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Significance and pedogenic variability of phytogenic mounds on the Loess Plateau of China

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ABSTRACT

Phytogenic mounds, a mound-type microtopography, always develop around plants as an interaction of individual plants with erosion, sedimentation, and bioturbation processes in many different ecosystems. In this study, the spatial variation of soil physical, chemical and biological properties was examined in different parts of phytogenic mounds and intercanopy surfaces on different slope gradients on the Loess Plateau of China. The key indicators that affect soil properties were identified. The results revealed that soil properties on mounds underwent a subtle change compared to intercanopy surfaces on $\alpha \leq 46.6\%$ slopes. However, an improvement of soil properties was observed on $\alpha > 46.6\%$ slopes. The spatial variability of soil properties did not obviously change among different mound parts on $\alpha < 46.6\%$ slopes. However, the soil indicators in the upper parts of the mounds increased by an average of 23.3% and 32.8% compared to the middle and lower parts, respectively, on $\alpha > 46.6\%$ slopes. Soil chemical and biological variables were positively correlated. However, the physical properties correlated negatively with other variables. The soil available nutrient, moisture, and microbial activity were the key indicators that affected soil quality. The findings all indicate that phytogenic mounds play an important role in preventing soil deterioration and influence long-term ecosystem processes on the Loess Plateau of China.

1. Introduction

Phytogenic mounds, which are a mound-type microtopography, typically develop under plants in many different ecosystems, including dryland ecosystems (Bochet et al., 2000), alpine environments (Isselin-Nondedeu and Bédécarrats, 2007), forest (Simmons et al., 2011), coastal areas (El-Bana et al., 2003), and wetlands (Peach and Zedler, 2006). These topographic structures break the overall slope continuity and provide heterogeneity while altering geomorphological and ecological processes (El-Bana et al., 2003; Bruland and Richardson, 2005; Schladweiler et al., 2005). Thus, numerous geomorphologists and ecologists have focused on the geomorphological processes of mound formation and the crucial role of mounds in ecosystem evolution (Naylor, 2005).

Several hypotheses have been advanced to explain mound formation in different environments. (1) In areas affected by water erosion, the mound develops by the deposition of sediment and organic matter below the plant canopy as a result of the plants acting as a natural obstacles that decrease overland water flow (El-Bana et al., 2003). The unbalanced water erosion rate between plant-covered area and bare soil surface is also a mechanism of mound formation (Parsons et al., 1992). (2) In areas affected by wind erosion, two mound formation processes can occur: the accumulation of wind-borne sediments within or around their canopies after a decrease in blowing wind and the protection of soil under plant canopy from wind erosion (Wu et al., 2016). (3) Mounds in forests are often created through root growth, which decreases soil bulk density under plants (Bochet et al., 1999), or disturbances, such as tree falls (Ehrenfeld, 1995). (4) Animals such as termites and fossorial rodents also act as geomorphic agents in structuring mound-type landscape units (Jouquet et al., 2016). Generally, phytogenic mounds reflect interactions between vegetation and erosion processes, particularly in water-limited systems with scattered plant distribution. In addition, mounds are largely associated with breaking the overall slope continuity, reducing water erosion, and retaining sediments transported from upslope and distant regions by runoff and wind.

Mounds produce a diverse microtopography by creating

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different site conditions, such as aspect and light intensity (El-Bana et al., 2003; Bruland and Richardson, 2005; Schladweiler et al., 2005). In addition, mounds can act as natural obstacles that regulate hydrological and atmospheric processes by intercepting runoff and wind (Buis et al., 2010; Wu et al., 2016). Such processes not only redistribute water but also retain litter (i.e., soil organic carbon) and sediments (i.e., soil nutrients) contained in runoff and wind (Cao et al., 2016). Therefore, several studies have demonstrated that mound soil samples display higher soil moisture, larger pools of organic C and total N, and higher concentrations of phosphorus (P), sodium (Na^+), and potassium (K^+) than samples from locations outside mounds (Maestre and Reynolds, 2006; El-Bana et al., 2003; Kondo et al., 2012; Kröpfl et al., 2013; Li et al., 2008). In addition, soil physical properties are improved on mounds, e.g., higher aggregate stability, infiltration rates and lower bulk density than in the surrounding soil (Bochet et al., 1999). Furthermore, the sediment trapped by mounds can result in the spatial heterogeneity of the soil texture, such that more silt and clay particles but fewer sand particles are found on mounds than in locations outside mounds (El-Bana et al., 2003). Moreover, the improvement of soil physical and chemical properties enhances biological activity, as observed in the form of higher microbial biomass and enzymatic activity (Hopmans, 2006; Li et al., 2008).

Among the factors that prevent the development of diverse plant communities are limited propagule availability and/or insufficient resources for investment in seed (Moore et al., 1999; Young et al., 2005). Fortunately, when mounds participate in the slope erosion processes, they not only provide climate heterogeneity, higher water, and soil nutrient concentrations (Bruland and Richardson, 2005) but also accumulate seed or another plant propagules on the plant basis (Isselin-Nondedeu and Bédécarrats, 2007). Additionally, decreasing soil bulk density can increase the depth of root growth, which promotes plant survival (Bhattacharjee et al., 2008). Thus, the improvement of topsoil properties and the enhancement of seed banks on mounds create a suitable habitat in which vegetation can establish and develop (Schladweiler et al., 2005). In semiarid or arid environments, phytogenic mounds act as biodiversity agents by nursing species that under the same climatic conditions would not survive in degraded ecosystems. In contrast, the decline of mound-forming tussocks in sedge meadows results in declines in native plant abundance (Werner and Zedler, 2002). In wetland ecology, mounds reflect variations in natural bottomlands and substantially influence hydrologic conditions, soil properties, seedling survival and growth, and the abundance and distribution of colonizing species (Simmons et al., 2011). Wetland mounds also accelerate the development of wetland species composition and functioning as well as increase plant species richness in restored wetlands (Bruland and Richardson, 2005; Moser et al., 2007). Therefore, mounds may be a means of creating heterogeneity that promotes higher diversity in restoration settings and influence long-term vegetation dynamics and ecosystem processes (Lane and BassiriRad, 2005).

Although numerous studies have focused on the geomorphological or pedological significance of phytogenic mounds in arid and semiarid hillside ecosystems (Bochet et al., 1999; El-Bana et al., 2003), less attention has been paid to the spatial heterogeneity of soil properties in different parts of mounds on different slope gradients. This neglect of the spatial heterogeneity of soil properties can result in large errors in estimating the ecological function of phytogenic mounds in an ecosystem. In addition, to our knowledge, no evaluation has been made of the ecological effects of phytogenic mounds in the hilly-gully areas of the Loess Plateau. Therefore, the main objectives of this research are to address two tasks: (1) to examine the extent to which phytogenic mounds alter soil physical, chemical and biological properties compared with intercanopy surfaces in the hilly-gully Loess Plateau and (2) to discuss the spatial heterogeneity of these soil properties in different parts of phytogenic mounds on various slope gradients.

2. Materials and methods

2.1. Study site description

The study was performed in Zhifanggou and Songjiagou, two adjacent small watersheds, using repetitive sampling plots (109°15′N, 36°44′E) located on the Yanhe River approximately 20 km north of Yan'an City in northern China (Fig. 1) at 1010–1430 masl. The loessal soil (Calcaric Cambisols, FAO) typically contains 64% sand (50–2000 μm), 24% silt (2–50 μm), and 12% clay (<2 μm). The area is characterized as a semiarid climate. The mean annual precipitation and temperature are 542.5 mm and 8.8 °C, respectively. However, annual precipitation primarily falls in summer, and much of this precipitation is characterized by torrential precipitation events with short duration and high intensity. Consequently, serious water erosion and substantial amounts of runoff occur on slopes. The area belongs to the forest-grassland vegetation zone, and its vegetation is dominated by Gramineae, Asteraceae, Leguminosae and Rosaceae species (Jiao et al., 2008). The vegetation includes trees (*Robinia pseudoacacia*, *Populus davidiana* and *Pyrus betulaefolia*), shrubs (*Periploca sepium*, *Sophora viciifolia*, *Zizyphus spinosa* and *Artemisia gmelinii*), and herbs (*Artemisia scoparia*, *Artemisia giraldii*, *Bothriochloa ischaemum*, *Stipa bungeana*, *Phragmites communis* and *Lespedeza davurica*).

2.2. Plot selection

The two sampling watersheds cover a total area of 14 km^2. On south-facing slopes, discontinuous vegetation cover appears that is characterized by isolated plants growing in bare soil surface, and a mound always develops under plant canopy (Fig. 2A &B). For this study, plots on south-facing slopes with 10–25% restored natural vegetation cover (>20 years) were selected. This approach ensured similar succession stages of vegetation and similar developmental stages of the phytogenic mounds. The selected phytogenic mounds occupied similar geomorphic positions ~50 m from the top of a loess hill, which is always the most erodible area on the overall slope. Thus, the influence of mound position on soil properties could be eliminated. To compare the ecological function of the phytogenic mound on different slope gradients, four slope gradient classes were identified according to the Standard for Classification and Gradation of Soil Erosion, Ministry of Water Resources (MWR) of the People's Republic of China (MWR, 2008), i.e., a gentle slope gradient ($0 < \alpha \leq 26.8\%$), a moderate slope gradient ($26.8 < \alpha \leq 46.6\%$), a steep slope gradient ($46.6 < \alpha \leq 70\%$), and a very steep slope gradient ($\alpha > 70\%$).

2.3. Sampling design and measurement of topsoil properties

Soil samples were collected in October 2011, 2014, and 2015 in repetitive sampling. In the field, 20 phytogenic mounds were sampled on each slope gradient, and 20 points were sampled on intercanopy surfaces (IS) on each slope gradient. To compare the spatial heterogeneity of the soil properties of the phytogenic mounds on different slope gradients, soil samples were taken from three parts of each mound according to the direction of slope runoff: upper, middle, and lower (Fig. 2C). By studying pedogenic variability in these three mound parts, the ecological effects of mounds could be accurately evaluated.

Soil samples from the phytogenic mounds in each part were collected at depths of 0–20 cm. In the laboratory, the soil samples