Earth, wind and water – trees as agents of progressive rock failure

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1. Introduction

Geomorphology and Critical Zone science are predicated on understanding how the intersection of tectonics, rock properties, climate, and associated ecosystems shape both process and form. The conversion of fresh bedrock into weathered, intact rock and- subsequently - into detached and thus mobile material that can be transported downhill and into rivers underpins the entire conceptual framework defining the physical structure of the Critical Zone (CZ), the life-supporting zone extending from where bedrock weathering begins to where vegetation intersects the troposphere. In turn, rock weathering- through its production of porosity in rock and soil - drives or limits a vast range of CZ processes, including those related to ecosystem structure, carbon storage, chemical weathering, water availability, the pace of erosion, and thus landscape evolution.

While over short timescales trees are often seen as soil stabilizers (Schmidt et al. 2011), over longer timescales, trees have the potential to damage and detach bedrock in thin soil settings, as evidenced by fresh rock observed in the roots of overturned trees (Lutz 1960; Pawlik, Phillips, and Šamonil 2016). In moderately to fast eroding forested landscapes, we have the expectation that tree roots define the boundary between mobile weathered material (soil) and the immobile weathered rock below (Brantley et al. 2017; Roering et al. 2010) In other words, forests and the type of landscape they insert themselves into are predicted to control the rates of bedrock to soil production, and thus the thickness of the soil. Conversely the rate of soil production dictates landscape type, be it rocky or thickly mantled in nutrient-rich soil, and thus controls forest structure and ecosystem function (Figure 1). Yet there is no true mechanistic way of predicting this tree-driven cracking process, despite the importance of understanding the particulars in terms of how rock weathers, develops porosity, and disaggregates into fragments that form the mineral component of soils.

While charismatic tree throw and expansive root-growth forces are often invoked as the physical mechanisms by which trees pry apart solid rock (Gabet & Mudd 2010; Pawlik et al. 2016), there are few data supporting or disproving these popular mechanisms as dominating - or even necessary - for the conversion of rock into soil. By combining novel force sensors at the tree-rock boundary with precipitation, solar radiation, wind, tree sway data, and acoustic emission sensors we have begun to quantify tree-driven soil-production mechanisms at Observatories with diverse forest types and climate conditions. **Our preliminary data suggests that trees exert subcritical stresses on rock due to daily root-water uptake, rain-driven root-swelling, and wind events. As such, we believe that the magnitude of these stresses is sufficient to turn rock into soil.**

2. The wind in the trees

Comparing data from four different tree species we find **that tree properties (controlled by climate, substrate attributes, and anthropogenic forest management) all likely influence the frequency and magnitude of wind-driven stresses and thus cracking in tree-hosting rock.** Massive, tall (> 60 m), stiff trees (e.g., Douglas fir, *Pseudotsuga menziesii*) with spatially constrained canopies (analogous to a lollipop), exhibit beam-like behavior when wind gusts are high enough (rare events). In contrast, we observe that slender trees with greater elasticity, less mass, and broad branch structures (e.g., tanoaks - *Lithocarpus densiflorus*) self-dampen (James, Haritos, and Ades 2006; Jackson et al. 2021) such that only the onset of a wind event transmits energy to the bounding rock. Intriguingly, these bendy trees _perhaps_ exhibit thigmomorphogenesis (an alteration of growth patterns in response to physical disturbances) in response to daily thermally derived winds, as our small data set shows a cessation of tree movement at the trunk base corresponding with the late morning onset of winds driven by windshed temperature differences between the stream valley bottom and the adjoining ridgetop where our instrumented tree resides. If true, this suggests that for certain tree species, daily winds may have little to no impact on tree-driven rock cracking. While our two other comparison tree species, Ponderosa pine (*Pinus ponderosa)* and Pacific madrone (*Arbutus menziesii*) have distinctly different canopy structures, with the pine having a classic triangular canopy extending low to the ground and the heliotropic broadleaf evergreen species discernible by an almost Seussian appearance, with single or multiple curved trunks topped by a large spreading crown with markedly asymmetrical limb structure. Yet the two tree species exhibit remarkably similar response to the wind at the tree-bedrock boundary, with each moving on and off the bounding rock in concert with the wind at windspeeds speeds as low as 2 m/s. Our results are generally, but not fully, consistent with previous tree sway studies, which found that a cantilever beam model describes conifer response to wind loading while broadleaf tree motion is best described by a simple pendulum model (Jackson et al. 2021). Our results suggests that that wood stiffness more than canopy structure may be the ultimate determinant of whether wind energy is translated to belowground forces on the near surface rock fractures into which trees insert themselves.

3. The water in the trees

Multiple sap-flow studies have documented diurnal fluid fluxes in trees. Our data shows a synchronous correlation with tree roots increasing the pressure on rock in the evening (as they take in water) and decreasing the pressure during the day - tightly correlated to the daily variations in sunlight. At one site, measured nocturnal root forces of ~ 0.02 kN on a 5 cm Douglas fir root were ~ 10% of the enfolding sandstone's tensile strength, the threshold believed to be **sufficient for subcritical cracking.** In subsequent experiments based on this data, we designed a physical model where we 'tapped' sandstone collected from rock outcrops surrounding our instrumented tree 10^4 times (modeling water uptake over the lifespan of a Douglas fir) using a controller-driven load cell to replicate forces simi-lar to those measured in the field. Samples were scanned pre- and post-loading in a microCT scanner in order to image at sub-mm resolution the void volume and micro-crack network. Results suggest an order of magnitude increase in the volume of void space (from 0.00025 ± 0.0004 mm^3 pre-loading to 0.0014 ± 0.003 mm^3, mean ± std. dev.). We see similar results with using a helium pycnometer and density analyzer on another sample set from the same physical experiments, with specific pore volume increasing from 0.0012 cm^3/g in unloaded sample compared to 0.012 cm^3/g in adjacent post-loading samples with an increase in porosity from 0.345 % to 3.087% **suggesting these minor loads imposed by root swelling due to ubiquitous water uptake have the potential to increase weathering susceptibility in significant ways.**

In water-limited settings, trees depend on rock water to sustain plant transpiration and growth during extensive periods of no rainfall (Witty et al. 2003; Rempe & Dietrich 2018). Some of these tree species- but not all- are known to redistribute water via deep (rock) water uptake and its subsequent release into shallower layers. **Thus, changes in species, water availability and tree structure, driven by variations in rock properties, anthropogenic forest conversions and cli-mate, may determine the suite of stressors that trees bring to physical rock weathering.**

4. Singing their own song – trees, rock, and the potential to amplify and uniquely convert rock into rolling stones

To discern if trees amplified and/or uniquely contributed to abiotic and biotic stressors generating subcritical cracking in a natural setting we instrumented adjacent tree-free and tree-hosting quartzite outcrops with an array of sensors comprised of force sensors, thermocouples, AE sensors, leaf wetness indicators and deployed a met station at our intensely instru-mented sites. We collected a week of pilot data before the well-used acoustic emission datalogger (circa 2007) failed. We observed two cracking clusters. Cracking Cluster #1 corresponds with a sudden change in temperature at mid-day brought on by weather - and an increase in forces in all the fractures- irrespective of whether the crack was 'empty' or fully occupied by roots. Thus, the concatenation of stress conditions for this cluster were markedly similar to previous observations (Eppes et al. 2016). In contrast, Cluster #2 only showed cracking in the tree-hosting rock, with no cracking recorded in the tree-free rock. Not only was the AE temporal pattern different (only two single minutes of ~ 1200 cracking events recorded), but there was no discernable increase in forces (e.g., wind gusts or a rapid change in relative humidity). Rather the cracking event corresponded with a steep decrease in root-driven forces as the root 'pulled away' from the rock in concert with the steep fluid flux gradient created by the onset of daily shortwave radiation. Additionally, in both clusters, the number of 'hits' recorded by individual sensors was significantly higher in the tree-free vs. the tree-hosting rock. This suggests that tree-driven subcritical cracking - or generally cracking from different stress sources - may have distinct AE signatures, and tree- vs. tree-free rocks may have different cracking characteristics, overall. Importantly this very small dataset, the first of its kind, suggests that in fast eroding forested settings, where sediment transport paces the rate at which fresh rock transits upward into the near-surface weathering zone, tree-driven rock cracking may proceed at a faster rate than slower eroding landscapes, even if the soil thickness is similar. **This has important implications for modeling CZ architecture and solute fluxes through time.**

5. Thinking (sub)critically about progressive tree-driven rock failure

Our results suggest that trees damage and detach rock due to even 'minor' water and wind driven forces, while charismatic tree throw may matter less than belowground damage. We are only beginning to explore the role of tree-driven subcritical cracking in shaping our earth and future collaborations among ecohydrologists, microbial ecologists, rock physicists, geo-chemists, geophysicists, integrative biologists etc. are imperative to understand rock evolution from the grain to landscape scale.

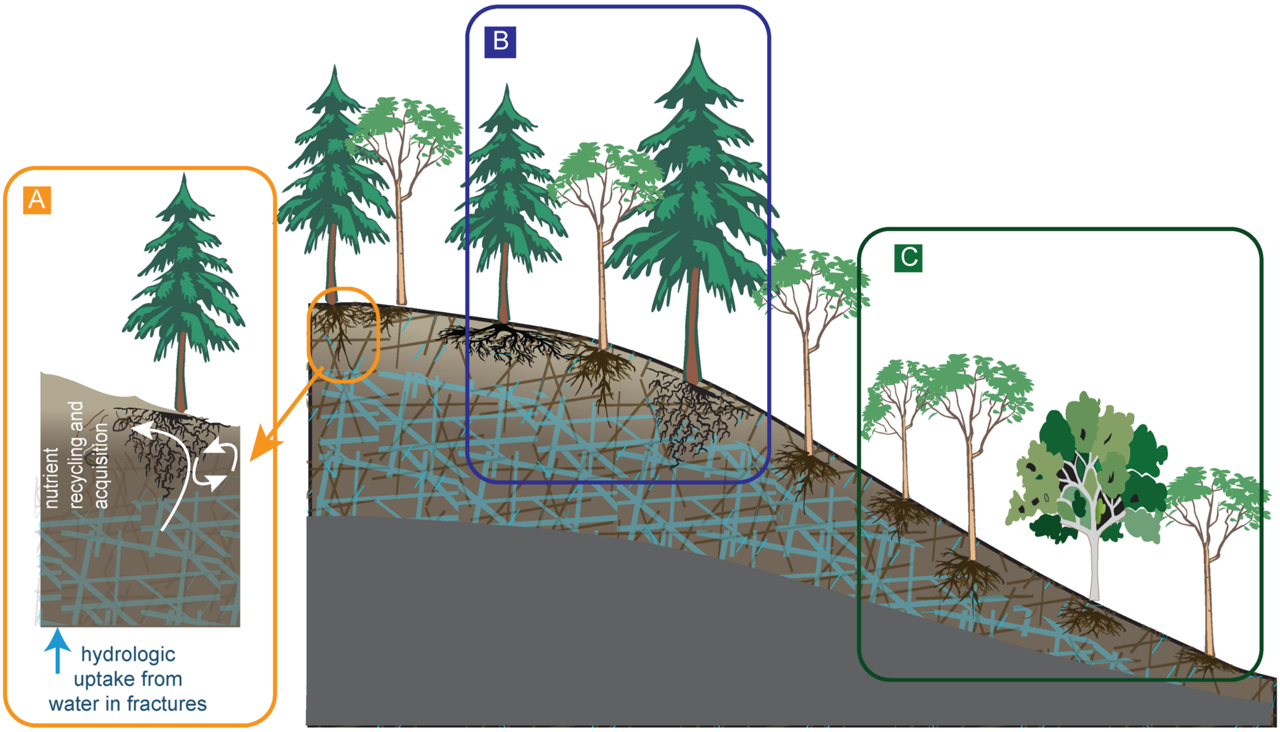

Figure 1. Conceptual model of tree-driven soil production mechanisms via subcritical cracking as well as arenas for future research collaborations. A) Degree of rock weathering due to hydraulic redistribution varies by species, water availability and fracture network. B) Root phenology vs. fracture geometry varies by species and sets how above-ground architecture, wood properties, and forest structure sets belowground response to wind and thus tree-driven cracking through time. C) Changes in species and forest structure due to changes in belowground architecture, seasonal shifts in water availability, or broader latitudinal shifts in climate may result in different magnitude-frequency drivers of bedrock to soil production.

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