Agriculture, Ecosystems and Environment 242 (2017) 1–8

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Effect of vegetation type on microstructure of soil aggregates on the Loess Plateau, China

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ARTICLE INFO

Article history:
Received 24 December 2016
Received in revised form 14 March 2017
Accepted 15 March 2017
Available online xxx

Keywords:
Aggregate pore
Micro-computed tomography
Soil organic matter
Soil texture
Vegetation restoration

ABSTRACT

Several types of vegetation restoration have been implemented on the Loess Plateau in China to control soil erosion and improve soil quality. Different revegetation types, however, have varying effects on soil structure; effects on the pore network of aggregates are especially not well understood. We used synchrotron-based high-resolution X-ray micro-computed tomography to quantify the microstructure of soil aggregates under four types of revegetation and an active cropland on the plateau. Five aggregates (3–5 mm) collected from the topsoil at each site were scanned at a voxel resolution of 3.25 μm, and the aggregate pore structure was visualized and quantified with ImageJ. Total porosities, >75 μm porosities, fractions of elongated pores, 3D mass fractal dimensions, and connectivity were higher and the numbers of pores, <75 μm porosities, the mean pore-shape factors, and the fractions of regular and irregular pores were lower in the revegetated sites than the control plot. Total porosities, macro-porosities, micro-porosities, fractions of regular pores, and 3D mass fractal dimensions differed significantly among the revegetated sites. We suggest that the fraction of elongated pores can be used as an important indicator for monitoring the recovery of soil structure. 3D mass fractal dimensions differed more than connectivity in the aggregates in the same samples, and thus could be a more sensitive indicator of changes in the pore network. Age and revegetation type both significantly affected the development of soil structure, but revegetation type was more important for the recovery of soil structure. We used a soil structural index (SSI) obtained by principal component analysis to assess the overall quality of soil structure. SSI values were higher in all revegetated sites than the cropland site and differed among the revegetated sites in the order: shrubland > grassland > woodland > pastureland. We recommend shrub plantation and natural grassland for the revegetation of degraded land on the Loess Plateau.

1. Introduction

Soil erosion is a worldwide problem with both social and environmental consequences (Duan et al., 2016). The restoration of vegetation in arid and semi-arid regions can increase the interception of rainwater and its retention in the soil (Sun et al., 2006). Revegetation has been widely used to control soil erosion and ecosystemic degradation (Bienes et al., 2016; Chen et al., 2010; Zhang et al., 2016). The Chinese government has initiated several projects for vegetation restoration on the Loess Plateau to conserve soil and water resources and restore damaged environments (Deng and Shangguan, 2012; Zhang and Shangguan, 2016). These projects have encouraged the conversion of cropland (particularly on steep slopes) to grassland, shrubland, or forest (Chen et al., 2007; Zhang et al., 2011). Proper adjustments of land use has increased the vegetation coverage on the plateau from 31.6% in 1999 to 56.9% in 2013, and the annual discharge of sediment from the Yellow River has been decreased to 0.2 billion tonnes, similar to historic levels (Chen et al., 2015; Wang et al., 2016).

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http://dx.doi.org/10.1016/j.agee.2017.03.014
0167-8809/

The structure of soil is central to its functioning, because it controls the fluxes and storage of water, gases, and nutrients and influences biological, physical, and chemical processes (Angers and Caron, 1998). The recovery of good soil structure by restoring vegetation is thus key to improving soil quality and fulfilling the essential functions of soil (Zhao et al., 2017). Revegetation practices can substantially change the physical and hydraulic properties of soil, including changes in organic matter content, porosity, hydraulic conductivity, and water retention (Kravchenko et al., 2011), and can affect soil structure in complex ways. In vegetation-restoration programs, forests and shrublands have improved soil structure more than grasslands (Zhang and Shangguan, 2016; Zhao et al., 2010). Evaluating the impact of vegetation recovery on soil structure is important for our understanding of the evolution of the ecological function of soil and can help the development of recommendations for eco-environmental reconstruction or rehabilitation.

X-ray computed tomography (CT), combined with image-analysis techniques, has recently been used to non-destructively study soil structure with a higher resolution and contrast and faster scanning than previous methods (Hu et al., 2016). X-ray CT scanning is also a unique tool for the 3D visualization and quantification of soil structure (Garbout et al., 2013; Zhou et al., 2012). For example, Luo et al. (2010) quantified 3D networks of soil macropores in various soil types and land uses in experimental columns using a medical CT scanner. Micro-CT, especially synchrotron radiation-based micro-computed tomography (SR-μCT), can enable researchers to quantify the internal structures of aggregates with a resolution of one to several microns (Ma et al., 2015; Peth et al., 2008; Zhou et al., 2016). Zhou et al. (2013) used SR-μCT to compare the effect of long-term organic and inorganic fertilization on the pore structure of aggregates (approximately 5 mm) and found that organic fertilization could improve pore network but the latter was ineffective.

Zhou et al. (2012) indicated that the pore system was improved after vegetation restoration on eroded bare land in the erodible red soil region of China. We visualized and quantified the microstructures of soil aggregates using SR-μCT in a previous study on the Loess Plateau over 32 years of revegetation (grassland) (Zhao et al., 2017). Revegetation significantly affected pore-size distribution, number of pores, and pore shape and facilitated the connection and development of aggregate microstructures by increasing the fractal dimension, anisotropy, and pore connectivity. Such information about aggregate pore characteristics would deepen our understanding of the mechanisms that determine soil structure (Kravchenko et al., 2011), but those studies were only concerned about one simple type of revegetation, and few studies have focused on the changes in aggregate microstructures by revegetation practices using SR-μCT. Evaluating the impacts of more types of revegetation (e.g. afforestation and artificial grassland) on the CT-measured characteristics of aggregate pores is therefore essential. A comparison of the impact of different revegetation types on aggregate microstructures is especially urgently needed, because it could be of guiding importance for the establishment of practices of adaptive ecological restoration in eco-fragile regions.

We hypothesized that vegetation restoration would improve the microstructure of soil aggregates and that different types of restoration could produce observable differences in the characteristics of aggregate pores. The objectives of this study were to: (i) evaluate the effects of different types of vegetation restoration on pore characteristics (number of pores, porosity, and pore morphological parameters), and (ii) determine the optimal type of vegetation for the recovery of soil structure on the Loess Plateau.

2. Materials and methods

2.1. Study sites

The sampling site was in the Zhifanggou Watershed in Ansai County, Shaanxi Province, northern Loess Plateau, China (109°13′46″–109°16′33″E, 36°43′11″–36°46′25″N; 1010–1431 m a.s.l.; 8.27 km^2). The area has hilly gullied loessial landscape with a temperate and semi-arid climate. The area's mean annual temperature is 8.8 °C (min −23.6 °C and max 36.8 °C) and annual evaporation ranges from 1010 to 1400 mm. The mean annual precipitation is 505 mm (1970–2006), 70% of which falls in the period of July to September (Zhao et al., 2017). The soil is a Calcaric Cambisol (FAO, 1990), originating from wind deposits and characterized by weak cohesion, high infiltrability, and low water retention (Fu et al., 2010).

The watershed is located in an ecotone of forest and grass. The vegetation has been widely rebuilt in this area in recent decades to remedy the problem of soil degradation (Zhang et al., 2011). Most of the cultivated land on the slopes has been gradually abandoned for natural and artificial revegetation. The main species used for artificial vegetation have included *Robinia pseudoacacia* L. (woodland), *Caragana korshinskii* Kom. and *Hippophae rhamnoides* L. (shrubland), and *Medicago sativa* L., *Astragalus adsurgens* Pall., and *Panicum virgatum* L. (grassland). Naturally restored areas contain *Artemisia capillaris* Thunb., *Heteropappus altaicus* (Willd.) Novopokr., and *Artemisia sacrorum* Ledeb.

2.2. Experimental design and soil sampling

We chose four typical types of vegetation restoration as the experimental sites: (1) pastureland (**PL**) based on alfalfa (*M. sativa*), which was annually drilled or broadcasted in April and harvested in late July; (2) grassland (**GL**) consisting of an endemic natural grass (*A. sacrorum*), which was allowed to naturally recolonize abandoned cropland; (3) shrubland (**SL**) based on Korshinsk peashrub saplings (*C. korshinskii*) planted in a 1.0 × 1.0 m grid; and (4) woodland (**WL**) consisting of black locust trees (*R. pseudoacacia*) planted 2.5–3 m apart in rows. A cropland (**CK**) planted with millet (*Setaria italica* L.) was selected as a reference site. All plants had grown for nearly 15 years under semi-arid conditions, without irrigation, fertilization, or disturbance after planting, except for the PL and CK sites. The CK site was annually tilled to a depth of 20 cm

Table 1
Detailed information for the experimental plots.

Plot name	Latitude (N)	Longitude (E)	Altitude (m)	Slope (°)	Slope Aspect	Dominant species
CK	109°14′35″	36°44′39″	1266	19	NE	*Setaria italica* L.
PL	109°14′57″	36°44′22″	1194	18	N	*Medicago sativa* L.
GL	109°16′31″	36°44′02″	1289	21	NE18°	*Artemisia sacrorum Ledeb.*
SL	109°15′29″	36°43′54″	1292	23	N	*Caragana korshinskii Kom.*
WL	109°15′20″	36°43′57″	1279	25	NE10°	*Robinia pseudoacacia* L.

Note: CK – slope cropland; PL – Pastureland; GL – Grassland; SL – Shrubland; WL – Woodland.