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Quantification of soil aggregate microstructure on abandoned cropland during vegetative succession using synchrotron radiation-based micro-computed tomography

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ABSTRACT

Information for the microstructure of soil aggregates is crucial for understanding the mechanisms of various soil processes. The quantification of complex aggregate microstructure and its relationship to vegetative restoration, however, remains elusive. The objective of this study was to evaluate the impact of natural revegetation on aggregate microstructure using synchrotron-based X-ray micro-computed tomography and image analysis. Soil samples were collected from an active cropland and from four former croplands that have been abandoned for 6, 12, 23, and 32 years on the Loess Plateau, China. Soil aggregates (3–5 mm) were scanned at a voxel resolution of 3.25 μm, and the aggregate pore structure was visualized and quantified with ImageJ software. The stability of wet aggregates and other soil properties were also evaluated. The amount of soil organic carbon increased significantly and soil bulk density decreased significantly with abandonment age. Aggregate water stability was higher after revegetation but did not differ significantly among the abandoned sites. Total porosity, percentage of pores >75 μm, and the fraction of elongated pores increased, but the number of pores, percentage of pores <75 μm, and fractions of regular and irregular pores decreased after the croplands were abandoned. The fractal dimension, degree of anisotropy and the Euler number all indicated that aggregate microstructures were more connected and developed at all abandoned sites than in the active cropland, but the fractal dimension was more sensitive for monitoring the quality of the soil structure. The results from this study can help to improve our understanding of the soil processes during natural vegetative succession and of the importance of pore morphology in monitoring the quality of soil structure.

1. Introduction

Soil structure plays a key role in determining the retention and transport of water, gases, and nutrients in soils, preserving soil productivity, and maintaining soil porosity and resistance to erosion (Barthès and Roose, 2002; Miller and Jastrow, 1990; Rillig and Mummey, 2006; Six et al., 2000). Soil structure can be broadly defined by form and stability (Bronick and Lal, 2005). Soil aggregates, i.e. clusters of soil particles that adhere to each other more strongly than to other surrounding particles (Barto et al., 2010), are widely regarded as principal soil structural units. Studies of soil structure usually focus on aggregate stability, size, and turnover (Bronick and Lal, 2005; Six et al., 2004; Kavdır and Smucker, 2005), ignoring the internal microstructure of aggregates. Aggregate stability has particularly been widely used to evaluate the stability of soil structure but cannot provide information about the status of aggregate structure (Young et al., 2001). The microstructure of soil aggregates determines soil stability and quality (Zhou et al., 2013), so information on the microstructure of aggregates can be essential for understanding the status and processes of soil structure.

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The direct investigation of aggregate structure has generally relied on the observation and quantification of thin sections or blocks using light microscopy, electron microscopy, and digital image analysis (Pagliai et al., 2004; Perfect and Kay, 1995; Zhou et al., 2012). These methods provide limited and fragmented information for aggregation structure, partly due to the lack of reliable methods for non-destructive observation and 3D measurements at an appropriate scale (Garbout et al., 2013a). These approaches also use destructive sampling and can be very laborious. The traditional methods have recently been supplemented with advanced nondestructive X-ray computed tomography (CT) scanning technology, which has the advantage of higher resolution and contrast and faster scanning (Garbout et al., 2012, 2013a, 2013b; Taina et al., 2008). Micro-CT, especially synchrotron radiation-based micro-computed tomography (SR-μCT), in combination with image analysis, can provide not only 3D data of porosity and pore-size distribution, but can also quantify and visualize pore orientation and complexity (Dal Ferro et al., 2013; Peth et al., 2008). Kravchenko et al. (2011), quantifying the effects of tillage on intra-aggregate porosity using micro-X-ray CT, indicated that long-term differences in land use and management practices may lead to substantial differences in intra-aggregate pore distributions and structures. Dal Ferro et al. (2013), using micro-X-ray CT to assess the effect of soil organic carbon (SOC) on the pore network of both undisturbed soil cores and aggregates, reported that SOC strongly affected the pore-size distribution in soil cores but weakly affected the pore network at an aggregate scale. These authors also suggested that morphological features such as connectivity were effective indices for differentiating the effects of management practices. Few studies, however, have specifically applied X-ray CT to visualize and quantify the influence of vegetative rehabilitation, particularly natural revegetation, on an aggregate microstructure.

The Loess Plateau in China covers approximately $58 \times 10^4\,\text{km}^2$, has a typical semiarid climate, and is known for its long agricultural history and serious soil erosion (Chen et al., 2007). Many erosion-prone slopes and sandy native grasslands have been converted into farmland to provide food security under the pressures of a growing population (Wei et al., 2006; Zhang et al., 2011), which produced serious soil deterioration due to erosion (Turner et al., 2011). Efforts have been undertaken to restore the eroded land by reconverting croplands into grasslands, such as the ‘Grain for Green’ project (An et al., 2013; Zhang et al., 2013). This conversion has increased the coverage of vegetation by the natural colonization of the abandoned fields by the surrounding natural vegetation (Wang et al., 2009; Zhang et al., 2012). The re-establishment of natural species-rich heaths on abandoned farmland is one of the main measures for controlling soil erosion on the plateau (Wang et al., 2011a). Abandoned croplands that have been stabilized by natural vegetation for different lengths of time thus offer a good opportunity for studying the mechanisms affecting soil structure during natural vegetative succession on the plateau.

We hypothesized that natural revegetation on abandoned cropland would improve the stability of soil aggregates, which would likely stabilize after several years of restoration. We also hypothesized that the microstructure of soil aggregates would become more connected and complex during natural revegetation. The objectives of this study were thus to (1) evaluate the effect of vegetative restoration on aggregate stability and (2) visualize and quantify the 3D aggregate microstructure with high resolution SR-μCT and image analysis during natural vegetative succession.

2. Materials and methods

2.1. Site description

The study was conducted in the Zhifanggou Watershed at the Ansai Research Station of Soil and Water Conservation in 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.; $8.27\,\text{km}^2$). The climate in this area is temperate semiarid, with a mean annual temperature of 8.8 °C (min −23.6 °C and max 36.8 °C) and a mean annual precipitation of 505 mm, about 70% of which falls between July and September. The annual evaporation ranges from 1010 to 1400 mm, and the average frost-free period is approximately 157 days. The soil at the study site was primarily Huangmian soil (Calcaric Cambisol, FAO, 1990), originating from wind deposits and characterized by a yellow color, absence of bedding, silty texture, and looseness (Zhang et al., 2011).

2.2. Experimental design and soil sampling

A common approach in studies of the effect of soil rehabilitation on vegetative coverage is to monitor changes in the plants and soil along a successional chronosequence on similar soils under similar climatic conditions (Bhojvaid and Timmer, 1998). Substituting space for time is an effective way to study changes over time (Li et al., 2007; Sparling et al., 2004). The Zhifanggou watershed has been protected for more than 30 years to allow natural

Table 1
Geographical features and vegetation characteristics of the sampling sites.

Plot name	Abandoned cropland (years)	Elevation (m)	Slope gradient	Geographical coordinates ψ(N), λ(E)	Dominant species	Accompanying species
Cr	0	1266	19°	36°44′39″ 109°14′35″	*Setaria italica*	
AC.6	6	1292	23°	36°44′47″ 109°15′12″	*Artemisia capillaries* Thunb *Heteropappus altaicus*	*Potentilla bifurca* L. *Lespedeza davurica* (Laxm.) *Poa annua* L. *Cleistogenes squarrosa* (Trin.)
AC.12	12	1289	21°	36°44′02″ 109°16′31″	*Artemisia capillaries* Thunb *Artemisia sacrorum* Ledeb	*Stipa bungeana* Trin *Heteropappus altaicus* *Poa annua* L. *Lespedeza davurica* (Laxm.) Schindl
AC.23	23	1283	23°	36°44′05″ 109°16′27″	*Stipa bungeana* Trin *Artemisia sacrorum Ledeb*	*Salsola collina* *Lespedeza davurica (Laxm.)Schindl* *Potentilla bifurca L.*
AC.32	32	1325	28°	36°44′15″ 109°15′55″	*Artemisia sacrorum Ledeb*	*Stipa bungeana* *Trin Vicia sepium L.* *Patrinia heterophylla Bunge*

Note: Cr—slope cropland; AC.6, AC.12, AC.23, AC.32—abandoned croplands for 6, 12, 23, 32 years.