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Editorial

Soil erosion and carbon dynamics

Abstract

Accelerated erosion involves preferential removal of soil organic carbon (SOC) because it is concentrated in vicinity of the soil surface and has lower density than the mineral fraction. The SOC transported by water runoff is redistributed over the landscape and deposited in depressional sites where it is buried along with the sediments. However, the fate of the SOC transported, redistributed and deposited by erosional processes is a subject of intense debate. Sedimentologists argue that SOC buried with sediments is physically protected, and that depleted in the eroded soil is replaced through biomass production. Thus, they argue that the erosion–sedimentation process leads to globally net SOC sequestration of 0.6–1.5 Gt C/year. In contrast, soil scientists argue that: (i) a large portion of the SOC transported by water runoff comprises labile fraction, (ii) breakdown of aggregation by raindrop impact and shearing force of runoff accentuates mineralization of the previously protected organic matter, and (iii) the SOC within the plow zone at the depositional sites may be subject to rapid mineralization, along with methanogenesis and denitrification under anaerobic environment. Whereas, tillage erosion may also cause burial of some SOC, increase in soil erosion and emission of CO_2 from fossil fuel combustion are net sources of atmospheric CO_2. Soil scientists argue that soil erosion may be a net source of atmospheric CO_2 with emission of 1 Gt C/year. It is thus important to understand the fate of eroded SOC by measuring and monitoring SOC pool in eroded landscape as influenced by intensity and frequency of tillage operations and cropping systems.

Keywords: Global carbon cycle; The greenhouse effect; Soil degradation; Gaseous flux; Soil erosion; Cropping systems

1. Introduction

Accelerated erosion, by water or wind, is a selective process and involves preferential removal of the light (e.g., low density) and fine (e.g., small size including clay and silt) fractions (Bajracharya et al., 2000). The kinetic energy of the impacting raindrops along with the shearing force of water runoff (or blowing wind in case of the wind erosion) disperses aggregates and exposes the organic matter hitherto encapsulated and physically protected to forces of water and wind and other pedological processes. Being concentrated in the surface soil and of low density, soil organic matter is preferentially removed by surface runoff and blowing wind. Thus, the enrichment ratio of eroded sediments is greater than 1 and often as much as 5 (Lal, 2003). The displaced material is either redistributed over the landscape or deposited in depressional sites. The high soil organic carbon (SOC) content of depressional sites is attributed to the deposition of SOC-enriched sediments.

The fate of SOC transported by erosional process is not very well understood. The impact of erosion on pathways of SOC displaced may depend on the specific process involved (e.g., detachment or

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deposition). This special issue of Soil & Tillage Research, comprising 14 manuscripts, addresses some aspects of the pathway of erosion-induced translocation of SOC. All manuscripts are based on the field research conducted by the North Central Regional Committee comprising ten university partners in the Midwestern U.S.A. The objective is to synthesize the available research data emanating from this coordinated project, and identify researchable priorities.

2. The fate of carbon displaced by soil erosion

The fate of carbon displaced by soil erosion is a matter of much debate. There are two distinct but opposite schools of thoughts as follows.

2.1. Soil erosion as a carbon sink

Sedimentologists argue that soil erosion is a carbon sink, and that as much as 0.6–1.5 Gt C/year may be sequestered through deposition and burial of carbon transported by erosional processes (Stallard, 1998; Smith et al., 2001; Renwick et al., 2004). This hypothesis is based on the following assumptions:

(i) Soil organic matter is preferentially removed from the eroded soil, thereby depleting SOC pool on site of erosion. Most of the depleted SOC pool is dynamically replaced at the eroding sites by vegetation regrowth and return of both above and below-ground biomass to the soil. Thus, restoration of SOC pool in eroded soils is a net gain to the ecosystem carbon (C) pool.
(ii) The eroded SOC is transported to depressional sites where it is buried. The SOC buried below the plow depth of 20 cm is protected and not readily mineralized. The dispersed material is also re-aggregated, physically protected, and is less mineralizable than in the soil from which it is derived.

Therefore, soil erosion is a net global sink and accounts for the so-called "missing" or the "fugitive C" (Stallard, 1998).

2.2. Soil erosion as a carbon source

Soil scientists and agronomists argue that soil erosion is a net C source, and as much as 1 Gt C/year may be emitted into the atmosphere through increase in rate of mineralization (Lal, 2003) along with emission of CH_4 and N_2O (Lal, 2004a,b; Lal et al., 2004a,b) (Fig. 1). This hypothesis is based on the following rationale:

(i) Eroded soils have lower net primary productivity (NPP) than uneroded phases, even with higher inputs of fertilizers and irrigation (Dick and Gregorich, 2003). Low NPP of eroded soils is due to decline in soil quality caused by reduction in the effective rooting depth, decrease in available water and nutrient retention capacity, water and nutrient imbalance, and disruption in elemental and hydrological cycles.
(ii) Erosion causes breakdown of aggregates and soil dispersion, and exposes hitherto protected soil organic matter to microbial/enzymatic processes. Furthermore, the light fraction transported by runoff is labile and easily mineralized. Therefore, soil organic matter in eroded sediments is easily mineralized and 20–30% of the displaced SOC may be emitted into the atmosphere (Jacinthe and Lal, 2001).
(iii) While the soil organic matter buried below 20 cm depth is protected, that contained within the plow layer is exposed to anthropogenic and climatic perturbations and easily mineralized.

Therefore, the total ecosystem carbon pool is lower in eroded than in uneroded landscapes, and the rate of mineralization of soil organic matter is more in sediments than in original soil.

3. Tillage and soil carbon dynamics

Similar to soil erosion and carbon dynamics, the impact of tillage on SOC pool and flux is also a debatable issue. Some soil scientists and agronomists believe that elimination of tillage leads to SOC sequestration. In contrast, others argue that tillage increases soil carbon sequestration.

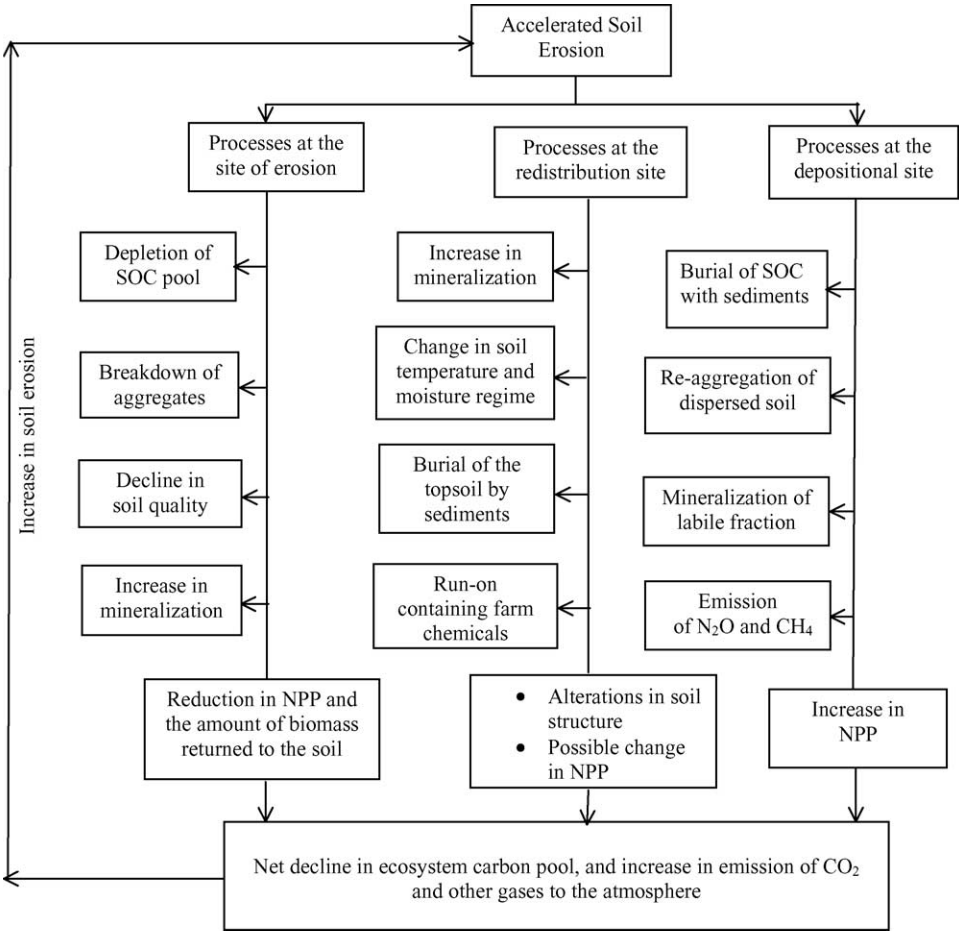

Fig. 1. Soil processes affected by accelerated erosion at the erosion, redistribution and deposition sites.

3.1. Soil tillage as a carbon sink

This hypothesis is based on the following assumptions:

(i) The soil moved by tillage erosion (i.e., tillage-induced movement of soil downslope) is buried and protected against erosion (Govers et al., 1999; Lobb et al., 1999). Tillage erosion leads to carbon sequestration rates which are of the same order of magnitude as those by conversion from plow-till to no-till (Van Oost et al., 2004).

(ii) Most soils prone to physical degradation (e.g., compaction, waterlogging) have low NPP. High NPP on physically degraded soil and those with sub-optimal soil temperatures during springs cannot be achieved without plow-based tillage. The problem of low NPP is also severe in some tropical soils containing predominantly low activity clays, low SOC content, and low activity and species diversity of soil fauna (Nicou, 1974; Charreau and Nicou, 1971; Charreau, 1972). Therefore, sub-soiling, inversion tillage, and soil pulverization by secondary tillage operations enhances NPP, increases the root and above-ground biomass, improves soil structure and tilth, increases available water holding capacity, and enhances the SOC pool.

(iii) Conversion from plow-till to no-till does not increase SOC pool in clayey and poorly drained soils, and those with a high antecedent SOC pool (Puget and Lal, 2004).

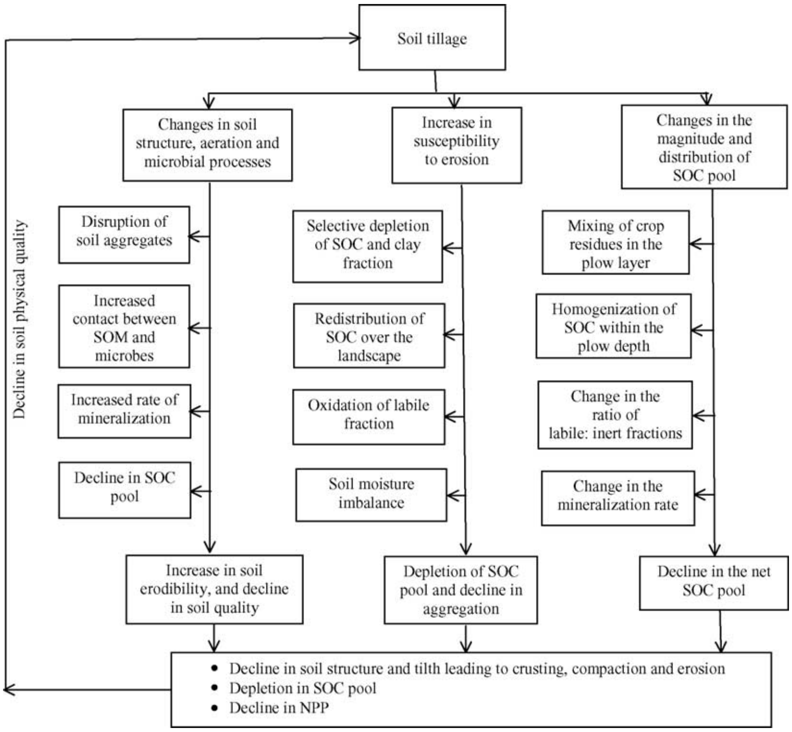

Fig. 2. Manifestations of soil tillage.

3.2. Soil tillage as a carbon source

Soil tillage can adversely affect soil quality, reduce long-term productivity, and lead to emission of CO_2 (Fig. 2). This hypothesis is based on the following rationale and assumptions:

(i) Tillage increases the rate of mineralization of soil organic matter (Reicosky, 2002). Therefore, conversion from plowing to no-till enhances SOC pool (Dick and Gregorich, 2004; West and Post, 2002).

(ii) Tillage increases risks of soil erosion by water and wind. Conversely, losses of SOC pool due to erosion are reduced by conversion from plow-till to a no-till system.

(iii) In the long-term, tillage degrades soil quality and reduced NPP. Conversely, no-till improves soil quality and enhances NPP. Reduction in NPP also reduces the amount of biomass

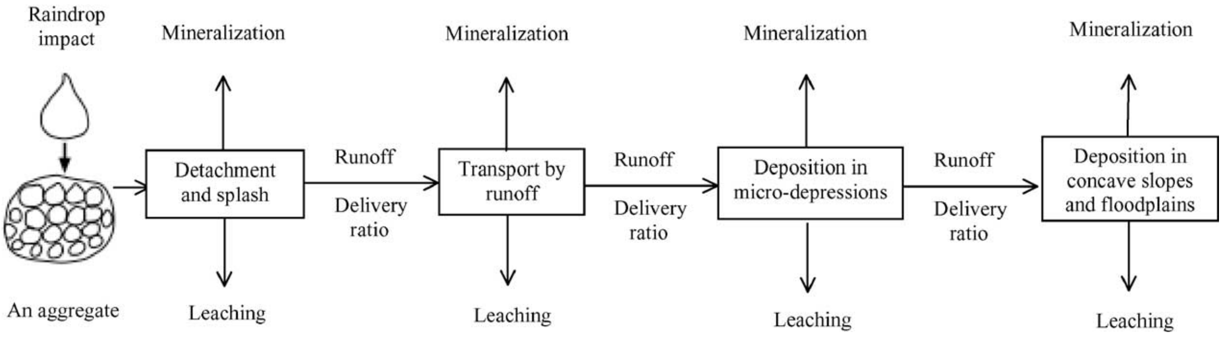

Fig. 3. The fate of eroded soil organic carbon during four stages of the erosional process.

humified into the SOC pool (Duiker and Lal, 1999).

(iv) Tillage operations involve fossil fuel consumption. Estimates of equivalent C emissions for tillage operations include 15.2 ± 4.1 kg C/ha for moldboard plowing, 7.9 ± 2.3 kg C/ha for chisel plowing, 8.3 ± 2.5 kg C/ha for heavy tandem disking, 5.8 ± 1.7 kg C/ha for standard tandem disking, 11.3 ± 2.8 kg C/ha for sub-soiling, 4.1 ± 1.9 kg C/ha for field cultivation, and 2.0 ± 1.9 kg C/ha for rotary hoeing (Lal, 2004a,b). Therefore, elimination of primary and secondary tillage operations results in saving 30–40 kg C/ha/season.

4. Is soil erosion a source or sink for atmospheric CO_2?

A holistic and a landscape approach is needed to assess the fate of eroded SOC and to determine whether accelerated soil erosion is a source or sink of atmospheric CO_2? Soil erosion is a 4-stage complex process. Four stages are: detachment, transport, redistribution and deposition. Mass balance of SOC pool is needed at each stage to assess the fate and pathways of erosion-induced SOC transport (Fig. 3). The proportion of SOC pool transported by erosional processes and that which eventually gets into the depositional sites (comprising concave slopes, flood plains) and is buried in aquatic ecosystems is protected against mineralization and is sequestered. On global scale, the SOC buried is estimated at 0.4–0.6 Gt C/year (Lal, 2003). However, a large fraction of the SOC displaced by the erosional processes does not reach the depressional sites nor gets buried in aquatic ecosystems. Some of this fraction is redistributed over the landscape, and the remainder is mineralized into CO_2 under aerobic conditions and CH_4 under anaerobic environments. Some depressional sites may undergo seasonal denitrification with an attendant emission of N_2O. Therefore, long-term field experiments are needed to assess the fate of eroded SOC by measuring and monitoring pools and fluxes (e.g. (i) acquisition, (ii) emissions, (iii) leaching, and (iv) transport) at landscape level. Conclusions drawn from the analyses of SOC pool at the depositional or detachment stage alone, disregarding the fate of SOC at other erosional stages, can lead to erroneous conclusions and misinterpretations. Whereas modeling can be a useful approach (Polyakov and Lal, 2004), long-term field experiments are essential to obtaining site-specific data.

5. The objective of this special issue

This special issue is a compendium of 14 papers that address the issue of erosional impact on SOC by quantifying the pool at different positions of eroded landscape managed by different tillage methods and cropping systems. Four manuscripts (e.g., Olson, Arriaga and Lowery, Fenton et al., and Shukla and Lal) describe the spatial distribution of SOC pool in different eroded phases of the soil. The manuscript by Reicosky et al. quantifies CO_2 emission during and after the tillage operations. Two manuscripts (e.g., Moncrief et al., and Ranaivoson et al.) specifically discuss SOC losses in snowmelt during spring. The remaining six manuscripts deal with the impact of tillage and cropping systems on SOC pool.

None of the manuscripts addresses the flux of SOC corresponding to different erosional stages, which remains a high priority if the debate on fate of eroded SOC is to be resolved. Furthermore, there is a strong need to establish long-term experiments which are specifically designed to perform the mass balance of SOC at each of the four stages.

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