Geoderma 249–250 (2015) 79–86

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

How rain-formed soil crust affects wind erosion in a semi-arid steppe in northern China

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ARTICLE INFO

Article history:
Received 23 December 2014
Received in revised form 2 March 2015
Accepted 7 March 2015
Available online 17 March 2015

Keywords:
Crust thickness
Soil texture
Soil organic carbon
Wind erosion
Simulated rainfall

ABSTRACT

There have been few studies on the formation and resistance of physical crusts to wind erosion for typical steppe soils in Inner Mongolia, China. The objectives of this study were to 1) examine the effects of rainfall quantity on soil crust thickness, 2) investigate the effects of soil crust on wind erosion, 3) determine the crust thickness (crust formed by various rainfall quantities) able to most effectively resist wind erosion, and 4) evaluate the differences between the responses of soils with different treatment histories to crust formation and subsequent wind erosion at given rainfall quantities. To this end, we simulated five light rainfall levels to investigate the impact of light rainfall on soil crusting and subsequent wind erosion for soils of a semi-arid steppe via a unique approach. The results show that the soil crust thickness increases linearly with an increasing amount of rainfall for all four soils. The soil crust formed by rainfall of more than 0.5 mm was able to nearly completely prevent wind erosion during the experimental period; soil losses of only 0.1–2.4% were observed for the high rainfall treatments (>0.5 mm) for all four soils. In contrast, soil losses of 9.4–33.1% occurred in the non-rainfall treatments for the four soils. The results show that the soil loss ratio increased with increasing clay plus silt content and SOC content for the non-rainfall treatment and 0.2 mm rainfall treatment.

1. Introduction

A physical crust is one of the major soil structural features in many arid and semi-arid regions of the world. The crusting process begins with the breakdown of aggregates and dispersion of clay when the soils are wetted or exposed to rainfall. As the soils dry after clay dispersion, a thin seal or skin forms (B.C. Feng et al., 2013; G. Feng et al., 2013). The presence of a physical soil crust alters many characteristics of the soil surface; thus, this crust plays an important role in many ecosystem functions. Soil crusts are generally undesirable because they can reduce water infiltration and increase runoff (Belnap, 2001), but they can also be favorable due to their ability to reduce evaporation by capping the soil surface and reducing porosity (Chamizo et al., 2011) in agricultural areas. However, in arid and semi-arid rangeland ecosystems, soil crusts play a critical role in conserving soil resources in regions where wind erosion is predominant over water erosion (Yan et al., 2013). The influence of crusts on erosion has been noted for a long time in many arid regions (Rajot et al., 2003).

The existing wind erosion models do not include the effect on erosion of crusts formed by light rainfall, although certain studies have reported the effect of rainfall characteristics on soil crust formation (Farres, 1978; Morrison et al., 1985; B.C. Feng et al., 2013; G. Feng et al., 2013). Usually, only events with more than 10 mm of rainfall are taken into account in these models (Fryrear et al., 2000; Hagen et al., 1995). In view of the lack of studies on the effect of light rainfall in soil crust formation, G. Feng et al. (2013) conducted a field experiment involving 5 soil types on the Columbia Plateau to evaluate this effect and found an increase in crust thickness and strength with increased rainfall amounts. The crust thicknesses were similar among the soils, whereas the crust strengths varied according to the amount of rainfall. Furthermore, the soil crust strength increased with increasing soil clay plus silt contents. Although these findings provided a detailed relationship between crust thickness/crust strength and the quantity of light rainfall, the resistance of the crusted soils to erosion was not measured further.

Soil surface seals or crusts often form in unconsolidated soils during rainfall. Crusts have a pronounced effect on the susceptibility of soils to wind erosion because their properties differ from those of unconsolidated soils (Zobeck, 1991). Soil crusts are characterized by an interlocking network of particles, and soil pore spaces become clogged with fine particles that are more compact and mechanically stable, which decreases or eliminates the availability of loose erodible material for saltation

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http://dx.doi.org/10.1016/j.geoderma.2015.03.011
0016-7061/

(Chepil, 1958; B.C. Feng et al., 2013; G. Feng et al., 2013). Furthermore, this crust or seal can protect the unconsolidated soils beneath them, consequently reducing the susceptibility of the soils to erosion when exposed to wind (Zobeck, 1991; Chepil, 1958). This process is particularly important in arid and semi-arid regions where vegetative cover may not sufficiently protect soils from erosion. Zobeck (1991) found that crusts formed on silt loam and clay soils can be much more effective in reducing the total soil erosion under various abrasion conditions than can those formed on sandy loam soil. In addition, soil crusts increase the entrainment threshold, as has been suggested by the large amount of work that has been conducted on how crust disturbances increase dust emission (Belnap and Gillette, 1997; Baddock et al., 2011). Although the soil crust effects on erosion have been quantified in the past (Chepil, 1953, 1958; Zobeck, 1991; Rajot et al., 2003), a majority of that research has focused on crusts formed by heavy rainfall, i.e., precipitation >10 mm, and the effects of soil crusts on abrasion flux. These results do not include quantitative estimates of the effect of a weak crust formed by light rainfall on erosion. In addition, soil erodibility has been observed to change dramatically under small quantities of rainfall (Yan et al., 2013). Therefore, it is important to investigate the effects of light rainfall on soil crust formation in many arid and semi-arid regions.

Wind erosion commonly occurs in arid and semi-arid regions where vegetative cover is sparse and may not sufficiently protect soils. This type of erosion has been accelerated by the clearing of vegetation for rangelands (Webb et al., 2012). Over the past decades, wind erosion has been identified as a primary reason for soil degradation in the semi-arid steppes of northern China (Yan et al., 2010). The relevant studies have primarily focused on how to prevent erosion through land-use changes or vegetation coverage (Hoffmann et al., 2008; Yan et al., 2013). However, few field datasets are available on the effect of rain-formed crust on wind erosion. The objectives of this study were the following: 1) to investigate the effects of rainfall quantity on soil crust thickness, 2) to examine the effects of soil crust on wind erosion, 3) to determine the levels of crust formation (crust formed by various rainfall quantities) that can most effectively resist wind erosion, and 4) to evaluate the differences between the responses of soils with different treatment histories to crust formation and subsequent wind erosion at given rainfall quantities.

2. Materials and methods

2.1. Site description

The study was conducted in the Baiyinxile pasture, a component of the Xilingele grassland in Inner Mongolia, China (43°26′N, 116°04′E) (Fig. 1). This semi-arid region comprises basalt plateaus that are primarily covered with fine-sand loess with the typical chestnut and calcic chernozem soil types. The area features a semi-arid steppe climate (cold and dry in winter but mild and humid in summer), with an annual average rainfall of 264 mm (1981–2010). Precipitation is highly variable, with 75% of the total occurring between June and September. The average daily temperature is −22.3 °C in the coldest month (January) and 18.8 °C in the hottest month (July). Strong winds associated with dust storms occur from March to May, with an average monthly speed of up to 4.9 m s^{-1}. Wind erosion and dust storms are common phenomena and contribute considerably to the dynamics of soil carbon and nutrients through dust emission and deposition in this area (Hoffmann et al., 2008).

2.2. Experimental design

The soils were sampled in May 2013 from four fields with various land-use types within an area of 2400 ha (Fig. 1). The sites include: 1) a field that has been ungrazed since 1979 (Y79), featuring greater than 70% vegetation coverage and representing the original climax community in the typical Inner Mongolian steppe, where vegetation is dominated by *Stipa grandis*, *Leymus chinensis* community; 2) a field that has been ungrazed since 1983 (T83), featuring well-recovered vegetation and soils (the dominant community type is similar to Y79); 3) a continuously grazed field (TW), with a grazing intensity of more than two sheep ha^{-1} (overgrazing has degenerated the community to the type dominated by *Artemisia frigid*), less than 30% vegetation coverage,

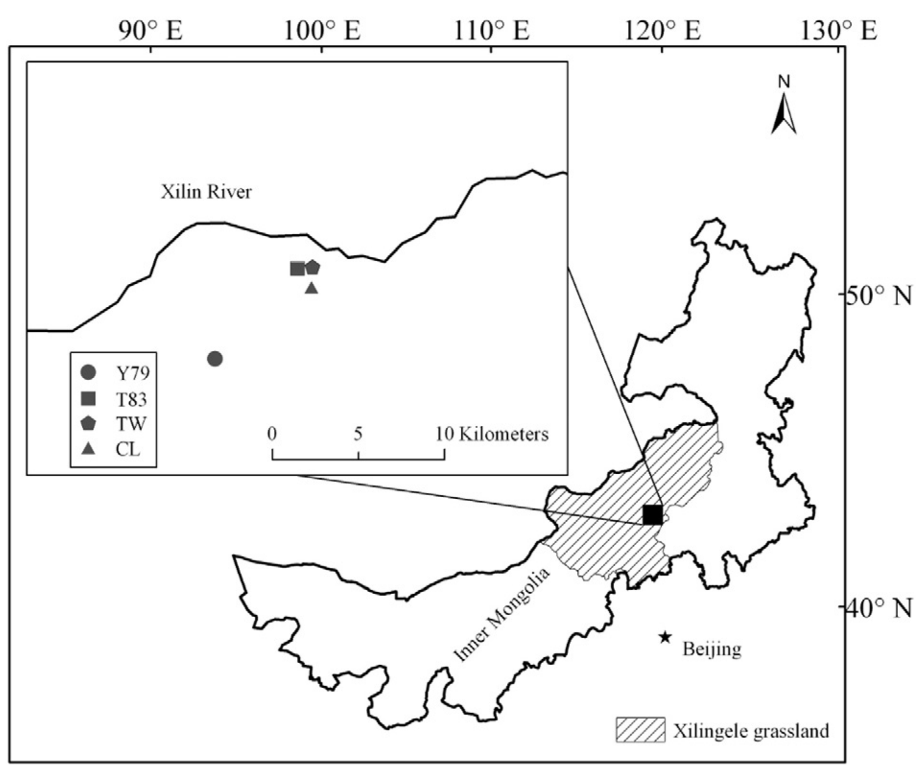

Fig. 1. Geographic location of the study area and the distribution of the fields where the soil samples were collected.