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Tracing the source of soil organic matter eroded from temperate forest catchments using carbon and nitrogen isotopes

Emma P. McCorkle [a,*], Asmeret Asefaw Berhe [b,c], Carolyn T. Hunsaker [d], Dale W. Johnson [e], Karis J. McFarlane [f], Marilyn L. Fogel [b,c], Stephen C. Hart [b,c]

[a] Environmental Systems Graduate Group, University of California, Merced, United States
[b] Life & Environmental Sciences, University of California, Merced, United States
[c] Sierra Nevada Research Institute, University of California, Merced, United States
[d] Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, Fresno, CA, United States
[e] Department of Natural Resources and Environmental Science, University of Nevada, Reno, United States
[f] Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, CA, United States

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ABSTRACT

Soil erosion continuously redistributes soil and associated soil organic matter (SOM) on the Earth's surface, with important implications 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). We used natural abundance levels of the stable and radioactive isotopes of C (^{13}C and ^{14}C) and stable isotope of nitrogen (^{15}N) to elucidate the origins of SOM eroded from low-order catchments along the western slopes of the Sierra Nevada of California, USA. Our work was conducted in two relatively undisturbed catchments (low elevation = 1800 m, and high elevation = 2300 m) of the Kings River Experimental Watersheds (KREW) in the Sierra National Forest. Sediment captured in basins at the outlet of each gauged watershed were compared to possible source materials, which included: upland surficial organic horizons (i.e., forest floor) and mineral soils (0–0.6 m) from three landform positions (i.e., crest, backslope, and toeslope), stream bank soils (0–0.6 m), and stream-bed materials (0–0.05 m). We found that most of the organic matter (OM) in the captured sediments was composed of O-horizon material that had high C concentrations. Radiocarbon analyses also showed that the captured OM is composed of modern (post-1950) C, with fraction modern values at or above 1.0. Our results suggest that surface (sheet) erosion, as opposed to channeling through established streams and episodic mass wasting events, is likely the largest source of sediment exported out of these minimally disturbed, headwater catchments. The erosional export of sediment with a high concentration of C, especially in the form of relatively undecomposed litter from the O horizon, suggests that a large fraction of the exported C is likely to be decomposed during or after erosion; hence, it is unlikely that soil erosion acts as a significant net sink for atmospheric CO_2 in these low-order, temperate forest catchments.

1. Introduction

Quantification of the fluxes of carbon (C) within and from terrestrial ecosystems is critical for generating an accurate global C budget and predicting future effects of soil C storage on the Earth's climate system (Falkowski, 2000). Soil is the third largest global C reservoir (>2500 Pg) and contains nearly double the C found in terrestrial living biomass (560 Pg) and the atmosphere (750 Pg) combined (Condron et al., 2010; Dungait et al., 2012; Smith, 2012; Tarnocai et al., 2009). Much of the C held within soil exists as free organic particles, or organic matter (OM) bonded to mineral particles or encapsulated in aggregates (De Baets et al., 2012).

Globally, soil erosion is an important and widespread flux in the C cycle that redistributes on the order of 75 Gt of soil and 1–5 Gt soil organic carbon annually (Battin et al., 2009; Berhe et al., 2007; Regnier et al., 2013; Stallard, 1998). In uplands, erosional transport of topsoil and associated OM can lead to loss of soil organic matter (SOM) through direct removal of soil mass. About 70–90% of the eroded topsoil material is redistributed downhill or downstream, while the rest is exported out of the source watersheds (Doetterl et al., 2016; Gregorich et al., 1998; Lal, 2003; Rumpel et al., 2006). For the material deposited locally, erosion leads to stabilization of at least some of the eroded SOM in depositional landforms through burial, and new and reconfigured associations of the eroded OM with soil minerals (Berhe et al., 2012a; Sharpley, 1985). Soil erosion and subsequent deposition lead to a net global

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* Corresponding author at: Reynolds Creek Critical Zone Observatory, Idaho State University, Pocatello, ID, United States.
E-mail address: mccoemma@isu.edu (E.P. McCorkle).

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terrestrial sink of 0.12–1.5 Gt C yr^{-1}, particularly when their contribution to C storage is assessed at a watershed scale and dynamic replacement of eroded OM by production of new photosynthate is taken into account (Berhe et al., 2008; Berhe et al., 2007; Doetterl et al., 2016; Harden et al., 2008; Harden et al., 1999; Stallard, 1998; Van Oost et al., 2007). Considerable uncertainty, however, still remains as to the fate of the OM that is exported out of eroding catchments.

Lateral distribution of topsoil by erosion can significantly alter the fate of soil C. The amount and composition of SOM found in soil-mantled hillslopes reflect the balance between inputs of OM, mainly from net primary productivity and deposition from erosion upslope, and outputs and transformations of OM by processes including decomposition, leaching, and erosion downslope (Berhe et al., 2007). The composition of SOM transported by erosion can be similar to the SOM in hillslope soil profiles (Bellanger et al., 2004). But, several variables control the rate and nature of soil erosion, including climate (specifically precipitation amount, distribution, and intensity), slope (angle and length), land use, and lithology. All of these variables can impose important controls on the amount and composition of eroded C and its post-erosional transport (Berhe et al., 2014; Kim et al., 2013; Nadeu et al., 2012).

Source pools of SOM from different landform positions can affect the persistence of eroded C post-erosion. For example, soil material eroded from the surficial soil horizons (e.g., O or A horizons) is likely to have a large proportion of relatively undecomposed OM with a high carbon to nitrogen ratio (C:N). Organic horizon material will also be largely freely associated rather than associated with soil minerals, making this SOM relatively easy to decompose and mineralize during transport or after deposition downstream. On the other hand, soil material eroded from deeper soil layers, such as B horizons by gully erosion, is likely to have a low proportion of relatively undecomposed OM, with much of the eroded C associated with soil minerals through aggregation or sorptive interactions. As a result, a higher proportion of the material eroded from deeper soil layers should be stabilized after it has been transported by erosion and deposited downslope, compared to material eroded from surficial soil horizons. Hence, tracing the movement of SOM from eroding landform positions, as well as identification of its ultimate depositional setting within a catchment, are essential for quantifying the fate of laterally transported C on the landscape (Berhe and Kleber, 2013).

Stable isotope analysis is a potentially powerful tool for sourcing eroded SOM in natural and agricultural landscapes. Traditionally, radioactive isotopes are used to estimate the rate of soil erosion (Heimsath et al., 1997; Kim, 2008; Kirchner et al., 2006; Kirchner et al., 2001; Portenga and Bierman, 2011; Riebe et al., 2001) and to infer associated rates of soil C erosion (Klaminder et al., 2009; Yoo et al., 2005). Some radionuclides (i.e., ^{137}Cs, ^{7}Be) are useful tracers for estimating the rate of soil erosion because they bind tightly to soil minerals and are only redistributed when the soil minerals are mobilized vertically or laterally (Alewell et al., 2009; Kim et al., 2013). Soil movement, relative to an undisturbed reference site, can then be estimated by enrichment (i.e., deposition) or depletion (i.e., erosion) of these isotopes in a soil profile. However, short half-lives (e.g., 30 years for ^{137}Cs and 53 days for ^{7}Be) and a lack of reference sites (i.e., sites with no erosion or deposition) make using radionuclides unreliable over time or in some environments. Furthermore, the relatively high cost of radionuclide analyses in soils and sediments limits their broad application across ecosystems (Schaub and Alewell, 2009).

Using the natural abundance of stable isotopes in the environment offers a more consistent and less expensive alternative to radionuclides for tracing pathways of erosion (Meusburger et al., 2013). Stable isotope compositions of C (δ^{13}C) and nitrogen (δ^{15}N) vary significantly among ecosystem pools because of isotopic fractionation during the cycling of C and N (Hogberg, 1997; O'Leary, 1988). Differences in the δ^{13}C and δ^{15}N values of OM pools in upland soils and floodplains have been used to follow the transport of soil materials mobilized by precipitation events in catchments and deposited in accumulated sediments (Bellanger et al., 2004; Fox and Papanicolaou, 2007). In addition, stable isotopes have been used to trace the sources of eroding material occurring on catchment hillslopes (Hilton et al., 2012; Meusburger et al., 2013) and to follow SOM bound to stream gravels (Collins et al., 2013). Radiocarbon (^{14}C) is routinely used to determine turnover and stability of SOM within an ecosystem (Torn et al., 2009; Trumbore, 2009; Trumbore et al., 1996; Trumbore et al., 1989; Wang et al., 1996) because the amount of ^{14}C remaining in SOM reflects the time since the original material last exchanged carbon dioxide (CO_2) with the atmosphere (Trumbore, 2009). The lower the amount of ^{14}C remaining in OM, the longer the material has been present within the soil. In stable landscape positions, SOM generally becomes older with depth, but if erosion leads to deep soil removal from hillslopes and subsequent burial downslope, SOM age can decrease with depth (Berhe et al., 2012a; Torn et al., 2009).

We studied the sources of OM transport by soil erosion, and how these sources varied as a function of elevation (proxy for type of precipitation), in two catchments within the rain-snow transition zone of the Sierra Nevada, California, USA. The higher elevation catchment receives the vast majority of its annual precipitation as snow, while the lower elevation catchment receives approximately half of its precipitation as rain and half as snow. These differences in precipitation type may alter the sources of erosion because snow-dominated catchments generate higher peak stream flows in the spring during snowmelt, while lower elevation catchments have greater potential for rain-on-snow events, possibly leading to the occurrence of overland flow during the winter months (Bales et al., 2006; Hunsaker and Neary, 2012). Furthermore, because these catchments are similar in their other state factors (i.e., parent material, vegetation, topography, and landsurface age), they are an excellent surrogate experimental system for evaluating possible changes in soil erosion processes as the climate warms (Bales et al., 2011; Jenny, 1941).

Rates of sediment yield and the C and N contents of these sediments were characterized previously in these catchments over multiple years by Stacy et al., (2015). They found that sediment yield and C and N concentrations showed high interannual variation. Annual sediment export was positively correlated with stream discharge, while both C and N concentrations were negatively correlated with stream discharge. They speculated that the primary source of the organic materials captured in sediment traps at the outlet of the catchments was OM-rich litter material and topsoil. Stream discharge, more than sediment source, was the primary factor controlling the magnitude of C and N export from these upland forest catchments. In addition, no significant difference in the amount or C and N content of sediment derived from catchments of different elevations was found, suggesting that differences in precipitation type may not be an important driver of sediment yield. The present study builds upon this previous investigation by evaluating if the sources of the SOM found in sediments across contrasting years and catchment elevations are indeed similar, and consist primarily of surficial SOM.

We used stable and radioactive isotopes of SOM to trace the origin of eroded materials within two, low-order montane watersheds of contrasting elevation in the Sierra Nevada. Our objectives were to: 1) evaluate the efficacy of stable isotopes of C and N as erosion tracers, 2) determine the origin of eroded SOM collected in sediment traps at the outlet of each catchment, and 3) infer fate of eroded SOM using ^{14}C at the catchment scale. By applying this approach to two similar, low-order catchments within the rain–snow transition zone, we were able to determine if precipitation type affects the sources of sediment leaving these catchments, and whether it altered the fate of the eroded OM.

2. Methods

2.1. Site description

Field sampling was conducted in the Kings River Experimental Watersheds (KREW) located within the Sierra National Forest of