Soil & Tillage Research 168 (2017) 176–186

Contents lists available at ScienceDirect

Soil & Tillage Research

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

Soil macropore characteristics following conversion of native desert soils to irrigated croplands in a desert-oasis ecotone, Northwest China

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ARTICLE INFO

Article history:
Received 16 July 2016
Received in revised form 18 December 2016
Accepted 8 January 2017
Available online 15 January 2017

Keywords:
Computed tomography
Cultivation
Desert-oasis region
Desert soils
Soil macropores

ABSTRACT

Sustainable use of cultivated desert soils is important for agricultural productivity in desert-oasis ecosystems. However, how soil macropore characteristics may change as a result of agricultural exploitation remains unclear. The objective of this study was to quantify and compare soil properties and macropore characteristics in an old oasis field (>50 years of cultivation, OOF), young oasis field (20 years, YOF), and adjacent uncultivated sandy land (0 year, USL) in Northwest China. Three replicated soil samples were collected from each site to investigate soil properties. Meanwhile, twelve (four replicates by three sites) intact soil core columns, 15 cm in diameter and 30 cm in height, were taken to analyze soil structure. Each soil column was scanned with a helical medical X-ray computed tomography (CT) at a voxel resolution of 0.469 mm × 0.469 mm × 0.600 mm. The results indicated that soil properties and macropore features improved after cultivation. Silt and clay content and dry mean weight diameter (DMWD) of aggregates increased with cultivation time, whereas bulk density decreased. Soil organic carbon and total nitrogen were 7.3 times and 6.7 times greater in soils at the OOF site than USL site, respectively. The increase in silt and clay content and aggregates formation likely resulted from irrigation with silt-laden river water, which in turn impacted soil nutrient accumulation. Soils at the OOF and YOF sites had greater macroporosity compared with soil at USL, and macroporosity also increased with cultivation time. X-ray CT revealed that soil macroporosity was 8.7–18.9 times greater in irrigated croplands than native desert. Soil macropores were mainly distributed at soil depths of 0–200 mm at the OOF and YOF sites, while smaller and less continuous macropores were randomly distributed across soil depths at the USL site. The larger number of macropores at the cultivated sites can be attributed to greater soil organic carbon, tillage-induced soil horizons, and alternate wetting and drying processes. Few soil macropores at the USL site may be associated with wind erosion and soil fauna burrows. Conversion of native desert soils to irrigated croplands had a positive effect on soil pore development in the desert-oasis ecotone.

1. Introduction

The history of agricultural exploitation in the Hexi Corridor of Gansu Province has been one of land conversion from virgin desert to arable soils. This continuous process of expansion of cultivated oases has intensified as the human population has increased. The expansion of oases has significantly increased the area of arable land as well as grain production, and it has altered landscape patterns in this arid region (Huang et al., 2007; Li et al., 2009a, 2009b; Su et al., 2010). Nonetheless, Environmental risks to agriculture such as water shortage, drought, and wind erosion remain serious. Owing to the hot, dry climate, the evolution of desert soils can be slow and clay and organic matter contents are often low (Zhao et al., 2006). As a result, these soils have a naturally loose structure, a shortage of aggregates (Li et al., 2006), and are susceptible to wind erosion, especially under conventional tillage. Therefore, sustainable agricultural use of cultivated desert soils has become a concern in desert-oasis regions. However, the effects of cultivation on soil structure, especially on macropore characteristics, remain poorly understood.

Soil macropores are critical to its function as a pathway for water, air, and chemical movement (Luo et al., 2010a, 2010b). Macropores are large soil voids and pathways including earthworm burrows, root channels, fissures and interaggregate voids,

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http://dx.doi.org/10.1016/j.still.2017.01.004

that are often distinct from the soil matrix, and which can permit preferential flow of water and nutrients through the soil profile (Jarvis, 2007; Li et al., 2009a, 2009b; Helliwell et al., 2013). Although macropores constitute only a small percentage of total porosity, they have a critical influence on saturated flow (Luxmoore et al., 1990; Lin et al., 1996). Macropores can cause chemicals and contaminants to be transported into the groundwater (Beven and Germann, 1982; Lin et al., 2005; Jarvis, 2007); nevertheless, they also have many benefits such as better aeration, root development, improved nutrient cycling in a well-developed soil structure (Jarvis et al., 2012). Macropore networks are shaped by factors related to soil structural hierarchy, including the abundance and activity of soil biota such as earthworms, soil properties (e.g. clay content), site factors (e.g. slope position, drying intensity, vegetation cover) and management (e.g. cropping, tillage, traffic) (Jarvis et al., 2012; Jassogne et al., 2007; Kumar et al., 2010; Li et al., 2016). Soil type, land use, and vegetation type are important factors influencing soil pore characteristics (Gantzer and Anderson, 2002; Udawatta et al., 2008; Mooney and Morris, 2008; Hu et al., 2016). For example, soil type, land use, and their interaction have been demonstrated to significantly alter macroporosity, macropore network density, surface area, length density, node density, and mean angle (Luo et al., 2010a). Hu et al. (2015) also reported that shrub encroachment resulting from anthropogenic disturbance significantly influenced soil macropores in grasslands. The alternate flooding and drying in paddy fields produced soil cracks which increased average macropore length but decreased the number of macropores, and changed macropore size distribution and macropore area density distribution with soil depth (Zhang et al., 2015). The process of converting desert to oasis is therefore expected to have a large impact on soil macropore characteristics. Thus visualization and quantification of soil macropore characteristics are essential for better understanding of soil hydrological processes in desert-oasis regions.

The three-dimensional (3-D) structure of soil macropore networks are complex but can be elucidated using X-ray computed tomography (CT) (Turberg et al., 2014; Zhang et al., 2015). A non-invasive imaging technique, CT scanning allows visualization at a much higher resolution than previous methods, such as dye tracing and soil thin sectioning (Grevers et al., 1989; Capowiez et al., 2003; Zhang et al., 2015). Compared with two-dimensional characterizations of soil macropore, such as from photography or manual measurement (Bandyopadhyay et al., 2003; Peng et al., 2006), the 3-D visualization by CT imaging provides greater detail about the shape and complexity of soil macropores. While some methods have been developed to quantity 3-D soil macropore networks (Abou Najm et al., 2010), these assume that the shape of soil macropores are regular, ignoring observed macropore complexity and irregularities (Ringrose-Voase and Sanidad, 1996; Bandyopadhyay et al., 2003). Katuwal et al. (2015) proposed that linking rapid X-ray CT scanning with classical fluid transport measurements on large, intact soil columns was very useful for characterizing soil macropore function. Hu et al. (2016) also quantified 3-D soil macropore networks beneath alpine vegetation using multi-slice helical medical CT. Therefore, quantitative data on soil pore features obtained by CT scanning, especially 3-D macropore networks, are expected to become more readily obtainable and widely available.

The oasis area in the Hexi Corridor has expanded as the desert has been converted to oasis. Previous studies have focused on the effects of land use changes and subsequent management practices on soil properties in this region (Li et al., 2006; Su et al., 2010). However, changes in soil macropore networks as a result of the agricultural exploitation of desert soils remain poorly understood in extremely arid regions. The objective of this study was to quantify the changes in soil properties and macropore features for soils beneath an old oasis field (>50 years of cultivation, OOF), young oasis field (20 years, YOF), and adjacent uncultivated sandy land (as a control, USL) in a desert-oasis region. This study should provide greater understanding of the evolution of soil pore characteristics as the desert is converted to arable land.

2. Materials and methods

2.1. Study site description

The study was conducted in the Linze oasis which is located in the middle reaches of the Heihe River, in the Hexi corridor of Gansu province (100°07′E, 39°24′N, AMSL 1383 m; Fig. 1a). The north of the oasis is the Badain Jaran Desert, covered by sand dunes and gravel Gobi. The study area has an arid climate characterized by cold winters and hot dry summers. The average annual temperature is 7.6 °C; while annual precipitation averages 117 mm and annual hours of sunshine reach 3051.1 h. Annual pan evaporation averages 2388 mm, which is twenty times greater than the annual precipitation. Annual wind speed averages 3.2 m/s. High winds and wind storms often occur in this area (Zhang and Zhao, 2015). Zonal soil is classified as the Calciorthids according to USDA Soil Taxonomy (Zhang, 2001). Owing to long-term wind erosion and deposition of aeolian sands, Psamments tend to form on the margin of the oasis (Su et al., 2010). Peripheral sandy lands have been gradually reclaimed for agricultural use since the 1960s; hence, irrigated croplands in this region range age from 1 year to more than 50 years old. Major landscape types in the study region include the peripheral desert, desert-oasis ecotone, and central oasis.

2.2. Soil sampling and analysis

Personal interviews were held with farm owners in the study area in order to document the history of land use for crop production. Prior to reclamation in the desert-oasis ecotone, the croplands were natural sandy land. The same soil parent materials were found in both the croplands and the adjacent sandy areas (Su et al., 2010). Particle size distributions and organic carbon concentrations in soil horizons were fairly similar at the beginning of croplands in different periods in the study area (Su et al., 2007). How long croplands have been cultivated was determined using the records from the Linze Inland River Basin Research Station, Chinese Academy of Sciences. The station was established in 1975 and is located in the center of the study area.

Two irrigated croplands reclaimed from natural sandy land and one uncultivated sandy land (as the control) were selected for study (Fig. 1b). The three sites were chosen to allow identification of potential changes in soil properties and macropores within different cultivation periods. Monitoring in the uncultivated sandy land was conducted 2–3 km away from the croplands (Fig. 1b). The first irrigated cropland was reclaimed for agricultural use 20 years ago and hence was designated for the purpose of this study, as the "young oasis field" (YOF). The other cropland had been cultivated for crop production for more than 50 years, and was designated the "old oasis field" (OOF). The adjacent "uncultivated sandy land" (0 year, USL) was considered to be the control as it had never been utilized for agriculture. In the YOF and OOF sites, major crops grown include maize (*Zea mays* L.) and spring wheat (*Triticum aestivum* L.), with only one annual harvest. Most cultivation consisted of strip intercropping of spring wheat and maize from 1980 to 2000. In recent years, however, seed maize production has become the pre-dominant agricultural use in these croplands. Monoculture of spring maize mulched with plastic mulching has been grown in the study area for more than ten years. Irrigated croplands were sown with maize on April 10th and harvested on