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Tracing the source of sedimentary organic carbon in the Loess Plateau of China: An integrated elemental ratio, stable carbon signatures, and radioactive isotopes approach

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A B S T R A C T

Soil erosion, which will induce the redistribution of soil and associated soil organic carbon (SOC) on the Earth's surface, is of critically importance for biogeochemical cycling of essential elements and terrestrial carbon sequestration. Despite the importance of soil erosion, surprisingly few studies have evaluated the sources of eroded carbon (C). This study used natural abundance levels of the stable isotope signature (^{13}C) and radioactive isotopes (^{137}Cs and $^{210}Pb_{ex}$), along with elements ratio (C/N) based on a two end member mixing model to qualitatively and quantitatively identify the sources of sedimentary OC retained by check dam in the Qiaozigou small watershed in the Loess Plateau, China. Sediment profiles (0–200 cm) captured at natural depositional area of the basin was compared to possible source materials, which included: superficial Loess mineral soils (0–20 cm) from three land use types [i.e., grassland (*Medicago sativa*), forestland (*Robinia pseudoacacia.*), shrubland (*Prunus sibirica*), and gully land (*Loess parent material.*)]. The results demonstrated that SOC in sediments showed significantly negative correlation with pH ($P < 0.01$), and positive correlation with soil water content (SWC) ($P < 0.05$). The sedimentary OC was not derived from grasslands or gullies. Forestland and shrubland were two main sources of eroded organic carbon within the surface sediment (0–60 cm deep), except for that in the 20–40 cm soil layer. Radionuclides analyses also implied that the surface sediments retained by check-dams mainly originated from soils of forestland and shrubland. Results of the two end-member mixing model demonstrated that more than 50% SOC (mean probability estimate (MPE) 50.13% via ^{13}C and 60.53% via C/N) in surface sediment (0–20 cm deep) derived from forestland, whereas subsurface sedimentary SOC (20–200 cm) mainly resulted from shrubland (MPE > 50%). Although uncertainties on the sources of SOC in deep soils exist, the soil organic $\delta^{13}C$ and C/N is still an effective indicator for sources of sedimentary organic carbon in the deposition zone in the short term (<10 years).

1. Introduction

Soil organic carbon (SOC), the main component of largest terrestrial carbon pool, has played a pivotal role in global carbon cycling (Xin et al., 2016). A small change in the SOC stocks may result in a significant variation in the atmospheric carbon dioxide, which will have impacts on global climate (Lü et al., 2012). Soil erosion, one of the most active mechanisms controlling soil formation and evolution, would facilitate not only the translocation of soil materials, but also the dynamic of soil organic carbon (Lal, 2003; Ran et al., 2014). Until recently, with the removal of C-rich topsoil from eroding slope positions and burial at a depressional and/or protected site, the redistribution of SOC caused by soil

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erosion site still has been intensely debated in the literature as to whether the net impact of erosion on C cycling acts as a C source or sink (Smith et al., 2001; Lal, 2004; Berhe et al., 2007; Harden et al., 2008; Vandenbygaart et al., 2015; Doetterl et al., 2016). The difference in sink/source terms mainly origins from variance in the approaches used in each study and incomplete understanding of the interactions between erosion and C cycling at the process level, especially the considerable uncertainty as to the fate of the OM that is exported out of eroding catchments (Liu et al., 2003; Doetterl et al., 2016). Therefore, tracing the movement of SOM from eroding platforms of different land use types, as well as identification of its ultimate depositional setting within a catchment, is essential for quantifying the fate of laterally transported C on the landscape (Berhe and Kleber, 2013; McCorkle et al., 2016).

Stable isotope analysis is a potentially powerful tool to determine the sources of organic matter supporting food webs in aquatic environments and the contributions of catchment sources to in-stream particulate organic matter (Hein et al., 2003; Gellis and Walling, 2011; Laceby et al., 2015; McCorkle et al., 2016). The successful application of carbon isotope for tracing the source and fate of carbon by using the characteristics that have distinct value between sources is found in previous studies (Ehleringer et al., 2000; Stevenson et al., 2005; Norra et al., 2005; Boeckx et al., 2006; Weihmann et al., 2007; Zhu and Liu, 2008). Traditionally, some radioactive isotopes (^{137}Cs, ^{210}Pb, and ^{7}Be) are used to estimate the rate of soil erosion and to infer associated rates of soil C erosion (Yoo et al., 2005; Simms et al., 2008; Kim, 2008; Klaminder et al., 2009; McCorkle et al., 2016), because they bind tightly to soil minerals and are only redistributed when the soil minerals are mobilized vertically or laterally (Alewell et al., 2009; Gellis and Walling, 2011; Kim et al., 2013). For instance, Li et al. (2006) demonstrated that ^{137}Cs and ^{210}Pb$_{ex}$, and SOC moved on the sloping land by the same physical mechanism during tillage operations, and fallout ^{137}Cs and ^{210}Pb$_{ex}$ could be used directly for quantifying dynamic SOC redistribution as affected by tillage erosion on a steep backslope of the Chinese Loess Plateau.

Even though stable carbon isotopes are most commonly used for tracing terrestrial carbon, the distinguishing of sources is not straightforward since the isotopic composition is often overlapping (Schoeninger and Deniro, 1984). For this reason, an additional tracer, the elemental C/N ratio, for example, is used along with the values of radioactive isotopes (^{137}Cs and ^{210}Pb) for distinguishing potential sources of soil and its associated SOC under different land cover types or landform positions (Simms et al., 2008). Combination techniques have been used to estimate organic carbon budgets and relate biomarker composition to the source organic material and depositional environment (Laceby et al., 2015; Wang et al., 2015b). Previous studies demonstrated that sedimentary carbon was mainly derived from 1) plants production in situ through tissue residues or via root exudates and symbiotic fungi (Trumbore and Czimczik, 2008) and 2) external soil and associated soil C inputs from the catchment sources by soil erosion (Zhang et al., 2013; Ma et al., 2016). With the application of an end-member mixing model based on the tracers, the relative contribution of SOC from different potential sources to sedimentary OC are accurately quantified, which would have significant impacts on evaluating the region or global carbon budget (Berhe et al., 2007). Recently, McCorkle et al. (2016) demonstrated that 58–100% of the OM in the sediments was sourced from O-horizon material in the Bull catchment and O-horizon material contributed 42–69% of the OM to the sediments in the Providence catchment, USA, by using a two-end member mixing model (i.e.,^{13}C and ^{15}N as the tracers, respectively). For instance, Yu et al. (2010) also used a simple two end member mixing model based on the bulk organic δ^{13}C and C/N as indicators to identify the sedimentary OC sources in the Pearl River delta and estuary, southern China, indicating that generally more than 50% TOM contributed to the sedimentary organic matter in the inner estuary.

The Loess Plateau in northwestern China is a well-known area, where severe soil erosion has induced more than 60% of the land being subjected to soil and water losses, with an average annual soil loss of 2000–2500 t km^{-2} (Shi and Shao, 2000; Fu et al., 2011). The main influencing factors are attributed to its high soil erodibility and intensive human activities in this region (Fu et al., 2011). A large quantity of sediment pouring to the Yellow River in the middle reach mainly originates from the Loess Plateau (Hassan et al., 2008). The SOC can also be exported from watershed by soil erosion along with transportation of associated sediment (Fang et al., 2012; Zhang et al., 2013; Ran et al., 2014; Xin et al., 2016). Carbon and nitrogen losses in the soil ecosystem have seriously depleted land resources and degraded the ecosystem in the Loess Plateau. Moreover, the loss of C and N nutrients have a significant impact on the biogeochemical cycles in the terrestrial and aquatic ecosystem, which contribute to aggravate global warming, air pollution, eutrophication, diversity decline and water quality deterioration (Melillo et al., 2002; Fu et al., 2010; Chen et al., 2015).

Since the 1950s, Chinese government has implemented long-term soil and water control measures, mainly including afforestation, grass planting, terrace building, dam construction in gully, and water conservancy projects in the tributaries (Xin et al., 2012). Check-dams are the most effective way to conserve soil and water and have been widespread constructed in gullies on the Loess Plateau (Xu et al., 2004). Consequently, the intensity of soil erosion has been greatly mitigated and the sediment originating from the Loess Plateau has shown a significantly decreased trend (Miao et al., 2010; Gao et al., 2010). In the past six decades, massive amounts of SOC were buried in the watershed along with sediments trapped by check-dams and reservoirs, and accordingly, significant reduction in organic carbon that is exported to the ocean has been observed (Lu et al., 2013a; 2013b; Ran et al., 2013, 2014). However, owing to the complex soil conditions and the diversity of potential carbon sources (autochthonous and allochthonous sources of carbon) during erosion and deposition process, little information regarding the identification of erosion-induced soil organic carbon source in sediments retained by check dams is available for the Loess Plateau, especially the contributions of potential carbon source under different land use types (Lü et al., 2012; Cooper et al., 2015).

Therefore, the main objectives of this study were as follows: (i) to analyze the vertical distribution pattern of SOC content in sediments retained by check dams and its influencing factor; (ii) to identify the sedimentary SOC source via combination of isotope traces and elements analysis; (iii) to assess quantitatively relative contributions of soil organic carbon from different land use types to sedimentary SOC retained by check dams.

2. Materials and methods

2.1. Study area

The present study was conducted in a sub-catchment trapped by one check dam (0.04 km^2), which is located within the Qiaozigou small watershed (2.45 km^2) in the loess hilly–gully region of the Loess Plateau near Tianshui City, Gansu Province, China (105° 43′ E, 34° 36′ N) (Fig. 1). The climate of study area is characterized by seasonal alternations of the East Asian summer and winter monsoons, with a mean annual temperature of 10.7 °C and an annual mean precipitation of 542.5 mm. The precipitation occurs in the form of intense, short duration rainstorms between June and September, with large inter-annual and annual variations. According to the U.S. Soil Taxonomy, the main distributed soil type is black