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# Storage and export of soil carbon and mineral surface area along an erosional gradient in the Sierra Nevada, California

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ABSTRACT

Steep soil-mantled hillslopes are thought to be important sources of sediments and organic carbon (OC) to rivers. Minerals in these sediments may protect OC from decomposition, yet the significance of such interactions in steep upland soils remains poorly constrained particularly in relation to erosion rates. We examined a tributary basin draining to the Middle Folk Feather River in California, where knickpoint migration has created a series of hillslopes with erosion rates varying over an order of magnitude (35 to 250 mm $kyr^{-1}$). This setting provides a unique opportunity to study soil OC pools and their erosional exports as a function of changes in erosion rates. Soil OC inventories were 37% lower at rapidly eroding sites relative to slowly eroding sites. This difference was driven by coarse rock contents as rapidly eroding soils had more rock fragments, limiting their capacities to store OC. Although clay contents in soils were negatively correlated with erosion rates, the total mineral specific surface area remained relatively invariant. Based on secondary phyllosilicate minerals present in the studied soils and our field observations of saprocks, we suggest that this discrepancy may have originated from different clay mineralogy (types and abundance) associated with different degrees of deep subsurface chemical weathering. Across the erosion gradient, the radiocarbon age of mineral associated organic matter (MOC) in saprock varied by a factor 2 (from 1045 to 2110 $^{14}C$ years), while soil turnover times estimated from soil thickness and erosion rates varied from 17 to 5.4 kyr. At the site eroding at the fastest rate, the soil turnover time approaches the $^{14}C$ age of MOC, suggesting erosion can potentially limit the timescale over which MOC is replaced. We found that organic matter generally covered < 50% of the total mineral surface. The remaining OC-free mineral surface area, once eroded, may thus have a significant, and to date unquantified, capacity to adsorb additional organic matter, which may act as a long-term atmospheric carbon sink.

## 1. Introduction

Riverine export of organic carbon from steep upland landscapes has drawn significant attention due to its critical role in connecting the terrestrial and oceanic carbon cycles (Galy et al., 2015; Hilton et al., 2008). Many previous studies have highlighted the role of minerals in protecting OC from decomposition during the transit of sediments via fluvial networks to their ultimate burial in oceanic depocenters (Aufdenkampe et al., 2011; Keil, 2017; Kennedy and Wagner, 2011; Mayer, 1994). Despite this attention, mineral-associated carbon is seldom examined in source areas in eroding, upland mountain landscapes. While much of our understanding of soil OC and its response to mineral interactions is derived from studies of upland soils (Torn et al., 1997; Kleber et al., 2015), the effect of topography or erosion are not central to these studies. More complex environmental controls over OC-mineral interactions are beginning to emerge (Kramer and Chadwick, 2016), but studies examining erosion of soil OC are constrained to single hillslope transects (e.g., Doetterl et al., 2016). Consequently, the impact of spatial or temporal changes in erosion rates on soil OC with respect to mineral interactions remains unaddressed. Additionally, applications of conceptual (Davidson and Janssens, 2006) and numerical models (Carvalhais et al., 2014) in which biological carbon input and decomposition control the soil OC inventory and pools are problematic in steep landscapes because the biophysical disturbance of soil particles and the supply of fresh minerals from underlying parent material (Mudd and Yoo, 2010; Roering et al., 2010; Vanwalleghem et al., 2013)

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may affect mineral–OC interactions and thus outweigh the biological processes.

Many soil toposequence studies and soil surveys address the significance of erosional processes in controlling the pattern and pace of landscape evolution but also in regulating various physical and biogeochemical soil properties (Rasmussen et al., 2017; Minasny and McBratney, 2016; Yoo and Jelinski, 2016). Erosion modulates ecosystem functions such as vegetation biomass productivity and spatial patterns and influences soil biogeochemical cycles over long time scales (Milodowski et al., 2015a; Chadwick and Asner, 2016). Furthermore, erosion rates are strongly linked to the residence time of minerals in the weathering zone (Almond et al., 2007; Mudd and Yoo, 2010; Riebe et al., 2015). In rapidly eroding landscapes, minerals spend less time in the soil than minerals in slowly eroding landscapes, thus their exposure to weathering and the potential for the formation of secondary clay and pedogenic iron (Fe) oxides may be limited (Mudd and Yoo, 2010). This has an important implication for the carbon cycle because organic matter is considered better protected from microbial decomposition when associated with secondary clay and iron oxide minerals (Kaiser and Guggenberger, 2003; Kleber et al., 2015; Kögel-Knabner et al., 2008). Sorption to mineral surfaces generally reduces the susceptibility and bioavailability of organic matter to microbial decomposition and oxidative attack (Eusterhues et al., 2005; Kaiser and Guggenberger, 2003; Mikutta and Kaiser, 2011). Therefore, erosion rates may significantly affect the sorption of plant-derived organic matter on mineral surfaces. To date, however, there are few direct observational constraints on the quantitative and mechanistic coupling between the carbon (C) cycle, chemical weathering, and erosion in steep upland landscapes.

Our goal is to quantify the effect of varying erosion rates on soil carbon inventories, carbon-mineral sorption, and erosional export of mineral-sorbed OC and OC-free mineral surface in a steep, soil-mantled, forested landscape. We examine a series of hillslopes within a tributary basin in the Middle Fork Feather River (MFFR) in California, USA (Fig. 1) where hillslopes are covered with soils but erosion rates differ sharply, by an order of magnitude (35 to 250 mm $kyr^{-1}$) (Attal et al., 2015; Hurst et al., 2012). The study sites are located in close proximity to ensure minimal differences in their bedrock compositions, climate, and vegetation. Erosion rate thus largely controls the variability found in the physical and chemical properties of the soils at the sites. Taking advantage of the erosional gradient within the tributary basin, we attempt to test three hypotheses: (1) soils become thinner and rockier with increasing erosion rate and thus their capacities to store OC become smaller, (2) the mineral surface area to sorb OC becomes smaller with increasing erosion rate due to decreasing clay and pedogenic iron oxides contents, and (3) the erosional export of OC-free mineral surface area decreases with increasing erosion rates because of coarser soil texture.

## 2. Materials and methods

### *2.1. Study sites and sampling*

Our study site is within the lower reaches of the MFFR within the Plumas National Forest in the northern Sierra Nevada (Fig. 1). In this region, the topography of the Sierra Nevada consists of a high-elevation, low-relief surface dissected by deep canyons. The area remained largely unglaciated during the Pleistocene (Wahrhaftig and Birman, 1965; Clark, 1995). The mean annual temperature and precipitation are 12.5 °C and ~1750 mm, respectively (http://www.prismclimate.org). The site is covered with mixed-conifer forests that are protected as a part of National Wild and Scenic River System. The forest is dominated by *Pseudotsuga menziesii; Pinus ponderosa*, *Calocedrus decurrens*, *Pinus lambertiana*, and *Quercus kelloggii* (Milodowski et al., 2015a). According to the scientists at Plumas National Forest Service, the site's steep hillslopes precluded logging activity at least during the last century. This personal communication agrees with numerous sugar pines at the site whose trunk diameters imply ages of over one hundred years. Forest fires are common, particularly during extended dry summer months (Stephens and Collins, 2004), and the canopy at one of our sites (POMD in Fig. 1) was damaged during the Canyon Complex Fires of June–July 2008. Sampling locations are all within the Bald Rock (BR)

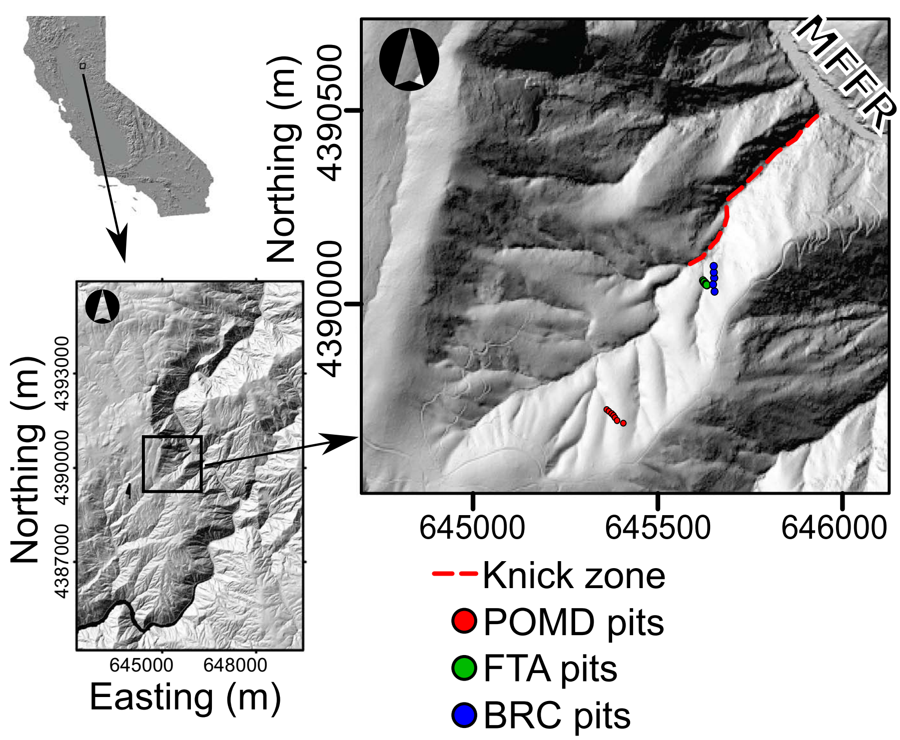


**Fig. 1.** Location of the study site and excavated soil pits (POMD, FTA, and BRC) in the Northern Sierra Nevada, California, USA. The coordinate system is WGS84 UTM zone 10 N.

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