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# The mineralization and sequestration of organic carbon in relation to agricultural soil erosion

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## ABSTRACT

The coupling of soil erosion (especially interrill erosion by water) and the dynamics of soil organic carbon (SOC) in agricultural landscapes has been widely studied over the past two decades. To date, however, the role of soil erosion in global C cycle remains a topic of debate. Numerous questions remain to be addressed before determining the C sink/source effect of soil erosion, especially for the mineralization and sequestration of eroded SOC upon erosion, transport and deposition. In this review, we provide a comprehensive cross-disciplinary review on SOC mineralization and sequestration at sites of erosion, along the transport pathway and at depositional sites. The current state of knowledge on the impacts of erosion-induced soil aggregate breakdown and formation, removal of SOC from eroding sites and deep burial of SOC at depositional sites on the mineralization and sequestration of SOC are presented. Furthermore, we provide an overview of the conceptual relations between soil biological properties (microbial abundance, species diversity, community composition and enzyme activity) and the mineralization and sequestration of SOC in eroded agricultural landscapes, which are often overlooked by previous research and reviews. The comprehensive understanding of physical, chemical and biological mechanisms affecting the mineralization and sequestration of eroded SOC provides important insights to balance the global carbon budget and finally holds the answer on the carbon sink/source controversy.

## 1. Introduction

Over the past 200 years, the emission of greenhouse gases (GHGs), particularly carbon dioxide (CO<sub>2</sub>), has rapidly increased (IPCC, 2014). The global CO<sub>2</sub> concentration has risen from 280 to 382 ppm in 2007, with an increase rate of 0.88 ppm yr<sup>-1</sup> (Canadell et al., 2007). This rapid increase in CO<sub>2</sub> concentration has raised concerns regarding the identification of sources and sinks of CO<sub>2</sub> (Lal, 2003). Although lots of significant efforts and works have been conducted over the past two decades, it is still difficult to quantify and balance the global carbon (C) budget according to currently known C fluxes (Stallard, 1998). The unknown C sinks are estimated at 2–4 Pg C yr<sup>-1</sup> (Lal, 2003). Identification of unknown C sinks is important for reducing the enrichment rate of GHGs in the atmosphere and developing strategies for mitigating potential climate change. Actually, the current understanding of global

C budget is grossly inadequate because all CO<sub>2</sub> sources and sinks related to soil erosion are not accounted for (Lal, 2005).

Soil erosion by water is a natural geomorphic process and is one of the widespread forms of soil degradation (Doetterl et al., 2016; Liu et al., 2010). The area subjected to accelerated erosion (referring to water erosion and similarly hereinafter) has reached approximately 8.6% of the global land surface area (Lal, 2003). Soil erosion is a three-stage process: (i) detachment of soil particles; (ii) migration and redistribution of sediment over the landscape; and (iii) deposition in low-lying sites or aquatic ecosystems (Doetterl et al., 2016; Ritchie et al., 2007; Zhang et al., 2013). These processes have strong impacts on soil organic carbon (SOC) dynamics (Lal, 2005; Xiao et al., 2017a), with influencing mechanisms mainly involving: (i) removal and replacement of organic carbon (OC) at eroding sites; (ii) OC mineralization during transport; and (iii) deep burial of allochthonous and autochthonous OC

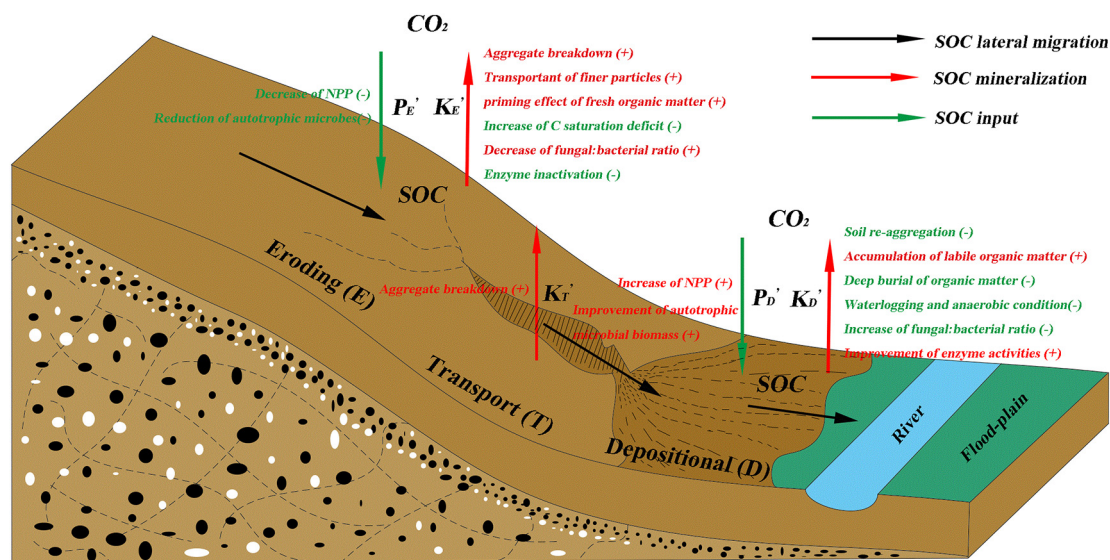
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**Fig. 1.** Migration, mineralization and input of SOC in an eroded slope.  $P_E'$  and  $P_D'$  represent the post-erosion condition of the SOC input rate at eroding and depositional sites, respectively.  $K_E'$  and  $K_D'$  indicate the post-erosion condition of the SOC mineralization rate at eroding and depositional sites, respectively.  $K_T'$  stands for the SOC mineralization rate during transport. The red letter and “+” in brackets represent a positive effect on the SOC dynamic; the green letter and “-” in brackets indicate a negative effect on the SOC dynamic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at depositional sites (Galy et al., 2015; Kirkels et al., 2014; Lal, 2003, 2005; Li et al., 2017). The influences of these mechanisms on SOC dynamics have been extensively studied in recent decades. Until now, however, there has been no consensus on whether soil erosion acts as a net source or sink of atmospheric  $\text{CO}_2$  (Lal, 2003; Van Oost et al., 2007). Stallard (1998) applied hydrologic-biogeochemical models to evaluate the impact of sedimentation of eroded soil on the global C cycle and concluded that terrestrial sedimentation contributes to soil C sequestration with a capacity of 0.6 to 1.5  $\text{Pg C yr}^{-1}$ . Similarly, Van Oost et al. (2007) by using caesium-137 and C inventories, estimated SOC erosion to result in a global C sink of 0.12  $\text{Pg C yr}^{-1}$ . However, contrary to Stallard and Van Oost, the work of Jacinthe and Lal (2001) and Lal (2003, 2004, 2005) indicated that soil erosion constitutes a source of atmospheric  $\text{CO}_2$ . They concluded that soil erosion releases 0.37 to 1  $\text{Pg C yr}^{-1}$  to the atmosphere due to the decrease in net primary production (NPP) and high mineralization rate of eroded SOC during transport.

The controversy over the role of erosion in global C cycle is largely attributed to different understanding on the fate of eroded SOC (predominately mineralized vs. sequestered), which is regulated by complex mechanisms (Berhe et al., 2008; Lal, 2003, 2005; Van Oost et al., 2007). For instance, the migration and mineralization of SOC during transport are closely related to aggregate stability. Chaplot and Cooper (2015) indicated that high aggregates stability induced low dissolved OC (DOC) and particulate OC (POC) losses (lateral migration) in a typical hillslope ( $r = -0.81$  and  $-0.77$ , respectively) due to increased soil infiltration by water and reduced transport by runoff. By establishing runoff plots on sloping agricultural lands, Polyakov and Lal (2008) investigated the effects of interrill erosion on SOC transport and mineralization, and indicated that approximately 20% of eroded SOC could be lost to the atmosphere during transport due to the breakup of initial soil aggregates. Splash, collision and shear forces induced by raindrops and runoff can decrease soil aggregates stability and accelerate SOC mineralization (Wei et al., 2016). At present, there are considerable disagreements in the existing literatures regarding the magnitude of SOC migration and mineralization during transport (Lal, 2003; Novara et al., 2016). By analyzing empirical data from 240 runoff plots of the world, Müller-Nedebeck and Chaplot (2015) indicated that the total amount of SOC displaced by interrill erosion from its source

approximately is  $1.32 \pm 0.20 \text{ Pg C yr}^{-1}$ . Assuming a decomposition rate of 20% for displaced SOC by interrill erosion, the annual C emission to atmosphere would represent  $0.26 \pm 0.04 \text{ Pg C yr}^{-1}$ . This is much lower, based on 20% decomposition rate, than the previous estimation by Lal (2003) of 0.8–1.2  $\text{Pg C yr}^{-1}$ . Differences in study methods, temporal-spatial scales and hypotheses may be the main reasons for these disagreements. For example, the mean POC loss rate of  $27.2 \text{ g C m}^{-2} \text{ yr}^{-1}$  was hypothesized by Müller-Nedebeck and Chaplot (2015), while a SOC delivery ratio of 2–3% was considered by Lal (2003).

On the other hand, the mineralization and sequestration of SOC at eroding and depositional sites are closely related to changes in soil micro-environments (Huang et al., 2013; Nie et al., 2014; Park et al., 2014). Interrill erosion, as a selective process, preferentially transports fine soil particles and light organic matter fractions (density  $< 1.8 \text{ Mg m}^{-3}$ ) from eroding sites to the low-lying depositional sites (Lal, 2003), which alters the soil texture in eroded agricultural landscapes and results in a high C enrichment ratio (the ratio of the concentration of SOC in the eroded sediments to that in the original bulk soil) in eroded sediments (Mchunu et al., 2011). Boye and Albrecht (2006) observed in Kenya that eroded sediments (interrill erosion) from 22.2 m long agricultural plot were enriched in SOC by an enrichment ratio of 3.3. Over 80% of eroded sediments are redeposited at the adjacent topography (Chaplot and Poesen, 2012), thus the deep burial of SOC-rich sediment at depositional sites leads to large amounts of SOC being stored in limited oxygen and moisture environments, which inhibits the rapid release of eroded SOC (Vandenbygaert et al., 2015). Furthermore, accompanied with changes in soil structure and nutrient availability, soil microbial abundance, community composition and enzyme activity at eroding and depositional sites also exhibit significant variation. For instance, the loss of SOC and dispersion of soil aggregates at eroding sites can inhibit the rapid growth of soil microorganisms (especially for fungi) and alter the community composition of soil microorganisms (e.g., fungal:bacterial dominance), which have strong impacts on SOC mineralization and sequestration (Trivedi et al., 2013). These changes in soil micro-environments together determine the fate of SOC (mineralization vs. sequestration) at eroding and depositional sites (Kirkels et al., 2014). Therefore, to scientifically identify the C sink/source effect of soil erosion, a comprehensive investigation of the influencing

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