Geoderma 333 (2019) 135–144

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

The generation and redistribution of soil cations in high elevation catenas in the Fraser Experimental Forest, Colorado, U.S.

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ARTICLE INFO

Handling Editor: M. Vepraskas

Keywords:
Soil catena
Soil calcium
Strontium isotopes
Atmospheric deposition
Weathering

ABSTRACT

Pedogenic processes imprint their signature on soils over the course of thousands to millions of years in most soil systems. Variation in soil forming processes – such as parent material weathering, organic material additions, hydrologic processes, and atmospheric additions – account for the distribution and sourcing of cations in ecosystems, and hence exert a strong influence on ecosystem productivity. Soil nutrient dynamics of cations also provide an indication of the dominant soil forming processes at work in a particular system. To gain insight into the generation and distribution of the soil cation pool in the Fraser Experimental Forest (FEF), we combined geochemical mass balance techniques and isotopic analyses of soil geochemical data to pedons across eight soil catenas in complex mountain terrain typical of the central Rocky Mountains. We found that mass gains in the FEF soils are primarily attributable to pedogenic additions of Ca to the soil mantle via atmospheric dust, and specifically that soil catenas on the summit landscapes were most enriched in Ca. Our data also show that atmospheric deposition contributions (calculated using Sr isotope ratios) to soils is as high as 82% (± 3% SD), and that this isotopic signature in A-horizons and subsurface soil horizons diverges along a soil *catena*, due to both vertical and lateral hydrologic redistribution processes. Our results suggest that long term soil development and associated chemical signatures at the FEF are principally driven by the coupling of landscape scale cation supply processes, snow distribution, and snowmelt dynamics. Soil development models describing pedogenesis across catenas in montane ecosystems must pay special attention to atmospheric inputs and their redistribution. Any changes to these dynamics will affect productivity and soil/water chemistry in such ecosystems as investigated here.

1. Introduction

Two major sources of base cations exist in terrestrial ecosystems—cations derived from parent materials (usually bedrock) and cations added via both wet and dry atmospheric deposition (i.e. dust). In terrestrial ecosystems, bedrock weathering is an important process whereby essential plant nutrients like Ca^{2+} become biogeochemically available (Johnson et al., 1968; Walker and Syers, 1976). However, local weathering inputs alone may be inadequate to maintain soil fertility without the addition of exogenous cations (Capo and Chadwick, 1999; Zaccherio and Finzi, 2007). Indeed, long term additions of atmospherically-derived dust provide a key geochemical input for various terrestrial ecosystems (Stoorvogel et al., 1997; Capo and Chadwick, 1999; Okin et al., 2004). While an important factor in pedogenesis (Simonson, 1995; Porder et al., 2007; Lawrence et al., 2013), the incorporation of dust into soil systems is dynamic and poorly quantified. Herein, we examine the important contribution that dust inputs have on soils across the mountainous catenary sequences and disparate geomorphic surfaces of Fraser Experimental Forest (FEF).

Atmospheric dust has been found to contribute to soil nutrient pools in mountain ecosystems of the West and specifically, Colorado (Clow et al., 1997; Mladenov et al., 2012; Lawrence et al., 2013; Brahney et al., 2014). Dust may become trapped under conditions promoting surface roughness like in vegetated areas and in soil crusts which, exert a pronounced influence on the concentrations of Ca, Na, K, and N at and near the soil surface (Reynolds et al., 2001; Blank et al., 1999). Dust

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https://doi.org/10.1016/j.geoderma.2018.07.024
Received 7 September 2017; Received in revised form 16 July 2018; Accepted 18 July 2018
Available online 21 July 2018
0016-7061/

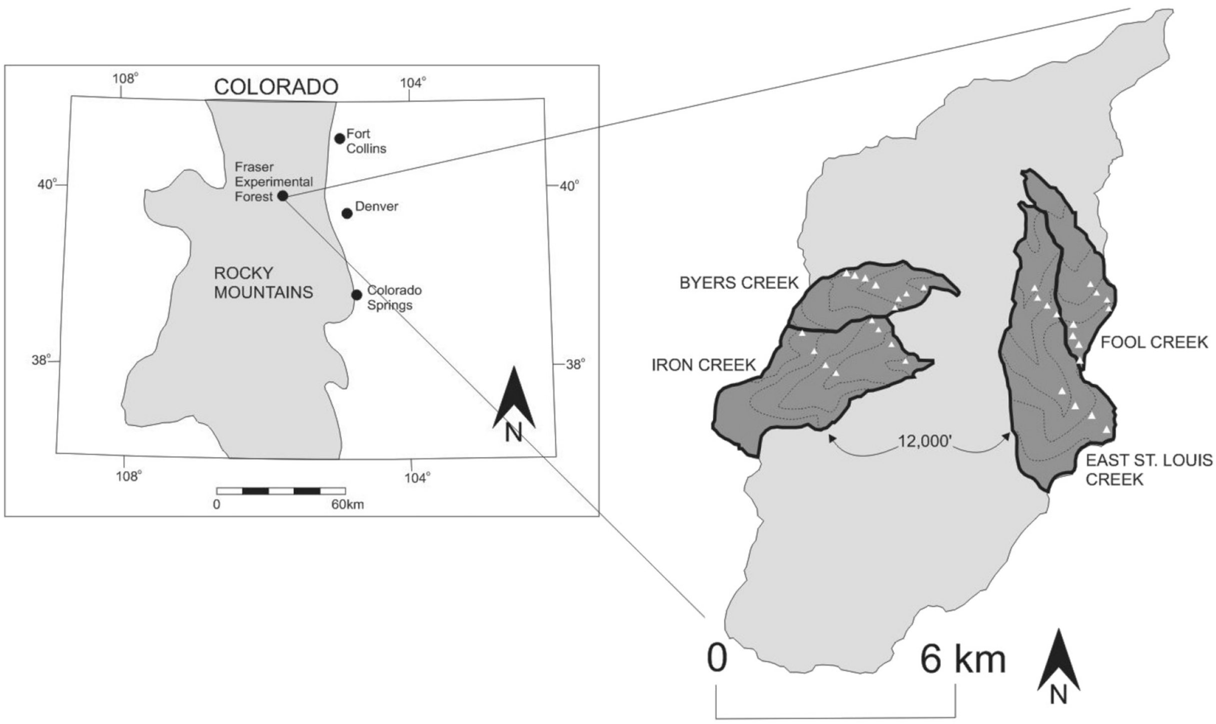

Fig. 1. The location of the Fraser Experimental Forest, Colorado. Soils were sampled along eight catenas in four catchments (dark gray) within the larger St. Louis Creek catchment (light gray). Sample points along the catenas are indicated by white triangles. Contour lines for elevation (countour interval = 500′) are represented by hachured lines; the highest contour line shown (12,000′) is labeled, for reference.

derived Ca, in particular, may regulate ecosystem function as soil Ca acts as a buffer to acid precipitation and surface waters, plays a main role in the base saturation of soils, and is an essential plant nutrient, exerting an important influence on the health of forest ecosystems (Richter et al., 1994; Schmitt and Stille, 2005; Groffman and Fisk, 2011). Human activities directly and indirectly impact dust production and, hence its potential influence in soil chemistry. It has been recognized for decades that drought conditions, in combination with agriculture and other land uses, markedly increase soil erosion and substantially contribute to airborne dust production (Middleton, 1985; Tegen et al., 1996). For instance, overgrazing by livestock has been shown to be a significant contributor to soil erosion and dust production (Niu et al., 2011; Su et al., 2005). Soil loss and production of airborne dust is also exacerbated by off-highway vehicles traveling on unpaved roads and trails (Padgett et al., 2008). It has also been suggested that wildfire may contribute to airborne dust production through the increase of wind erosion (Balfour et al., 2014; Santin et al., 2015).

Constituent mass balance techniques have been used to quantify soil weathering in a variety of ecosystems (Bern et al., 2011; Porder et al., 2007; Anderson et al., 2002) and the application of the constituent mass balance model allows for the identification of pedogenic gains that may indicate dust inputs (Chadwick et al., 1990; Egli et al., 2000). This approach has been used traditionally to quantify soil development by estimating soil strain, volumetric gains or losses within a pedon (Brimhall et al., 1992). Recently, supplemental analytical techniques, such as the utilization of XRD and application of Sr isotopes have been combined with the mass balance approach to quantify soil weathering (Bern et al., 2011; Porder et al., 2007; Anderson et al., 2002).

Strontium (Sr) isotope ratios are regularly employed to determine the relative contribution of soil nutrients from differing weathering pools in ecosystems, including the importance of atmospheric processes (dust) in soil across a variety of ecosystems (Capo and Chadwick, 1999; Blum et al., 2002; Drouet et al., 2005; Chadwick et al., 2009; Reynolds et al., 2012). In studies based in arid climatic zones, where rates of soil development are strongly controlled by eolian dust (Gile et al., 1966; Gile, 1979; Chadwick and Davis, 1990; McFadden et al., 1991), Sr isotopes were used to determine the provenance of Sr, and therefore Ca, available in the soil environment (Grausetin and Armstrong, 1983; Capo et al., 1995). Strontium is a powerful isotopic tracer in terrestrial ecosystems and is frequently used as a proxy for Ca, due to their chemical similarity (Dasch, 1969; Brass, 1975). Numerous studies have demonstrated the potential of using stable Sr isotopes in quantifying atmospheric deposition in ecosystems (Grausetin and Armstrong, 1983; Aberg et al., 1989; Gosz and Moore, 1989; Graustein, 1989), weathering and chemical processes in soil environments (Miller et al., 1993), and paleoenvironmental applications (Quade et al., 1995; Capo et al., 1995). Use of isotopic tracers has shown that some terrestrial ecosystems rely more on soil cations received from atmospheric deposition than from bedrock weathering (Drouet et al., 2005; Vitousek et al., 1999; Lawrence et al., 2013).

To date, dust studies have been confined to alpine ecosystems, or to multiple, unconnected sites within various landscapes (Capo and Chadwick, 1999; Reynolds et al., 2006; Lawrence et al., 2010, 2013). The work presented here builds on these previous alpine studies and follows prior investigations conducted at the FEF that document the occurrence of dust deposition events (Retzer, 1962; Rhoades et al., 2010); importantly, dust's overall impact on soil functions at the FEF remains undetermined. As in many other studies, Sr isotopic techniques will be employed, though our innovation is using Sr isotopes to characterize the contributions of dust to soil chemistry along soil *catenas*.

The goals of this research were to 1) determine whether landscape position along catenas imparts a control on the distribution and sourcing of soil cations in the FEF and 2) evaluate the contribution of atmospherically-derived Ca to the soil cation pool in FEF soils. We focus on soil Ca here because of its chief role in ecosystem function. There is also recent interest in the effects of changing forest harvest practices on soil Ca stocks (Brandtbert and Olsson, 2012; Zetterberg et al., 2016). To our knowledge, this is the first study to offer a comparison between dust and weathering additions along a topographic continuum, and to describe how they contribute to pedogenesis along a soil catena. Mass