Catena 150 (2017) 317–327

Contents lists available at ScienceDirect

Catena

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

Understanding soil carbon sequestration following the afforestation of former arable land by physical fractionation

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ARTICLE INFO

Article history:
Received 8 October 2016
Received in revised form 25 November 2016
Accepted 27 November 2016
Available online 13 December 2016

Keywords:
Afforestation
SOC
Hippophae
Robinia
Physical fractionation of soil organic matter
Loess hilly region

ABSTRACT

To determine soil organic carbon (SOC) sequestration and storage mechanisms following the afforestation of arable land, soil samples were collected from a depth of 0–100 cm from cropland as well as six hippophae (*Hippophae rhamnoides*) and robinia (*Robinia pseudoacacia*) stands, which represented two afforestation chronosequences that were converted from arable land 13 and 39 yrs ago, respectively, in the Loess Hilly Region of China. The SOC in the whole soil profile was separated into four specific size/density fractions: coarse free (cf) particulate organic carbon (POC) inter-macroaggregates ($>$250 μm), fine free POC (ffPOC) inter-microaggregates ?thyc=5?> (53–250 μm), intra–microaggregate POC (iPOC) and mineral–associated organic carbon (MOC) in silt + clay ($<$53 μm). The concentrations of SOC in the whole soil profile and its fractions under robinia stands were generally on the order of 39 yrs $>$ 25 yrs $>$ 13 yrs, whereas under the hippophae stands, the order was 38 yrs = 28 yrs $>$ 13 yrs. The concentrations of SOC in all of the fractions in each soil layer were significantly higher under afforested stands relative to cropland, especially in the topsoil layer (0–10 cm). At a soil depth of 0–100 cm, the SOC sequestration rates in the fractions under robinia over 39 yrs were ranked on the order of MOC (0.94 Mg C ha^{-1} yr^{-1}) $>$ iPOC (0.41 Mg C ha^{-1} yr^{-1}) $>$ cfPOC (0.35 Mg C ha^{-1} yr^{-1}) $>$ ffPOC (0.12 Mg C ha^{-1} yr^{-1}), whereas the order under hippophae over 38 yrs was MOC (0.27 Mg C ha^{-1} yr^{-1}) $>$ cfPOC (0.18 Mg C ha^{-1} yr^{-1}) $>$ ffPOC (0.09 Mg C ha^{-1} yr^{-1}) = iPOC (0.07 Mg C ha^{-1} yr^{-1}). Furthermore, MOC accounted for 47.0% and 52.1% of SOC sequestration under hippophae 38 yrs after afforestation and under robinia 39 yrs after afforestation, respectively. Our results indicate that the afforestation of former arable land with robinia and hippophae in the loess hilly gully region could greatly increase SOC sequestration in all four fractions, especially the MOC.

1. Introduction

In China and many other countries, tree planting (afforestation) is prevalent on former agricultural lands that have poor soil fertility and productivity. The total area of afforestation in China on former arable lands was 32 million hectares in 2010 (Zhang et al., 2010), which is the largest afforestation area in the world. This widespread shift in ecosystem structure has a strong potential to alter key ecosystem processes that could affect C cycles at ecosystem and regional scales. In fact, the conversion of cropland to forest has been estimated to have the potential to increase SOC worldwide by 1.9% per year at <-30 cm soil depth (Paul et al., 2002). Thus, soil in afforested ecosystems should be identified as a potential carbon sink of atmospheric CO_2 (Paul et al., 2002; Shi and Cui, 2010; Vesterdal et al., 2002).

During the past 40 yrs, trees and shrubs have been planted on former cropland as part of a series of afforestation projects that have been implemented on the Loess Plateau of China (Chen et al., 2007; Zhang et al., 2012). This change in land use from agriculture to forestry has resulted in the replacement of the annual cycle of cultivating and harvesting crops by a much longer forest cycle. Consequently, forestry increases the net primary productivity and reduces the degree of soil disturbance, leading to increased C storage in the biomass and soil (Vesterdal et al., 2002; Zhang et al., 2010). Several studies have recently evaluated the capacity of SOC sequestration in the afforestation of former arable land (Chen et al., 2007; Wang et al., 2010; Xue et al., 2009). In a review, Shi and Cui (2010) also concluded that afforestation of former agricultural land usually results in substantial increases in SOC, and they estimated that the average C-sequestration rate in China could be 1.07 Mg C ha^{-1} yr^{-1} in <-40 cm soil depths. However, these studies have generally addressed the changes to SOC in the whole soil profile and have been limited in evaluating the mechanisms contributing to the stabilization and accumulation of SOC in these afforested soils.

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http://dx.doi.org/10.1016/j.catena.2016.11.027
0341-8162/

Evaluating SOC changes in labile carbon pools, such as microbial biomass C (Zhang et al., 2006; Sofi et al., 2016), light fraction C (Laik et al., 2009; Wang et al., 2016), particulate organic C (Leifeld and Kögel-Knabner, 2005; Wei et al., 2012) and permanganate oxidizable carbon (Tong et al., 2013), is a frequently used approach to assess management practices. These C fractions are likely to be more sensitive to management practices than the total SOC and can serve as indicators of future changes in the total SOC stock because of the fast turnover rate (von Lützow et al., 2007). However, these fractions are often loosely associated with measurable quantities. Recently, the role of the physical structure of soil as a determinant of SOC sequestration and turnover has generated much interest (Christensen, 2001; Ladd et al., 1993; Six et al., 2004; Tisdall and Oades, 1982). SOC occurs throughout the soil matrix in a variety of different sizes, shapes, levels of degradation, and degrees of association with soil minerals. The position of SOC with respect to pores and aggregated structures causes differential accessibility for decomposers and results in a range of SOC pools that differ in stability and dynamics (Ladd et al., 1993; Liao et al., 2006). The conceptual view of an aggregate hierarchy is that microaggregates (53–250 μm), together with primary particles (sand, silt, clay), are bound together within macroaggregates (>250 μm) by easily decomposed root residues and fungal hyphae and polysaccharides. Soil primary particles are stabilized into microaggregates and macroaggregates. Primary particles are cemented together by clay–organic matter complexes that incorporate persistent binding agents (e.g., humified organic matter). Microaggregates often have cores of partially decomposed POC and are considered to be relatively stable against disturbance (Oades and Waters, 1991). Based on this hypothesis, Six et al. (2002) proposed dividing the SOC into different conceptual C pools according to the C position and turnover rate in soil: free POC (unprotected C inter–aggregate), intra–microaggregate POC (physically protected C) and minerals–associated organic C (MOC, chemically and biochemically protected SOC). This conceptual SOC model provides an opportunity to understand the processes and mechanisms of C sequestration as influenced by different soil management practices or land uses (Liao et al., 2006; Six et al., 2002).

Physical fractionation procedures use the differences in the size and density of organic matter to isolate pools that are related to conceptual SOC model pools. Although the physical fractionation of SOC has been widely used to study the effects of land cover/land use on agricultural systems (Liao et al., 2006; Sleutel et al., 2006; Tong et al., 2014), the application of these techniques to the study of SOC storage and dynamics in afforestation systems on former arable land is less frequent (Laik et al., 2009; Liao et al., 2006). Therefore, the objectives of this study were to use physical fractionation techniques to identify the changes in SOC fractions and to elucidate SOC dynamics and storage mechanisms in afforested soil that has been converted from former cropland.

2. Materials and methods

2.1. Site description

The study area is located in the Zhifanggou watershed of Ansai County with an area of 8.73 km^2 at elevations ranging from 1100 m to 1400 m (Fig. 1), Shaanxi Province, China (109°13′46″–109°16′03″E, 36°46′42″–36°46′28″N), which is a typical hill-and-gully region on the Loess Plateau (Li et al., 2013). The area is characterized by a semiarid climate, with a mean annual temperature of 8.8 °C and average annual precipitation of 510 mm yr^{-1}, with 75% of the precipitation events occurring from July–September. The soil is mainly composed of Huangmian soil (a Calcaric Cambisol in the Food and Agriculture Organization classification of the United Nations, 1988), which develops on wind-deposited loessial parent material and is characterized by yellow particles, absence of bedding, silt loam texture, looseness, and wetness-induced collapsibility. Since 1973, the area has been used as an experimental field base to control soil erosion through wind and water by the Institute of Soil and Water Conservation at the Chinese Academy of Sciences. Integrated management of vegetation restoration and soil and water conservation has been carried out gradually. In particular, all of the croplands with slopes higher than 25° were converted to forestlands and grasslands. Currently, artificial forestlands with robinia (*Robinia pseudoacacia*), shrublands with *Caragana korshinskii* and hippophae (*Hippophae rhamnoides*) and grasslands with alfalfa (*Medicago sativa*) have become the main vegetation rehabilitation areas in the region. Moreover, *Robinia*, *Caragana* and *Medicago,* which are leguminous, have higher rates of net primary productivity than the previous cropland.

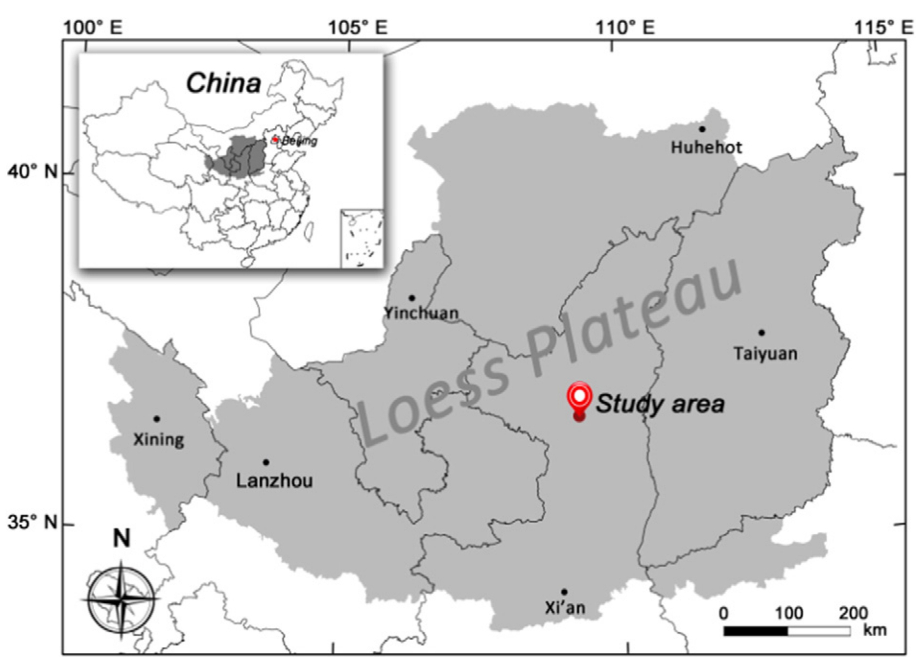

Fig. 1. Location of the study area (Zhifanggou Watershed).