and wind erosion in temperate steppe areas.

2. Methods

2.1. Site description

The study area is composed of three sites that represent the three different grassland types in Inner Mongolia corresponding to the different climate and plant community properties as follows (Fig. 1): 1) The meadow steppe site (MS) lies at the center of Hulunber meadow steppe (49°19′N, 119°56′E) in northeastern Inner Mongolia, China. The annual mean precipitation is 352.02 mm, and the annual mean air temperature is −0.43 °C (1985–2015). The soil type is generally chernozem or chestnut, and the vegetation is characterized as typical MS. The dominant species are *Leymus chinensis* and *Stipa baicalensis*. 2) The typical steppe site (TS) is located at Baiyinxile pasture (43°33′28.7″N, 116°40′20.2″E) within the central Xilin Gol grassland of Inner Mongolia in northern China. This semiarid region comprises basalt plateaus that are primarily covered with fine-sand loess with typical chestnut and calcic chernozem soil types. The annual mean precipitation is 277.15 mm, and the annual mean air temperature is 3.13 °C (1985–2015). 3) The desert steppe (DS) site is located in the western Xilin Gol grassland of Inner Mongolia (42°16′26.2″N, 112°47′16.9″E). The annual mean precipitation at this site is 180.57 mm, and the annual mean air temperature is 3.00 °C (1985–2015).

2.2. Field experiments and laboratory analyses

To examine the responses of the dry aggregate/particle size distributions and nutrients of the three steppe soils to wind erosion, we simulated different wind erosion intensities by manipulating the duration of soil exposure to natural wind. To obtain soil samples with characteristics that were representative of the three types of grassland, we selected three protected plots that had not been subjected to grazing for at least five years. In the MS site, a plot that had been ungrazed since 2009 was selected for sampling. The vegetation coverage in this plot was > 75%. In the TS site, a field that had been ungrazed since 1979 was selected for sampling. The field featured > 70% vegetation coverage and represented the original climax community of typical Inner Mongolian steppe. In the DS site, a plot that had been ungrazed since 2010 and that had 40% vegetation coverage was selected. The soils were sampled in May 2015 from the above-described three plots, which were representative of three grassland types in Inner Mongolia. Soils were collected from the top 5 cm of the surface of each site and then air dried and sieved in the laboratory to remove roots and debris > 2 mm. For each soil type, the pre-treated samples were divided into 36 subsamples of 400 g each, which were used in wind erosion experiment.

The wind erosion experiment was conducted in Baiyinxile pasture (43°26′N, 116°04′E) (Fig. 1). The 400-g treated samples of the three steppe soils were placed in trays (20 × 20 × 4 cm). In total, 108 trays with soil samples (3 soils × 36 sub-samples) were prepared for the wind erosion experiment. A similar method was used in previous studies by Yan et al. (2011, 2013, 2015). Use of the 4-cm-deep tray inevitably results in some wind deflection and turbulence. Therefore, the saltation of particles below a height of 4 cm may have been prevented, resulting in an underestimation of soil loss. We anticipated that all these influences are the same for all treatments (Yan et al., 2013). Therefore, these effects did not influence our analysis because the main aim in this study was to collect samples of soils affected by different wind erosion intensities (soil loss ratio). A 24-ha, long-ungrazed grassland area with flat terrain and largely even vegetation coverage (community coverage > 80% and community height = 20 cm) was selected. This location provides relatively uniform surface conditions and ensures that there is almost no local dust emission, except during strong dust-forming weather conditions (Yan et al., 2015). The trays were mounted in reinforced brackets at a height of 1 m above the ground at the site to minimize the influence of windblown sediments from the ground. Thus, soil removal by wind was the only process present, and the soil loss associated with different treatments could be accurately evaluated (Yan et al., 2015). The synchronous wind speed at 1 m above the ground was measured at 1-minute intervals using a wind measurement instrument that consisted of a data logger (FC-2, China), a three-cup anemometer and a wind vane.

The wind erosion experiment began at 8:56 am and ended at 6:45 pm on May 13, 2015. The total duration was 587 min. In this experiment, we achieved different wind erosion intensities through different durations of exposure to natural wind. According to the wind speed dynamics and visible degree of soil loss, we calculated the soil loss ratio 12 times for MS and TS soil and 11 times for DS soil for different durations of wind exposure. The detailed collective time interval of each experiment for the three soils is shown in Fig. 2. Each time, three trays (3 replicates) of each soil were taken to the laboratory to calculate the wind erosion intensity (soil loss ratio). The soil loss ratio (SLR, %) of the samples was calculated at different times using formula (1):

$$SLR(\%) = \frac{MOS - MRS}{MOS} \times 100 \quad (1)$$

where MOS is the mass of the sub-sample (400 g) and MRS is the mass of the soil remaining in the tray after erosion.

The amount of the residual soil samples (total 105 soil samples for three soils) after different wind erosion treatments of the three soils was