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Review

The fate of soil organic carbon upon erosion, transport and deposition in agricultural landscapes — A review of different concepts

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ABSTRACT

Erosion and deposition redistribute large quantities of sediment and soil organic carbon (SOC) in agricultural landscapes. In the perspective of global carbon cycling, the coupling between erosion processes and the fate of SOC is of particular interest. However, different concepts have been proposed to assess the impact of erosion-induced lateral and vertical carbon fluxes. On landscape scale, this resulted in contrasting conclusions if agricultural soils represent either a carbon sink or source. The large global area of arable soil and generally high erosion rates, make these insights important. In this review, we aim to give an overview of the different conceptual relations described governing C dynamics at sites of erosion, along the transport pathway and at depositional sites and the current state of knowledge on the fate of SOC upon erosion, transport and deposition in agricultural landscapes.

The impact of erosion on SOC dynamics differs for sites of erosion, deposition and during transport, with further influences by agricultural practices (e.g. tillage and fertilisation). Controlling processes are the detachment of sediment and SOC, net primary production resulting in dynamic replacement and changes in mineralisation upon transport and deposition due to aggregate breakdown and deep burial, respectively. However, the exact magnitude and dominance of these processes are debated, resulting in a controversy whether arable land functions as a sink or source for atmospheric CO_2. Global estimations range between a net sink strength of 0.06–1 versus a source of 0.27–1.14 Gt C yr^{-1} for agricultural soils.

An eco-geomorphologic approach, which encompasses physical- and biological-driven factors (e.g. spatio-temporal variation in biological, geomorphological and biological processes, environmental conditions, mineralisation, and net primary production) is of importance to balance the carbon budget and ascertain sink or source formation at landscape scale. High spatio-temporal variability on process-scale imposes constrains, to measure and model the fate of SOC upon erosion, with limited quantitative data available. Prospective research across the landscape (eroding sites, transport pathway, and depositional sites) should include all relevant processes at broad temporal and spatial scales. Definitive resolution of the sink/source controversy lies in further eco-geomorphologic research on the fate of SOC, focussing on long-term and spatial extensive monitoring studies, combined with advanced measuring, modelling and extrapolation techniques to cover broad spatio-temporal SOC dynamics. Ascertainment of carbon dynamics in agricultural landscapes provides important insights to balance the carbon budget and finally holds the answer on sink/source formation.

1. Introduction

In agricultural landscapes, erosion and deposition redistribute large amounts of mineral soil and soil organic carbon (SOC) (Van Oost et al., 2007; Quinton et al., 2010) and erosion rates are one to two magnitudes larger if compared to areas with native vegetation (Montgomery, 2007). In the perspective of global carbon cycling, the link between sedimentary processes, the fate of eroded SOC and its replacement at the site of erosion is of particular interest (Stallard, 1998; Kuhn et al., 2009; Quinton et al., 2010). This is especially the case in these disturbed agricultural systems, the more so as the role of erosion in the exchange of carbon between agricultural soils and the atmosphere is debated.

From a geomorphologic point of view, soil erosion is well understood and involves three phases; detachment, transport associated with potential aggregate disruption and finally deposition (Morgan, 2005; Berhe et al., 2007; Quinton et al., 2010). Soil erosion, with water and tillage erosion as dominant processes, is responsible for widespread soil degradation on arable land (Lal, 2003a; Van Oost et al., 2009), and is largely affected by anthropogenic activities (Lal, 1995, 2003a, 2010). The impact of soil erosion on agricultural land is generally considered negative for eroding sites (i.e. soil degradation and low productivity)

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and positive for depositional sites (i.e. input of nutrients and SOC) (Stallard, 1998; Harden et al., 1999; Van Oost et al., 2005a; Quine and Van Oost, 2007; Ritchie et al., 2007). Whereas erosion and deposition result in redistribution of sediment and SOC (lateral flux) on landscape scale, SOC is affected differently within each phase while moving through the landscape, which can cause changes in carbon mineralisation and vertical flux (Gregorich et al., 1998; Lal, 2003b; Jastrow et al., 2007) (Fig. 1).

The exchange of carbon between agricultural soils and the atmosphere and thus sequestration or emission (i.e. sink or source of CO_2) represents an important gap in our knowledge of global carbon cycling (Stallard, 1998; Harden et al., 1999; Liu et al., 2003; Berhe et al., 2007; Kuhn et al., 2009; Quinton et al., 2010) or as Denman et al. (2007) state: “the land use carbon source has the largest uncertainties in the global carbon budget” (Denman et al., 2007, p. 518). Globally, the soil carbon pool is estimated at 2300 Gt C with 1500 Gt of organic C (Berhe et al., 2005; Lal, 2010), and exceeds both the biotic/vegetational and atmospheric pool by 4.1 and 3.3 times, respectively (Schlesinger, 1990; Lal, 2003a,c). Each year, 4% of the entire SOC pool is emitted, equivalent to 10 times the emission by fossil fuels (Lal, 2003a). While the major part is attributed to natural soil respiration (approximately 2/3) (Lal, 2004), the contribution of erosion on arable land is not yet exactly quantified (Liu et al., 2003; Van Oost et al., 2005a). Agricultural soils can function as a net sink or source for atmospheric CO_2; a positive balance means sequestration by SOC accumulation (sink) while a negative balance implies CO_2 emission (source). Recently, rapidly increasing atmospheric CO_2 concentrations arose specific interest in the sequestration potential of agricultural land (Gregorich et al., 1998; Stallard, 1998; Harden et al., 1999; Lal, 2003a,b; Lal et al., 2004a; Ritchie et al., 2007), by combining reduced emission and enlarged, long-term SOC storage (Gregorich et al., 1998; Lal, 2003b; Post et al., 2004).

Dynamics of the SOC pool are nevertheless complex and heterogeneous, thus assessment of impacts of erosion, transport, deposition and agricultural perturbations on lateral and vertical SOC fluxes presents a challenge (Smith et al., 2001; Doetterl et al., 2012a,b). SOC, which is a substantial part of soil organic matter (SOM), has varying characteristics which can affect mineralisation (e.g. molecular structure, origin) (Liu et al., 2003), and also increasing levels of physicochemical protection are recognised among different soil fractions (e.g. distinguished by density fractionation). The free fraction comprises unprotected SOC of relatively undecomposed, labile nature, the occluded fraction contains SOC stabilised within aggregates and the complexed fraction in which SOC is protected by strong association with soil minerals (Golchin et al., 1994; Christensen, 2001; Lützow et al., 2006; Cerli et al., 2012; Wang et al., 2013). The free fraction (i.e. labile/active pool) is directly impacted by redistribution, and the latter two fractions (i.e. stable/passive pool) are effectively protected with reduced susceptibility to mineralisation (Christensen, 2001; Lützow et al., 2006; Jastrow et al., 2007). Importantly, erosion, transport and deposition can induce transitions in SOC from one fraction to another (i.e. active to passive or vice versa) for example by aggregate disruption or deep burial, which may change C mineralisation rates.

The key question is whether redistribution of sediment and SOC in agricultural landscapes results in a carbon sink or source, which is subject to an ongoing debate for two decades. The large area of arable soils worldwide with generally high erosion rates and their significant economic and societal function (Lal, 2004; Lal et al., 2004a), make these insights important. However, different conceptual relations have been proposed for erosion-, transport- and deposition-induced lateral and vertical carbon fluxes. First approaches by Lal and colleagues focused on global estimations based on conceptual lines of thought; selective SOC erosion, soil degradation with loss of vegetation production and mineralisation during transport and deposition are assumed to create a net source (early paper by Lal, 1995; elaborated by e.g. Jacinthe and Lal, 2001; Jacinthe et al., 2001; Lal, 2003a, 2004; Lal et al., 2004a; Lal and Pimentel, 2008). Oppositely, more recent (modelling) studies across various scales allowed refinement of insights in erosion-induced C fluxes and pointed towards enhanced SOC sequestration, thus a net sink (e.g. Harden et al., 1999; Liu et al., 2003; Smith et al., 2005; Van Oost et al., 2005a; Ritchie et al., 2007; Van Oost et al., 2007). These different concepts resulted in two contrasting conclusions, and thus a sink/source controversy for global agricultural land.

An eco-geomorphologic approach, which encompasses physical- and biological-driven factors (e.g. net primary production (*NPP*) and mineralisation) associated with erosion, transport and deposition to assess C fluxes, offers perspective to gain insight in essential differences

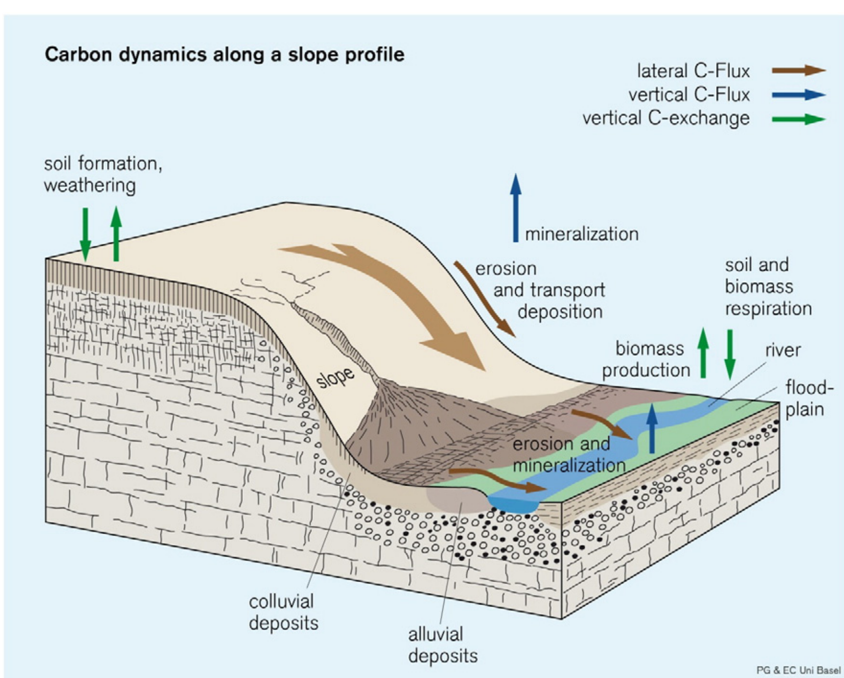

Fig. 1. Carbon dynamics along a slope profile, showing interactions between biomass production, soil formation, erosion and deposition processes and their effects on lateral and vertical carbon fluxes on landscape scale in a terrestrial system with an adjacent aquatic environment.