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Soil aggregate stability under different rain conditions for three vegetation types on the Loess Plateau (China)

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ABSTRACT

Soil aggregate stability is essential for moderating the soil quality and preventing soil erosion. Vegetation restoration may effectively increase the stability of soil aggregates via soil organic matter. This study was designed to investigate the effects of vegetation types with long-term revegetation on the soil aggregate characteristics. Three vegetation type zones (grass land, forest-grass land and forest land) were selected in the Yanhe Watershed (northwest China) as the subjects. Soil aggregate stability was determined by the method of Le Bissonnais, including three disruptive tests: fast wetting (FW), slow wetting (SW) and mechanical breakdown (WS). The results showed that the mean weighted diameter (MWD) significantly differed from the tests and vegetation types. In the 0–10 cm soil layer, MWD ranged from 2.65 to 3.26 mm for the SW test, which corresponded to very stable soil aggregate; they ranged from 0.53 to 1.08 mm for the WS test, and from 0.57 to 1.96 mm for the FW test, both of which corresponded to very unstable soil aggregates. In the 10–20 cm soil layer, MWD ranged from 2.75 to 3.33 mm for the SW test, 0.39 to 0.83 mm for the WS test, and 0.44 to 1.37 mm for the FW test. The MWDs under the three tests were the lowest for the grass land at both soil layers, and the MWDs for the WS and FW tests were significantly lower than the MWD for the SW test. In all three tests, MWDs showed the same order: forest land > forest-grass land > grass land. MWD indicated that forest land had much stronger ability to resist soil erosion no matter the rain conditions. The correlations between soil organic matter content and MWD for the FW and WS tests were significant ($P < 0.05$). These results demonstrated that vegetation types had significant effects on the soil aggregates under the different rain conditions, and the soil organic matter and clay contents were significantly related to the soil aggregate stability. These results will guide the practice of reducing soil erosion for the different conditions and different vegetation types.

1. Introduction

Soil aggregate stability, an ability to resist breakdown by external forces, influences several soil physical or chemical processes, such as soil nutrient storage, water infiltration and the ability to resist soil erosion (Barthes and Roose, 2002). Specifically, aggregate stability affected the movement and storage of water in soils, soil aeration, soil erosion, biological activity, and crop growth (Zhang and Miller, 1996). Aggregate stability is a key factor in questions of soil fertility and environmental problems. Enhancing soil aggregate stability is an effective way to increase soil quality and prevent soil erosion and other environmental problems caused by soil degradation (Hortensius and Welling, 1996; Six et al., 2000; Zhu et al., 2017).

Human activity has had large impacts on the ecosystems of the world, especially in the Loess Plateau, China. Human activity in the Loess Plateau has had significant effects on the local environment via a variety of methods, such as over-grazing, the conversions from forest land or grass land into farm land and urbanization (Fu and Chen, 2000). These events have caused a lot of environmental problems, such as soil degradation, soil erosion, the serious decline of vegetation cover and the disbalance of ecosystems. To prevent further land degradation and recover the ecosystems and enhance the service function of the ecosystem, the Chinese government has launched a series of ecological projects. The 'Grain for Green' project was implemented to recover the degraded ecosystems in the Loess Plateau since the 1990s (Cao et al., 2009). In the Loess Plateau, soil water erosion is a major threat that seriously affects the processing and functioning of the ecosystem. Recently, vegetation restoration has been proven to be an effective measure for the sustainable development of terrestrial ecosystems (Lü et al., 2012; Zeng et al., 2017). According to previous studies, soil water-

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stable aggregation can sensitively reflect the ability to resist erosion with the process of vegetation restoration (Algayer et al., 2014; An et al., 2010, 2013b; Cheng et al., 2015; Zhao et al., 2013). The land type is an important factor affecting soil aggregates via the binding agents in soils, such as soil organic matter and fungal hyphae (Ayoubi et al., 2012; Khormali et al., 2009; Zhao et al., 2017). In the Loess Plateau, most of the results related to soil aggregate stability were obtained from the conventional wet sieving method (for example, An et al., 2013b; Xu et al., 2016; Yoder, 1936). The Le Bissonnais' method, a new standard (ISO/DIS 10930, 2012), involves several mechanisms of soil aggregate breakdown (Le Bissonnais, 1996), including fast wetting (FW), slow wetting (SW) and mechanical breakdown (WS). This method can separate the mechanisms (such as slaking and differential clay swelling) and provide more information regarding soil aggregation, which has only recently begun to be applied to the Loess Plateau. For example, An et al. (2013b) reported that the Le Bissonnais method could well evaluate the stability of forest soil aggregate in the Loess Plateau (An et al., 2013b). However, few studies are available regarding the evolution of soil aggregate stability during revegetation on a large scale with different vegetation ecosystems in the Yanhe Watershed using different tests of the Le Bissonnais method. The three tests of the Le Bissonnais method represent different rain conditions (heavy storm rain, gentle rain and disturbance by external force), so it is well worth providing more specific information in order to understand the effects of vegetation types on soil aggregates.

The Yanhe Watershed is one of the most important tributaries of the Yellow River, which has great importance for the Loess Plateau. It is also an ideal research area. As the precipitation is unevenly distributed throughout the year, most occurred during the growing seasons (from June to September). Therefore, this research was conducted in this area with three selected different vegetation areas representing different land use types, including forest land, grass land and forest-grass land. The objectives of this study were to evaluate the characteristics of soil aggregate stability in different vegetation zones under different rain conditions in the Yanhe Watershed. We addressed the hypothesis that (1) forest land had the highest ability of soil aggregates for the three tests due to its higher soil organic matter; and (2) the difference in the aggregate stability differed from the diverse land uses and unique tests, which represented distinctive rain conditions. This finding will promote the understanding of the effects of revegetation on soil quality and will help guide the practice and management of enhancing soil aggregate stability.

2. Materials and methods

2.1. Experimental site

The study sites were conducted in three small watersheds, including the Dongzigou watershed (DW) (109°15′33″–109°17′42″E, 36°55′50″–36°57′46″N), the Xiaohegou watershed (ZW) (109°11′58″–109°14′39″E, 36°59′33″–37°2′40″N) and the Gaojiagou watershed (GW) (108°58′5″–109°2′52″E, 37°12′31″–37°16′36″N), located in the Yanhe River Basin, northern Shaanxi Province, China (Fig. 1). The Dongzigou watershed mainly consists of trees and grasses, a typical forest vegetation land. The Xiaohegou watershed consists of shrubs and grasses, a typical forest-grass vegetation land. The Gaojiagou watershed consists of grasslands, a typical grass vegetation land. The soil type is loess, according to the Genetic Soil Classification of China (Zeng et al., 2016), or entisol, according to the USA taxonomy (Soil Survey Staff, 1999). The climate is characterized by cold dry winters and warm moist summers. The mean annual precipitation is approximately 400 to 500 mm, mostly occurring in a few heavy storms during the summer (Wang et al., 2014). The mean annual temperature ranged from 7.8 °C to 10.7 °C.

2.2. Soil sampling

Soil samples were collected from 0 to 10 cm and 10 to 20 cm depths in June 2013. In each land use, we selected 8–13 sample sites that have similar terrain (slope position and aspect) and similar plant communities. The plants and environments are described in Table 1. In every sample site, three 20 m × 20 m subplots were selected for sampling. Two types of samples were collected in each subplot for the analysis of soil properties and soil aggregates. Firstly, seven core samples were taken from each plot and mixed to form a composite sample. The fresh samples were sealed in plastic bags and transported to the laboratory for analyses of the chemical and physical properties. Secondly, large roots, stones and macro fauna were removed from the soil samples. These samples were used for the measurement of basic soil properties, including pH, soil organic matter (SOM), total nitrogen (TN), total P (TP) and dissolved organic phosphorus (DOP). Soil particles were classified into 3 size fractions (Table 2): clay (< 0.002 mm), silt (2–0.05 mm), sand (0.05–2 mm) (Liu et al., 2005).

Additionally, undisturbed soil samples were taken for the aggregate stability analysis from each plot with three replicates in the subplots, sealed and transported to the laboratory, where they were air dried at room temperature (20 °C). Each soil sample was sieved at 3–5 mm to generate aggregates for the stability tests by the method described by Le Bissonnais (1996).

2.3. Analysis of soil physical and chemical properties

Soil pH was determined with a pH electrode, extracted from 0.01 M $CaCl_2$ with a ratio of 1:2.5 (Bao, 2000; Huang et al., 2015). The bulk density (BD) was determined using a stainless steel cutting ring method (100 cm^3) to collect the undisturbed soils at different soil layers (Huang et al., 2015). Soil organic matter (SOM) was determined by wet digestion with a mixture of 5 mL of 0.8 mol/L potassium dichromate ($K_2Cr_2O_7$) and 5 mL of concentrated sulfuric acid (H_2SO_4) (Kalembasa and Jenkinson, 1973), and the total N was measured by the Kjeldahl method (Sparks et al., 1996). Soil total P (TP) was determined by colorimetric analysis (UV 2800) with a spectrophotometer after wet digestion with H_2SO_4-$HClO_4$ (Nelson and Sommers, 1982). Soil particle size distributions were measured by laser diffraction (Mastersizer 2000, Malvern Instruments, Malvern, England), including clay, silt and sand content (USDA taxonomy) (Liu et al., 2005).

2.4. Aggregate stability measurements

Aggregate stability was determined using the method described by Le Bissonnais (1996). This method included three disruptive tests that correspond to various wetting conditions and energies: fast wetting (FW), slow wetting (SW) and mechanical breakdown (WS). Before testing, the 3–5 mm aggregate samples need be dried at 40 °C for 24 h to a constant weight. Three replicates were conducted for each test. After each test, the fragmented samples were collected and dried at 40 °C for > 48 h to a consistent weight and gently sieved using a column of six sieves: 2, 1, 0.5, 0.2, 0.1 and 0.05 mm. The mass of each size aggregate was weighed and calculated. Finally, the mean weighted diameter (MWD) was calculated using the following equation (Oguike and Mbagwu, 2009). Five classes of the soil aggregate stability were identified according to the values of MWD (Table 3).

$$\mathrm{MWD} = \sum_{i}^{n} \chi_i \omega_i / \sum_{i}^{n} \omega_i$$

where ω_i is the proportion of aggregates in the size class i, and χ_i is the mean diameter of each size class.