Watershed-scale runoff–erosion–carbon flux dynamics: current scope and future direction of research

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Soil plays an important role in the ecosystem with regard to plant growth, soil biota functioning, reduction of greenhouse gases, modification of pollutants and maintenance of soil quality. The great importance of C stocks emphasizes the need to understand the role of soil organic matter (SOM) dynamics and quantitative changes as affected by natural conditions and site-specific management. Soil carbon inventories and turnover rates are influenced by climate, vegetation, parent material, topography and time. Studies attempting to understand the influence of a specific factor (e.g. temperature or moisture) on soil properties have found it useful to identify a group of soils for which the factor in question varies. Nevertheless, soils are the largest pool of terrestrial carbon containing 1550 Pg of soil organic carbon (SOC)[1]. This vast carbon pool is subjected to perturbation as a result of anthropogenic activities (land-use change) and natural reasons (climate change, soil erosion, etc.). The maintenance and enhancement of this terrestrial carbon can occur only through better land-management practices. The exchange of carbon between the terrestrial biosphere and the atmosphere is an important yet poorly constrained portion of the global carbon cycle[2]. Though terrestrial carbon cycling has a strong influence on atmospheric CO_2, quantitative estimates of production and loss at the watershed scale are rare. Watershed being a discernable landscape unit to study the integrated hydrological and biogeochemical processes, a study on quantitative estimation of gain and loss of carbon assumes importance in current climatic aberrations and future climate-change scenarios.

Soil constitutes both abiotic (non-living) and biotic (living) components. In addition to air and water, it also contains minerals (sand, silt and clay) and organic matter. The presence of organic matter, although very small in fraction, is important for plant productivity and other ecological functions. SOM is defined here as the non-living component of organic matter in soil. The ultimate source of organic matter in soils is CO_2 fixed by plants, including leaf litter, roots and root exudates. The activity of soil microorganisms (especially fungi and microbial communities) metabolizes some of these substrates and transforms others into more resistant organic compounds (collectively referred to as humus). The stabilization and fate of organic matter residues is affected by the quality of the original plant substrate[3], and the physical environment in the soil (clay content and mineralogy[4], pH, O_2 availability[5], formation and disruption of soil aggregates[6–8]). Carbon is lost from soil mostly as CO_2 produced during decomposition of organic matter, though losses of carbon through leaching or erosion may be important when considering C balance in soils on long timescales[7,9,10]. Soil-respired CO_2 is produced either by metabolic root respiration or by decomposition of fast-cycling SOM pools. Some of the major factors that contribute to the net decline of SOM on an anthropogenic landscape include (a) decomposition of organic matter due to higher soil temperature, (b) lower inputs of carbon due to residue/biomass removal, (c) increased oxidation due to tillage and breaking down of soil aggregates, and (d) soil erosion on sloping lands that relocates the SOM-rich topsoil.

Soil erosion is traditionally conceived as a three-step process involving the detachment, transport and deposition of soil particles. Soil erosion by water has a first-order influence on the distribution of SOC within field landscapes by removing SOC from eroding sites, redistributing and depositing along the landscape position[11]. This process derives disequilibrium between SOC content and carbon input at each position of the landscape[12]. Change in SOC stocks at various landscape positions is controlled by the magnitude of two opposing vertical carbon fluxes, SOC formation (atmosphere C–Plant C–Humus) and decomposition. When SOC stocks are at equilibrium state, the fluxes balance and formation gains equal decomposition losses. When erosion/deposition occurs, it directly alters the local SOC stocks by removing (or redistributing) or adding SOC. This lateral SOC flux results in SOC redistribution within field or watershed and change in the spatial distribution of SOC storage. The redistribution of OC in soil largely depends on landscape position. At mid-slope positions where net soil loss may approach zero, the effect of erosion/deposition on SOC stocks, soil quality and crop productivity reflects the impact of down-slope transport of soil material. The environmental impact of soil erosion is now being debated as to whether the process is a source[13–18] or a sink[19–22] for atmospheric C. However, many unanswered questions remain as to whether the rate of replacement of eroded OC through input management is equally distributed in different OC pools, or, if it can only be effective for certain carbon pools reducing the capacity of the sink and its temporal significance[23]. Resolving this issue objectively requires a thorough understanding of mechanisms involving systematic observations with eroded and deposited soil environment. The extent to which this drives a source or sink will be dependent on lateral transport rates, the degree to which soil mineral surfaces are saturated with carbon, and the presence or absence of equilibrium between SOC stocks and inputs.

The development of a relationship between the various pools of SOM and soil erosion is a complex task. Process-based models are helpful for understanding the relationships between soil and SOC losses in specific watersheds, and statistical estimates of accuracy may be established once the models are calibrated. Simulation models play an increasingly important role in the assessment of C pools at different spatial scales as well as in understanding of processes underlying C fluxes in the ecosystems[24]. Models are also essential tools for devising and evaluating management practices intended to balance global C fluxes. Each of the modelling strategies has associated advantages and disadvantages, but these strengths and weaknesses generally complement one another.

Complete spatially explicit modelling of SOC on watershed scale is only possible when both horizontal and vertical fluxes between different land-use systems are modelled at a particular spatial resolution. Site-based estimates do not provide any idea about the horizontal input/output of SOC at any particular location. This creates the need for merging process-based SOC and erosion models[25]. Amongst the currently available SOC models, only CENTURY[26] and Erosion-Productivity Impact Calculator (EPIC)[27] account for erosion. In the former model, erosion is modelled with the universal soil loss equation (USLE). The latter model simulates soil losses with the modified USLE (MUSLE) equation. Both models focus only on the erosion part of the process (i.e. soil loss from point locations) and do not account for transport and deposition processes[28]. It is evident that modelling of the movement of SOC across landscapes has not been effectively realized in any SOC model. This leaves a lot to be desired regarding spatially explicit modelling of SOC over a landscape unit such as a watershed[29,30]. Development and validation of a spatially explicit simulation framework utilizing a suitable process-based hydrological model and a process-based biogeochemical model to study the interaction between runoff, soil erosion, deposition and carbon dynamics on watershed scale, in different agro-ecological regions of India, would immensely help in devising carbon management and credit policies on micro-watershed basis at the national level. It is emphasized that a good understanding of carbon transfer through overland flow and discharge is important for policy decisions and management of soil and carbon loss of a watershed, as it is sensitive to land-use/cover changes[31].

SOM plays a fundamental role in various ecosystem functions under natural as well as managed landscapes. Therefore, monitoring long-term prediction of erosion-induced fate of carbon will help in understanding the direction and extent of change in a landscape. A great deal of work remains to be done to improve our assessments of the role of soil erosion in the landscape scale C cycle. Some areas of particular importance are as follows:

- Whether erosion process favours watershed as (or to be) a sink or a source of atmospheric carbon?
- Can integration of simulation models help better understanding runoff–erosion–carbon flux interaction at watershed scale?
- Can land management be manipulated in favour of watershed as a sink of atmospheric carbon?
- How do soil environment and plant litter quality interact to stabilize organic matter?
- How can we provide a better understanding of C accumulation and turnover in different ecosystems and how will these be affected by climatic and land-use change?

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