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Weathering of rock to regolith: The activity of deep roots in bedrock fractures

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ABSTRACT

Many areas in the world are characterized by shallow soils underlain by weathered bedrock, but root-rock interactions and their implications for regolith weathering are poorly understood. To test the role of tree roots in weathering bedrock, we excavated four pits along a *catena* in a shale-dominated catchment at the Susquehanna Shale Hills Critical Zone Observatory (SSHCZO) in central Pennsylvania. We measured a variety of biological, physical, and chemical properties including: 1) root density, distribution, and respiration, 2) soil gas, and 3) elemental compositions, mineralogy, and morphology of soil, rock, and rock fracture fill at ridge top, mid-slope, toe-slope, and valley floor sites. As expected, root density declined rapidly with depth; nevertheless, fine roots were present in rock fractures even in the deepest, least weathered shale sampled (~180 cm below the land surface). Root densities in shale fractures were comparable between the ridge top and mid-slope pits. However, they were significantly lower in the toe-slope, despite increasing rock fracture densities, which is likely due to a shallower water table depth at the downslope site. Average root respiration (per mass of dry root tissue) in rock fractures was comparable to rates in the soil. Thus, the total flux of CO_2 from root respiration tracked root densities, decreasing with depth. Potential microbial respiration, estimated as the laboratory C mineralization potential, was about an order of magnitude lower than measured root respiration in both the soil and shale fractures. Roots were only observed in large aperture (>50 μm) shale fractures that were filled with particulate material. The fill in these fractures was mineralogically and geochemically similar to the lowest soil horizons with respect to clay composition, element mobility, extractable dissolved organic C (DOC), inorganic N-species, and potentially mineralizable C and N, while total C and total N values for the fracture fill were similar to the shale bedrock. In the bulk soil, depletion profiles (Al, Fe, K, Mg, and Si) relative to unweathered shale reflected characteristic weathering of illite and vermiculized chlorite to kaolinite and are similar between soils and fracture fill. Such similarities indicate that the fracture coatings are likely the result of pedogenic processes that occur at depth in the fractures rather than translocation of soil particles downward into the fractures. Overall, our data suggest that roots and fill in shale fractures down to ~180 cm are qualitatively similar to those in surface soil horizons. Thus, the deepest manifestation of the chemical depletion profiles observed in the pits consists of the rock fracture fill, and this fill is present at low concentrations with similarly low concentrations of fine roots.

1. Introduction

Plants play a key role in weathering regolith in the critical zone, but this role varies as a function of water use, rooting depth and distribution, and associated mycorrhizal fungi (Reneau and Dietrich, 1991; Van Breemen et al., 2000; Balogh-Brunstad et al., 2008; Fimmen et al., 2008; Graham et al., 2010; Schulz et al., 2016). Of particular importance are the mineral weathering reactions that consume CO_2 and organic acids produced by plant roots and soil microorganisms (Leake et al., 2008; Ahmed and Holmström, 2015). Such weathering processes exert important controls on global C cycling and climate change over geological timescales. Interactions between physical, chemical, and biological processes transform bedrock into soil and provide inorganic nutrients to terrestrial biota. When bedrock is physically and chemically weathered, it enhances rock porosity, which is crucial for changing

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biologically inert rock into materials from which plants and microorganisms can extract water and nutrients (Brantley, 2010; Wald et al., 2013). For example, as early as the 1800s, Jackson (1840) found that the expansion of biotite due to oxidation may further enhance fracture propagation and the degradation of rock to regolith. Plant roots can also promote these chemical and physical weathering processes and alter the morphology of the bedrock (Graham et al., 1994; Frazier and Graham, 2000; Schenk and Jackson, 2005; Graham et al., 2010).

The weathering potential of tree roots depends, in part, on rooting depth. Rooting depth is a direct function of climate, particularly annual precipitation and potential evapotranspiration (Schenk and Jackson, 2002a, 2002b), species (Gale and Grigal, 1987), soil thickness (Stone and Kalisz, 1991; Anderson et al., 1995; Sternberg et al., 1996; Hubbert et al., 2001a, 2001b; Witty et al., 2003; Bornyasz et al., 2005; Graham et al., 2010), inherent and dynamic soil properties (Kochenderfer, 1973; Nicoll et al., 2006), and bedrock properties (Witty et al., 2003). Plant roots are predominantly located in the upper portions of the soil profile, and Schenk and Jackson (2005) found that on a global scale around half of all roots are located in the top 30 cm of soil and 95% are in the top 2 m. Vertical rooting depth is generally assumed to be limited in shallow soils because root growth is restricted by the solid bedrock below, and thus most studies of root dynamics are confined to the uppermost soil horizons. Nevertheless, many landscapes are characterized by shallow soils that are underlain by actively weathering bedrock containing fractures that can allow soil, gases, water, and roots to move downward. Roots have been observed to penetrate many meters into bedrock along joints and fracture planes, particularly in upland areas (Hellmers et al., 1955; Scholl, 1976; Stone and Kalisz, 1991; Anderson et al., 1995; Canadell and Zedler, 1995; Jackson et al., 1999; Hubbert et al., 2001a, 2001b; Egerton-Warburton et al., 2003; Rose et al., 2003; Witty et al., 2003; Bornyasz et al., 2005; Graham et al., 2010; Estrada-Medina et al., 2013). Despite the common observance of roots in rock fractures, rarely has the rooting environment within fractures been explored, partially due to the difficulties and expense of excavating solid rock (Maeght et al., 2013).

Studies of the distribution of deep roots in rocks are largely restricted to arid and drought-prone environments where deep roots allow woody vegetation to access water from below the soil in weathered bedrock reserves (Lewis and Burgy, 1964; Zwieniecki and Newton, 1995; Hubbert et al., 2001a, 2001b; Egerton-Warburton et al., 2003; Rose et al., 2003; Witty et al., 2003; Bornyasz et al., 2005; Schenk, 2008; Duniway et al., 2010; Graham et al., 2010; Schwinning, 2010). The majority of these studies focus on the water-holding capacity of weathered rocks, but they rarely address the physical and biogeochemical dynamics of this environment. Moreover, in temperate regions with higher rainfall, trees do not experience the same water limitations as arid environments. Indeed, Gaines et al. (2015) found that the isotopic signature of stem water in a central Pennsylvania forest showed that trees mainly obtained their water from the upper soil horizons. Thus, the advantages of deep roots in humid environments are less clear. Additionally, studies of deeply rooted systems have investigated only a few lithologies including limestone (Hasselquist et al., 2010; Estrada-Medina et al., 2013) and granite (Hubbert et al., 2001a, 2001b; Witty et al., 2003; Bornyasz et al., 2005; Graham et al., 2010; Poot et al., 2012).

We tested environment of deep roots in rock fractures as well as the role of deep roots in weathering bedrock. In detail, we investigated the abundance and activity of roots in shale bedrock fractures, characterized the growing environment of the roots within the fractures by examining the adjacent materials and porefluid chemistry, and assessed the potential of roots in rock fractures to promote rock weathering along a *catena* in a forested catchment in the northern Appalachian Mountains (i.e., a catchment close to the Shale Hills experimental watershed in the Susquehanna Shale Hills Critical Zone Observatory; SSHCZO) where the climate is temperate and humid. Assessing the role of deep roots in rock will lead to a better understanding of controls on rooting depth and hillslope regolith development.

2. Material and methods

2.1. Site description

Our study area, Missed Grouse Gulch, is a temperate, forested watershed located in the Appalachian Valley and Ridge Province of central Pennsylvania. The site is just two valleys (~0.25 km) north of the Shale Hills experimental watershed in the SSHCZO (Fig. 1). We selected the Missed Grouse Gulch site to study deep root activity because it features lithology, soils, and vegetation similar to the well-studied Shale Hills catchment and is easily accessed by excavation equipment. We could not excavate at Shale Hills due to the risk of disturbing ongoing experiments. Furthermore, the Missed Grouse Gulch watershed is immediately next to three en echelon catchments (including Shale Hills) that have been previously studied and shown to have identical geology and geomorphological evolution (West et al., 2014). The Missed Grouse Gulch watershed is 48 ha, with a valley and perennial stream that roughly align east-west near the outlet and northeast-southwest near the headwaters. The mean annual air temperature is 10 °C, but varies between a minimum of −28 °C and maximum of 39 °C, while annual precipitation is 99 cm, with the highest rainfall months occurring in the spring (period of record is 1931–2015; NOAA, 2016). The Missed Grouse Gulch catchment is covered by mostly deciduous trees including oaks (*Quercus* spp.), maples (*Acer* spp.), and hickories (*Carya* spp.), while conifers are less abundant and include Eastern hemlocks (*Tsuga canadensis*) and pines (*Pinus* spp.). The excavated *catena* lies along a north (i.e., south-facing) planar hillslope that is convex-upward near the ridge and concave-upward near the valley floor. The *catena* is defined as "planar" following Jin et al. (2010) because it does not experience convergent flow of water and sediments; rather, the flow is strictly vertical (one-dimensional) or directly downslope (two-dimensional).

The entire basin is underlain by Silurian Rose Hill Formation shale (Berg et al., 1980), which consists of quartz, illite, chlorite, "vermiculitized" chlorite (i.e., chlorite interlayered with vermiculite), Fe-oxides, minor feldspar, and, at depth, variable amounts of Fe-Mn-Ca carbonates (Jin et al., 2010; Brantley et al., 2013; Sullivan et al., 2016). We follow Jin et al. (2010) and use "chlorite" to refer to true chlorite, vermiculitized chlorite, and hydroxy-interlayered vermiculite. Important geochemical reactions involved in weathering shale to soil

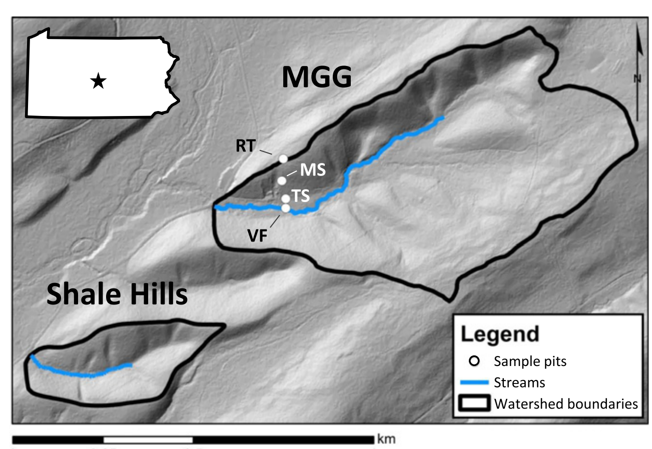

Fig. 1. The Missed Grouse Gulch (MGG) watershed is located ~ 0.25 km north of the Shale Hills watershed in the SSHCZO. Both feature similar vegetation and are developed almost entirely on Silurian Rose Hill Formation shale. Pits were excavated along a north planar slope *catena* that included sites at the ridge top (RT), mid-slope (MS), toe-slope (TS), and valley floor (VF).