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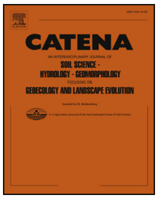

Aggregate stability and associated organic carbon and nitrogen as affected by soil erosion and vegetation rehabilitation on the Loess Plateau

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ABSTRACT

Although soil erosion and land use change have long been focuses in carbon research, the combined influence of soil erosion and vegetation rehabilitation on aggregate stability and the associated soil organic carbon (SOC) and total nitrogen (TN) remains unclear. The current study evaluated the effects of soil erosion on aggregate stability and the associated SOC and TN dynamics in relation to vegetation rehabilitation after the implementation of the "Grain-for-Green" project in the hilly Loess region. A check dam sediment sequence was dated using ^{137}Cs activity and erosive rainfall events. The SOC and TN in the bulk soil and aggregate fractions were measured in soils from rehabilitated grasslands and sloping croplands and in sediments retained by the check dam. The results showed that vegetation rehabilitation led to 78%, 27% and 9% average increases in the macroaggregate amount, mean weight diameter (MWD) and mean geometric diameter (MGD), respectively. In addition, rehabilitation resulted in the highest SOC and TN concentrations and contents in macroaggregates among all the aggregate size fractions. Soil erosion facilitated the modification of the aggregate size distributions along with soil mineralization and induced the incorporation of deeper SOC-poor soils during transport. These processes resulted in the aggregate-associated SOC and TN concentrations and contents in the sediments being significantly lower than those in the eroding sloping cropland soils. The highest reductions were found in microaggregates, which exhibited decreases of 48% and 44% for SOC and TN, respectively. Moreover, reaggregation and gully soils incorporated during soil erosion led to higher values of macroaggregate amount and aggregate stability at depositional sites than those at eroding sloping cropland sites in this study. Our study contributes to the understanding of the effects of soil erosion and vegetation rehabilitation on SOC and TN dynamics, which is crucial for understanding the restoration efficiency in soil erosion control and ecosystem security evaluation.

1. Introduction

With the trend of global warming, reducing the emissions of carbon (C) and nitrogen (N) oxides (i.e., CO_2 and N_2O) into the atmosphere has been an important goal toward sustainable development in recent decades (Fu et al., 2010; Melillo and Morrisseau, 2002). The potential CO_2 emissions from terrestrial ecosystems are significant for the continental- and regional-scale C balance (Bernoux et al., 2010; Murty et al., 2002). Soil organic carbon (SOC), the primary composition of the terrestrial C pool, greatly impacts global C cycling (Lü et al., 2012; Post and Kwon, 2000). Changes in the SOC pool can influence the CO_2 emissions to the atmosphere (Smith, 2008), and the cycling and availability of SOC are closely related to major nutrients, especially N (Murty et al., 2002; Yimer et al., 2006). Consequently, understanding SOC dynamics is crucial for developing effective management strategies to mitigate global warming and improve soil quality, which can contribute to the sustainable development of environment and ecology.

Previous studies have demonstrated that several factors influence the biogeochemical cycling of SOC, such as land use (Wei et al., 2013; Zhang et al., 2013), climate (Post et al., 1982; Wang et al., 2012), management practices (Zhong et al., 2015) and soil erosion (Berhe et al., 2007, 2008; Lal, 2003; Wang et al., 2014a). In ecologically fragile regions, the two most important of these factors are soil erosion and land use changes. Soil erosion, especially soil erosion by water,

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facilitates the translocation of soil materials and affects the SOC dynamics (Lal, 2003; Ran et al., 2014). Soil erosion redistributes approximately 75 Pg of soil and 1–5 Pg of SOC annually in worldwide (Berhe et al., 2007; Stallard, 1998). The SOC redistribution caused by soil erosion removes C-rich topsoil from eroding uplands and buries it at depositional environments. Globally, soil erosion and subsequent sedimentation result in a net terrestrial sink of 0.12–1.5 Pg C yr^{-1}, particularly when assessed at a watershed scale (Berhe et al., 2007, 2008; Stallard, 1998; Van Oost et al., 2007).

Land use changes affect SOC storage by changing the input rates and the decomposition of organic matter (OM) (Cambardella and Elliott, 1992). Vegetation rehabilitation of sloping cropland is widely used as an effective method to protect soils from erosion and degradation (Feng et al., 2016; Zomer et al., 2008). Over the past decade, significant changes have occurred in land use and land cover on the semi-arid Loess Plateau due to the conversion of sloping cropland to other land use types, such as fallow land, artificial grassland, shrub-land and forest (Liu et al., 2014), which occurred under the aim of the “Grain-for-Green (GFG)” project (Chen et al., 2007). This project increased SOC at rates of 0.33–0.37 $\text{Mg ha}^{-1}\text{ year}^{-1}$ on a regional scale (Deng et al., 2014) and contributed to C storage in the hilly Loess area (Cao et al., 2009, 2010; Yang et al., 2010). Consequently, accurately estimating land use changes in terrestrial ecosystems has become increasingly important for evaluating the C balance on regional scales (Gregorich et al., 1998).

Numerous studies have demonstrated that soil erosion and the conversion of land use have significant impacts on the dynamics of SOC and nutrients in soils and sediments (Fu et al., 2009; Gregorich et al., 1998; Kirkels et al., 2014; Wu et al., 2003; Zhou et al., 2007). However, reports of the effects of soil erosion and vegetation rehabilitation on the distribution of aggregates and aggregate-associated SOC and total nitrogen (TN) storage at the catchment scale are relatively few. Aggregation is an index used to assess the stability and erodibility of soils (Bryan, 1971). Reports have indicated that as the structural units of the soil, aggregates control the changes of SOC and nutrient cycling (Oades and Waters, 1991; Six et al., 2004), and aggregate formation appears be closely related to SOC storage and stability (Barreto et al., 2009; Golchin et al., 1995; Salomé et al., 2010; Wang et al., 2017b). Thus, a greater understanding of the aggregate-associated SOC dynamics during soil erosion under the implementation of vegetation rehabilitation is needed.

Check dam systems have been constructed to reduce soil erosion in the Loess Plateau area since the 1950s (Fu et al., 2011; Wang et al., 2011) and play important roles in C sequestration in the Loess Plateau ecosystems (Lü et al., 2012; Wang et al., 2014c; Zhang et al., 2016). By 2005, 122,028 check dams had been constructed on the Loess Plateau, within which > 21 billion m^3 of sediment and 95.2 Tg of eroded SOC have been stored (Ministry of Water Resources of the People's Republic of China, 2010; Wang et al., 2014c; Xu et al., 2004). In addition, the sediments intercepted by check dams exhibit a clear sedimentary sequence (Zhang et al., 2006). This favorable condition provides ready access to flood couplet records, and the sediments can reflect the soil erosion process as natural archives in these small catchments.

The aims of the study were (1) to determine the effects of vegetation restoration on the soil structure and aggregate-associated SOC and TN dynamics and (2) to determine the effects of soil erosion on the soil deposition, aggregate stability, and aggregate-associated SOC and TN dynamics in a small hilly loess catchment on the Loess Plateau.

2. Study area and methods

2.1. Study area

The Shayangou catchment (37°54′28″N to 37°55′02″N, 110°08′59″E to110°09′39″E), located in Mizhi County, Shaanxi Province, was selected as the study area. With an elevation ranging from 1024 m to 1124 m (Fig. 1), the drainage basin exhibits terrain fragmentation and complex topography characteristics and is vulnerable to erosion. The mean annual precipitation of this catchment is 451 mm, of which > 64% occurs in the form of high-intensity rainstorms and rainfalls during the rainy season.

A check dam was constructed in the 1960s near the catchment outlet (Figs. 1 and 2). The siltation area currently covers approximately 34,583 m^2. A topographic catchment map (scale 1:10,000) was constructed based on high-precision global positioning system (GPS) data associated with QuickBird imagery. The local villagers provided information on the land use history of this catchment. The terraced fields were constructed around the 1950s before the check dam construction, and the soils were resistant to erosion at that time. The apple orchards and residential areas covered 1.21% and 1.96% of the total area, respectively (Fig. 2). During the siltation of the check dam, extensive croplands were converted to grassland around 1999, and since then, there have been no obvious changes in the land use in this catchment. The croplands were mainly distributed in the gully and hilly zones; those with slope gradients > 25° were the most likely to suffer severe erosion in this catchment.

2.2. Sample collection

The fieldwork was conducted in October 2015, which included the collection of land use materials from sloping cropland and grassland and a sediment deposit profile of the Shayangou catchment (Fig. 1). The main crops in the sloping cropland were *Zea mays* L. and *Glycine* max (*Linn.*) *Merr.* The grassland is dominated by weeds, and the main grassland species is *Medicago sativa*. The method used to sample land use material followed that of Wang et al. (2017a). In brief, for each sample, only the 0–5 cm surface material was collected, and 10 subsamples were collected along transects in a $5 \times 5\ \text{m}^2$ grid and combined in the field to form a single composite sample. In total, 69 samples of sloping cropland (35 sites) and grassland (34 sites) were collected. The sloping cropland samples were collected after crop harvest, and straw had not been returned to the field at the sampling locations. In addition, being restricted by economic conditions, farmers do not apply fertilizer in the sloping cropland.

A sediment deposit profile was excavated and carefully separated into 44 flood couplets (S1–S44) (Fig. 3). The boundaries of the couplets were readily identified because they had distinct layers, with the bottom layer being coarse, and the upper layer being fine (Fig. 1; Zhang et al., 2006). The thickness of each couplet ranged from 3 cm to 52 cm (Fig. 3). A total of 45 sediment samples were collected from the deposit profile and the first sample was obtained from the cultivated layer (Fig. 3).

2.3. Laboratory analysis

All the eroded soil samples and sediment samples were air-dried until reaching a constant weight in the laboratory. Then, all the samples were dry sieved through a 2-mm mesh sieve to eliminate rhizomes, gravel and any coarse fragments before further analysis.

The ^{137}Cs activity was determined by gamma spectrometry using a hyperpure coaxial germanium detector (GMX50P4-83, ORTEC, USA) connected to a multichannel digital analyzer system (Wang et al., 2017a, 2017b; Zhao et al., 2015). The sediment particle size distribution was analyzed using a Malvern Mastersizer 2000 laser diffraction device (Malvern Instruments Ltd., UK) following sample pretreatment with hydrogen peroxide to remove OM. Carbonate was removed with hydrochloric acid, and the samples were chemically dispersed with sodium hexametaphosphate before being ultrasonically dispersed. Additionally, the bulk sediment samples were fractionated into three size fractions through 0.25-mm and 0.053-mm sieves according to the wet sieving method (Cambardella and Elliott, 1993; Wei et al., 2013). The macroaggregate (2–0.25 mm), microaggregate (0.25–0.053 mm) and silt-clay (< 0.053 mm) fractions were obtained and then weighed after