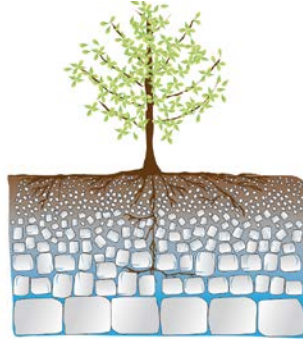


Exploring Four Critical Puzzles about Trees, Water, and Soil: A Vision for Research

A workshop to be held September 9th – 11th, 2015 at the Susquehanna Shale Hills Critical Zone Observatory at Penn State University



Confirmed attendees at the workshop:

1. Sue Brantley (Penn State, sxb7@psu.edu)
2. Dave Eissenstat (Penn State, dme9@psu.edu)
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Location: EES Building, Pennsylvania State University, PA

Workshop rationale: Trees contribute to the carbon, water and nutrient cycles in forested systems and impact the weathering engine that shapes landscapes and soils. On the other hand, the water, soils and landscapes also affect trees, sometimes determining species or size distributions and other characteristics of forests. To understand the influence of trees in shaping the critical zone requires a multi-disciplinary approach. This workshop will host ~30 people from ecology, physiology, hydrology, geochemistry, soil science, and geology who will spend 2.5 days outlining a research agenda to understand the tree-landscape interface. The goal of the workshop is to produce a Vision Paper describing the research agenda for the next five years and to show how this agenda can be addressed at CZOs and other similar settings. A sub-team of authors will emerge from the broad group as determined by effort and interest.

The talks: During the workshop, four Tree Puzzlers will be posed: for each question, two team leaders chosen from complementary disciplines will coordinate an interdisciplinary discussion of questions, hypotheses, data, approaches, and models. Researchers from within and outside the CZO community are participating, including within and outside of the Susquehanna Shale Hills CZO.

The plan: The four puzzlers are delineated below. Two leaders are associated with each puzzler and these leaders will organize how to introduce their puzzler: they can each give a talk or they can ask others to give short talks. This is up to the team leaders (if they want the details of who will talk on the schedule pls send that info to Jennifer Williams). These Puzzler Introductions will frame up the question, pose provocative hypotheses, and present tantalizing data that address the questions. On the second day, one highlight speaker will present data from a CZO or multiple CZOs or something similar to a CZO that exemplifies or elucidates the question: it is hoped that these speakers will work before the workshop with their team leaders to know how to present data relevant to the question. In some cases talks may be exploratory in nature, where formal models may not have yet been attained. A graduate student or postdoctoral scholar is associated with each team to help test datasets, plot, find literature articles, find figures, or whatever is needed. The leaders will engage their teams ahead of the workshop by organizing the writing and thinking and collating of data or models. The exact structure of the sessions will be determined by the leaders.

The product: The paper will summarize i) the four puzzlers listed above, ii) questions we can address, iii) hypotheses we can pose, and iv) proposed approaches that we should use to explore the puzzlers over the next five years. Examples will be drawn from CZOs or any other sites.

AGENDA

Day 1. 117 EES Building (attendees walk from Atherton hotel to EES; attendees will not return to hotel room until 9pm or so after dinner; very little cell ph coverage in the afternoon)

7:30am – Continental Breakfast inside 117 EES

7:45am – Welcome, Introductions, Discussion of Goals of Workshop (Sue Brantley/Dave Eissenstat)

8:15-9:15am – Overview of Puzzler 1: Where do trees derive their water and how does the subsurface impact this water uptake? *Team leaders:* Todd Dawson (*UC Berkeley*) and Jeff McDonnell (*U of Saskatchewan*). Student leader: Jaivime Evaristo (*U of Saskatchewan*); Holly Barnard (*UC Boulder*) team contributor.

- **Water worlds, trees, and isotopes**

9:30-10:30am – Overview of Puzzler 2: How are stream chemistry and flow affected by trees in an intact forest and why? *Team Leaders:* Kathy Weathers (*Cary Institute of Ecosystem Studies*) and Sarah Godsey (*Idaho State University*). Student leader: Wei Zhi (*Penn State*); Shirley Papuga (*U of Arizona*) team contributor.

- Sarah Godsey - **Exploring global stream chemistry patterns**

10:30-10:45am – Break – 1st floor foyer EES Building

10:45-11:45am – Overview of Puzzler 3: How do trees influence soil formation and hillslope evolution (and the reverse)? *Team leaders:* Josh Roering (*U of Oregon*) and Ed Johnson (*U of Calgary*). Student leader: Yu Zhang (*Penn State*), Xin Gu (*Penn State*); Zsuzsanna Balogh-Brunstad (*Hartwick College*) team contributor.

- Facilitated by Jill Marshall
 - Josh Roering - **Trees and soil: Making it and moving it**
 - Ed Johnson - **Forest ecology and the CZO**
 - Zsuzsanna Balogh-Brunstad - **Plant regulated processes at the bio-geo-interface**

12:00-12:45pm – Drive to Civil Engineering Lodge

12:45-1:30pm – Box lunches at the Lodge

1:30-2:30pm – Overview of Puzzler 4: How does lithology affect the distribution of trees and subsurface carbon? *Team leaders:* Oliver Chadwick (*UC Santa Barbara*) and Whendee Silver (*UC Berkeley*). Student leader: Lillian Hill (*Penn State*); Diana Karwan (*U of Minnesota*) team contributor.

- Oliver Chadwick – **How does lithology affect distribution of nutrients and subsurface carbon?**

2:30-3:15pm – Introduction to Shale Hills

- Sue Brantley and Dave Eissenstat – The puzzler connection in the CZO
- Roman DiBiase – Geomorphology and Geology of the CZO

3:30-6:30pm – Field trip to Shale Hills and Garner Run (Susquehanna Shale Hills Critical Zone Observatory) – Rough Itinerary

- 3:30-4:00: Dave Eissenstat – Trees in the Shale Hills catchment
- 4:00-4:15: Ken Davis – Carbon budget and eddy flux measurements
- 4:15-4:30: Sue Brantley / Diana Karwan / Yu Zhang: Soils and pits and mounds
- 4:30-5:00: Roman DiBiase: Geology, Quarry Outcrop
- 5:00-5:15: Drive to Garner Run
- 5:15-5:40: Roman DiBiase: Lithology and soil differences in Garner Run
- 5:40-6:00: Tess Russo and Beth Hoagland: Hydrology in Garner Run, C vs Q
- 6:05-6:30: Dave Eissenstat: Vegetation in Garner Run, differences between Shale hills and Garner Run

6:30pm – Picnic Dinner at Civil Engineering Lodge

Day 2. 117 EES Building (attendees walk from Atherton hotel to EES)

8:00-8:30am – Continental Breakfast inside 117 EES

8:30-10:30am – The Four Highlight talks about each puzzler (20 minutes each + 10 minutes discussion). These talks are meant to be edgy, unfinished, nimble, not definitive nor formal. They are meant to show data (from CZOs and other sites) that could help in understanding the four puzzlers.

Puzzler 1 Highlight Speaker: Katie Gaines (*Penn State*) – ***Ecohydrologic patterns and processes in tree water use at the SSHCZO: a stable isotope approach***

Puzzler 2 Highlight Speaker: Mark Green (*Plymouth State*) – ***Coupling catchment ecological stoichiometry and hydrology***

Puzzler 3 Highlight Speaker: Jill Marshall (*UC Berkeley*) – ***Which came first: trees, fractures, or soil?***

Puzzler 4 Highlight speaker: Cliff Riebe (*U of Wyoming*) –***Lithology and tectonics as templates for forest ecosystems***

10:30-10:45am – Break – 1st floor foyer EES Building

10:45-11:45am – 117/217B EES Building – Break-out groups for questions 1 & 3. Discuss a) hypotheses b) existing data c) new measurements needed at CZOs or elsewhere d) what new methods, models, experiments, sites or sensors are needed to move forward?

11:45-12:45pm 117/217B EES Building – Break-out groups for questions 2 & 4. Discuss a-d.

12:45-1:30pm – 217 EES foyer – Buffet Lunch

1:30-2:30pm – 117 EES Building – Report back in plenary session

2:30-3:15pm – Discussion of topics which cross-cut all topics. Relaxation time. Walking. Thinking. Arguing.

3:15-4:30pm – 117/217B/225C/3rd floor EES Building – Break-out groups reconvene as determined by team leaders.

4:30-5:30pm – 117 EES Building – Plenary session discussion of where we stand. Breakout groups report back.

5:30pm – Dinner on your own or small groups – self organize

Day 3. 117 EES Building (attendees walk from Atherton hotel to EES)

8:00-9:00am – Breakfast on your own downtown, no continental breakfast served

9:00-10:30am – Each Puzzler Team takes the one-pager developed at the beginning of the workshop by the team leaders and develops it into a two-pager + 2 figures. Cross team contributions encouraged. No one is relegated to just one team.

10:30-12:30pm – Plenary session. Each team presents their paper. Brantley/Eissenstat lead discussion to frame up the overall paper and discuss a timeline.

12:30pm – Lunch discussion – 117 EES

1:30pm – Adjourn

Puzzler #1) Where do trees derive their water and how does this compare with the diversity of water reservoirs in the subsurface?

Team leaders: Todd Dawson (*UC Berkeley*) and Jeff McDonnell (*U of Saskatchewan*). Student leader: Jaivime Evaristo (*U of Saskatchewan*); Holly Barnard (*UC Boulder*) team contributor.

Context

Trees play a significant role in the chemical (*VanBreeman et al., 2000; Balogh-Brunstad et al., 2008*), and physical (e.g., *Reneau and Dietrich, 1991*) evolution of the critical zone. Recent work suggests that in seasonally dry climates, trees derive a significant portion of their moisture from weathered bedrock sources below the soil (*Jones and Graham, 1993; Jones and Graham, 1993; Zwieniecki and Newton, 1996; Rose et al., 2003; Witty et al., 2003; Querejeta et al., 2006; Schwinnig, 2010; Nie et al., 2012*). This deep water source links deep unsaturated zone moisture to the atmosphere and hydrologic cycle through root uptake and transpiration. Our ability to accurately inform models that predict future climate scenarios depends on a robust characterization of the movement of plant available water throughout the shallow and deep critical zone. Additionally, water use by trees is presumed to be responsible for the diurnal oscillations seen in streams across climates and drainage areas. The water use of different species may have a direct impact on the baseflow of streams (*Western, 1835; Troxell, 1936; Burt, 1979; Bond and Kavanagh^{a,1999}*). In Mediterranean climates, the links between wintertime precipitation, tree water use, and baseflow sustaining drainage of the hillslope are particularly important to understand. Furthermore, the source and timing of uptake by vegetation will affect the water balance on the hillslope as well as the regional climate. Differences in tree physiology lead Douglas-fir and madrone to partition water across seasons, with Douglas-fir using more water in winter and early spring, and madrone peaking in their water use (transpiration) in late summer (*Link et al., 2014*). Link et al., (2014) predicts that an entirely Douglas-fir forest would transpire far less water to the atmosphere in late summer, leading to a 2°C warming of the subsurface. Our long held view based on greenhouse experiments is that there is no fractionation during water uptake (*Friedman, 1969; Dawson and Ehleringer, 1991, 1993*) by plants but recent evidence from field-based measurements suggests that old growth Douglas-fir trees may be altering the isotopic composition of their subsurface reservoirs (*Oshun et al., in prep*).

One method for ‘seeing’ inside the hillslope is the use of stable isotopes (*Dawson and Simonin, 2011*). And recent work by Brooks et al. (2010), Goldsmith et al. (2013), and Hale et al., (2011) have employed such methods to show that trees rely on unsaturated zone water that has an isotopic composition distinct from the water that transits the hillslope to become runoff. This curious finding led Brooks et al. (2009) to draw upon previous studies that showed that water can be held at variable tensions in the subsurface (e.g., *Biggar and Nelson¹⁹⁶²; De Smedt and Wierenga, 1979; Gvirtzman and Magaritz, 1986*) and argue that streamflow was hydrologically disconnected from vegetative source water in the hillslope. Other studies have shown that the tension under which water is held quantitatively affects its isotopic composition (*Gvirtzman, 1986; Landon et al., 1999*), and that the different material properties that make up the subsurface critical zone might impart their own ‘fingerprint’ on the isotopic composition of their waters (*Oerter et al., 2014, Oshun et al., in prep*). Moreover, when water infiltrates some soils isotopic fractionation can occur (*Phillips and Bentley, 1987*).

These cautionary tales highlight the need to sample deeply through the critical zone and to define the isotopic composition of *all* subsurface reservoirs.

We might therefore ask what are the sizes of the plant available water pools in the unsaturated zone, and by what processes do these reservoirs get recharged and become drained? Some future challenges include: 1) How is water partitioned between that which goes up into trees, and that which drains down to the water table? 2) How do different species of trees access and use rock moisture across different seasons? 3) What is the role of mycorrhizae in providing rock moisture to vegetation, and how might this pathway lead to isotopic fractionation? 4) What is the effect of vegetation uptake on stream flow (either through diurnal cycles or through the recession to baseflow?)

Content for discussion

a) What important and edgy hypotheses can be addressed?

- a1. Tree water use is decoupled from the mobile water flow in the subsurface that forms groundwater recharge and streamflow. How do source, timing of uptake, and quantity of uptake affect baseflow?
- a2. Trees use subsurface water pools based on their needs (demands) for water at the time of their peak growth and this may decouple them from the "most likely" (most available) water pool(s).
- a3 Large old growth trees (Douglas-fir; *Pseudotsuga menziesii*) show isotopic fractionation that is associated with mycorrhizal water uptake.

b) What measurements already exist that could be used to test these hypotheses?

- b1. Stable isotopes are a useful way to tackle these questions. But, synthesis is needed across different biomes and the techniques for water extraction from soil- and plant material need critical re-evaluation given their potential to affect interpretations.
- b2. Combining isotope, water content, water potential and water use measurements may be a way to reveal answers to hypothesis a2.

c) What measurements should be made at different CZOs or elsewhere to test the hypotheses?

- c1. Sampling of soil water profiles via lysimetry, centrifugation, vapor extraction and cryogenic extraction should be made across CZO sites and compared with local vegetation water from these sites (twigs and xylem water).
- c2. Sampling soil chemistry in the rooting zones where water is being extracted by plants is needed because recent literature suggests that clay-fraction and cation chemistry may influence either the O or H isotope composition of water.
- c3 Apply natural abundance and enriched (^2H) water isotopes to trace and quantify the possible isotope effect associated with mycorrhizae transport of rock moisture to trees that seem to be isotopically invariant or possess unusual values (e.g., Douglas-fir).

d) What new measurements, models, experiments, or sensors are needed to move forward?

- d1. Some new data are challenging to interpret and so we may need new ways of extracting water at a range of known tensions so that water mobility and water isotope composition can be examined together. Models that couple plant water use and mobile water movement vertically and laterally in macroporous soils are needed for use as learning tools and virtual experiments to go alongside field work.

d2. Controlled greenhouse experiments where isotope labels are applied to known soils of varying water holding capacities and to different species of woody plants could be another fruitful pathway to learning the relative roles that species and soils play in water uptake dynamics.

d3. Also, controlled experiments on plant water uptake under different soil chemical conditions (see c2) are largely lacking but would go a long way in helping us understand if this is important in general or only under very special conditions or perhaps not at all.

Puzzler 2:

How are stream chemistry and flow affected by trees in an intact forest and why?

Team Leaders: Kathy Weathers (Cary Institute of Ecosystem Studies) and Sarah Godsey (*Idaho State University*). Student leader: Wei Zhi (*Penn State*); Shirley Papuga (*U of Arizona*) team contributor.

Context: Stream chemistry patterns are often used to provide insight into the integrated earth system processes occurring in a watershed. These patterns have often been invoked to describe patterns of weathering, storage, mixing and transport within a watershed (Hem 1948, Johnson et al. 1969, Evans and Davies 1998, White et al. 1996, Godsey et al. 2009, inter alia). Although silviculturalists and farmers have long managed plant yields by shifting soil chemistry, the linkages among plant and stream water chemistry in natural systems are less well-understood. Some studies have compared stream chemistry across vegetation and water-stress gradients (e.g., Marchman et al. 2015, Lofgren et al. 2014) or before and after harvests (e.g., Neal et al. 2004), but the degree to which biological processes trump hydrochemical processes is unknown.

As noted in puzzler Y (renumbered from 2?), trees may partition water such that plant water use is effectively decoupled from streamwater: Brooks et al. (2009) showed that sources of plant and stream water differ seasonally in a Mediterranean climate. However, we do not know the extent of this decoupling across climate gradients, species, and events. There is also evidence that tree and soil water chemistry may not always be decoupled: in the humid northeast US, soil calcium amendment at Hubbard Brook Experimental Forest recently boosted transpiration by 18-25% [Green et al. 2013]. At the plant scale, xylem cation concentrations have recently been shown to affect short-term xylem conductance and how much transpiration occurs [Nardini et al. 2011]. Thus xylem chemistry can affect tree drought response, including embolism repair [van Doorn et al. 2011; Wegner 2013].

Integrating these approaches and scaling up to the watershed scale remains a challenge. Stoichiometric analyses in addition to Ca (or Sr) isotopes to track Ca sources could be useful for linking xylem and stream C-Q patterns. However, many questions remain about the role of fractionation processes of Ca isotopes in vegetation [Schmitt et al. 2012 & 2013, Fantle and Tipper 2014]. Modeling efforts, such as Isomap [Weyer et al. 2014] or DAYCENT's forest-specific modules [Hartman et al. 2013], could present an opportunity for developing additional testable hypotheses building from tree-scale to watershed-scale studies.

We might ask:

1. When do biological processes trump hydrochemical and weathering processes in determining stream solute chemistry? Which processes dominate and over which time scales?
2. How resistant or resilient is tree water chemistry to changes in meteorological conditions? How do these patterns affect stream chemistry?
3. Do trees discriminate among weathering products and water sources? How does rooting depth affect solute discrimination?

Content for Discussion

- A. What important or edgy hypotheses can be addressed?
 - A1. Biological processes trump hydrochemical/weathering processes in determining stream solute chemistry when transpiration is limited by nutrients rather than water.

 - A2. Transpiration in drought-resistant tree species is resistant to changes in weather conditions because these trees have the most diverse root distributions, reflected by the most variable xylem water chemistry. Stream chemistry in watersheds dominated by these drought (or extreme) resistant species will be more variable than in watersheds with less well adapted species. (e.g., red maple as drought-adapted species)

 - A3. Tree roots at different depths provide water during different conditions with different chemistry. Trees will use the least “expensive” water near the surface whenever possible (i.e., xylem chemistry will reflect water limitations and not nutrient limitations).

- B. What measurements already exist that could be used to test these hypotheses?
 - B1. Stream chemistry during drought and flood conditions coupled with chemistry of soil and ground waters, and adjacent tree distributions.

 - B2-3. Maps of root distributions of different tree species. Tree water chemistry by species.

- C. What measurements should be made at different CZOs or elsewhere to test the hypotheses?
 - C1. Site selection to encompass regions where nutrient and water limitations dominate is critical. Coupling ET flux estimates with isotopic and nutrient chemistry of streams, trees, and ground water would help to address these hypotheses.
 - C2-3. Measure soil water and root water chem. at different depths under different flow conditions.

- D. What new measurements, models, experiments, or sensors are needed to move forward?
 - D1. Fertilization experiments, extreme events (droughts/floods) to test extent of conditions under which different controls dominate.
 - D2. New coupled high-resolution xylem, soil, groundwater, and stream chemistry measurements.
 - D3. Stoichiometric, potentiometric, isotopic measurements with higher resolution subsurface mapping of flow and its chemistry.

PUZZLER #3) How do trees influence soil formation and hillslope evolution?

Team leaders: Josh Roering (*U of Oregon*) and Ed Johnson (*U of Calgary*). Student leader: Yu Zhang (*Penn State*) and Xin Gu (*Penn State*); Zsuzsanna Balogh-Brunstad (*Hartwick College*) team contributor.

Context:

Trees play a significant role in soil formation and the evolution of hillslope form. The vast majority of geomorphic studies regarding the influence of trees on erosional processes involves characterizing the ability of root networks to stabilize soils and resist soil erosion by minimizing overland flow or shallow landsliding (e.g., Schmidt et al., 2001). When viewed over long timescales, however, trees can be thought of as biotic engines that perform significant work altering near surface materials and sculpting the critical zone. Adopting this perspective at the most fundamental level, one can conceptualize hillslope and critical zone evolution by focusing on tree-related processes that contribute to: 1) bedrock weathering and soil formation and 2) soil transport.

With respect to soil formation, numerous studies have addressed the physical role of root networks extricating shallow (and often weathered) bedrock and roughening the topographic surface through the formation of pit and mound features (Lutz and Griswold, 1939; Schaetzl et al., 1990). These pit and mound features are known to persist for decades to millennia depending on their scale and the vigor of non-tree disturbance mechanisms that erase the signature of pit/mound features, such as rainsplash and worm bioturbation (Schaetzl and Follmer, 1990). In some situations, tree turnover can confound soil stratigraphy interpretations by inverting otherwise typical spodosol forest soil profiles (Schaetzl, 1986). In this respect, trees essentially serve as macro disturbance agents. Roering et al. (2010) used a suite of measurements to show that tree root action imparts a biotic signature on the landscape surface as well as the soil-bedrock interface in a steep, closed canopy coniferous forest. In that setting, large roots penetrate deep (2-3m) into shallow bedrock fractures such that given the regional erosion rate average (~0.1 mm/yr), fire frequency timescales (~ 250- 400 yrs) that set forest stand age, and tree root basal area values (1%), virtually all parcels of bedrock and soil are impacted by root networks as they are exhumed in the near-surface environment. In other words, tree roots 'touch' the vast majority of shallow bedrock and soil. Gabet and Mudd (2010) constructed a numerical simulation of tree uprooting, sediment transport and hillslope evolution to determine how the integrated effect of bedrock and soil disturbance translates into a depth-dependent soil production function. Their results show that tree-driven soil production is consistent with a 'humped' soil production function that predicts maximum production rates under a finite (non-zero) soil depth. Importantly, they also suggest that the stochastic nature of tree root activity should preclude the emergence of a systematic soil production function estimated with cosmogenic radionuclides. This finding challenges the results of Heimsath et al. (2001), who showed that soil production rates decline with soil depth in the heavily forested Oregon Coast Range. The ability of tree root networks to disturb shallow bedrock likely depends on bedrock properties although few studies have systematically addressed substrate controls on root penetration. Marshall and Roering (2014) hypothesize that tectonic and perhaps topography-induced bedrock fractures are a requirement for root penetration, which suggests that characterization of coupled critical zone processes, particularly bedrock structure, topographic stresses, and weathering is essential (e.g., Slim et al., 2014; Rempe and Dietrich, 2014). Field studies by Graham et al. (2010) show that root networks and hyphae are deeply intermingled with shallow bedrock through fractures and grain-scale porosity.

With respect to biogeochemical weathering processes, quantifying the effects of biota on elemental cycles, chemical weathering, water quality, and soil formation have been a long time interest in geochemistry (Brantley et al., 2011). Numerous laboratory and field studies (e.g. Kelly et al., 1998; van Hees et al., 2006; van Scholl et al., 2006a, b; Finlay et al., 2009; Smits et al., 2012; Burghelca et al., 2015) have been conducted in attempts to isolate the bacterial, fungal and plant induced chemical weathering processes, even though these three players are invariably found together in natural environments (Leake et al., 2008). Zhu et al. (2014) provided an extensive review on soil-microorganism-plant systems in the perspective of chemical weathering and elemental cycling, pointing out that plant-regulated processes are able to both weaken and strengthen soil structure via breaking down chemical bonds of primary minerals, precipitating secondary mineral phases, and forming soil aggregates in addition to physical processes.

The rhizosphere is “where the action is” as the roots provide carbon for the microbial and fungal community (Berner and Berner, 2003; Calvaruso et al., 2009; 2014; McGahan et al. 2014). Mycorrhizal fungi and associated bacteria increase weathering/dissolution of soil minerals by acidification as proton exchange (pH effect) and also via secretion of low molecular weight organic acids (complexation and chelation; Leake et al., 2008; Ahmed and Holmström, 2015; Finzi et al., 2015). The low molecular weight organic acids are short lived and thus hard to quantify (Drever and Stillings, 1997; Shi et al., 2012; Lawrence et al., 2014). Large portions of the organic secretions within biofilms/biolayers form on the root/microbe/fungi and mineral interface (Lawrence et al., 2014) and biofilms enhance dissolution and decrease loss to bulk soil water (Banfield et al., 1999; Balogh-Brunstad et al., 2008). At the same time, however, secondary phases of minerals form such as clays, organo-amorphous phases and oxides, can seal the surfaces of soil minerals from further dissolution (Kleber et al., 2007; Zhu et al., 2014). As a result, it is not well understood how microbes/fungi/biofilm influences weathering rates (Grantham et al., 1997; Balogh-Brunstad et al., 2008; Graham et al., 2010). At the watershed scale, many studies have shown that the presence of trees increased dissolution rates (Berner and Berner, 2003; Calvaruso et al., 2009; 2014; Augustin et al., 2015) compared to areas of bare rocks and/or lichen/moss covered areas (Berner and Berner, 2003). It has been hypothesized that plants have high demand for non-nitrogen nutrients, thus plants may promote weathering and use the weathering products (Brantley et al., 2014; Shi et al., 2014). Feedbacks between these processes and physical disturbances (natural and/or man-made) that frequently expose fresh surfaces have not been well-established (Berner and Berner, 2003) as few studies have linked physical and biochemical processes (Fletcher et al., 2006).

With respect to soil transport, several studies have shown that mounding processes can be quantified through field surveys beginning with Denny and Goodlett (1956). A notable study by Norman et al (1995) quantified how mound geometry depends on slope angle, which essentially represents event-based transport distances. Their findings demonstrate that downslope mound length increases nonlinearly with slope angle such that friction becomes increasingly limited in resisting mounding transport on steep slopes. By integrating the total downslope rate of soil transport due to tree mounding, Dietrich and Bellugi (2006) calculated that tree-driven transport is much lower than the total soil flux inferred from cosmogenic erosion rates and a linear transport model in the Oregon Coast Range. In other words, pit/mound transport of soils constitutes a small fraction of the total flux on forested hillslopes such that additional disturbance processes must be invoked to explain observed rates of landscape lowering. Gabet and Mudd’s (2010) modeling is consistent with this finding and a study by Gallaway et al (2009) similarly shows that forest stand dynamics driven by fire can be used to calculate stochastic soil fluxes that are lower than regional erosion rates. Taken together, these studies imply that pit-mound formation may serve as a catalyst for rainsplash and other bioturbation processes on exposed soils. Thus, while tree-driven soil and bedrock disturbance creates iconic and readily

recognized landforms, the complete forest ecosystem must be interrogated in setting hillslope form (Phillips and Marion, 2006).

a) What important and edgy hypotheses can be addressed?

- What processes determine the efficacy of trees as soil producers? e.g. rock properties (such as fracture density and weathering state) are known to regulate the effectiveness of root action. other factors include: rock properties and regolith thickness.
- What biotic metrics are needed to scale the impact of individual trees across space and time?, e.g. tree population dynamics or net primary productivity.
- What meteorological processes are needed? e.g. are particular topographic settings often subject to winds that produce critical bending moments that uproot trees or frequent sway harmonics that damage bedrock?
- How do biogeochemical processes associated with tree root systems contribute to bedrock alteration and soil conversion and how is this related to trees as soil producers? Are there biogeochemical processes specific to species or mineral composition that impede rock weathering? (e.g lichen that precipitate minerals that protect rocks from water penetration)
- What fraction of soil transport is facilitated by biotic vs. abiotic processes? How might this vary with climate, rock properties and ecosystem type? Can we separately analyze biotic and abiotic transport processes? How are biotic and abiotic processes coupled?
- Over what timescales do tree-related processes become relatively continuous as opposed to punctuated and stochastic? Do landscape properties record events and for how long?
- When and do trees control fundamental landscape properties such as relief, slope, and drainage density?
- Are biogeochemical system processes species specific or mineral specific?
- Can we separate abiotic and biotic chemical processes in soils?
- How does the timescale of biogeochemical processes compare to that of physical processes?
- How do “three-way” symbioses affect soil formation/bio-weathering and soil transport?

b) What measurements already exist that could be used to test these hypotheses?

- Given that the forestry literature includes numerous detailed studies of root system morphology and topology; how can we use these hard-won datasets to extrapolate root-bedrock interactions over broader areas?
- Near surface geophysics and borehole data from the CZ ‘Drill the Ridge’ campaign can be used to correlate tree density with underlying fracture density
- Spectral data of vegetation cover and other image-based biotic proxies can be used to map the extent of tree canopy for correlation with soil and hillslope properties.
- Topographic patterns generated by trees can be quantified using airborne and terrestrial lidar.
- Existing CZ lidar datasets can and should be re-analyzed to extract information such as patterns in tree gap-formation (Frazer et al., 2005) and underlying abiotic and biotic controls on forest stand property scaling (Drake and Weishampel, 2000).

c) What measurements should be made at different CZOs or elsewhere to test the hypotheses?

- Rates of disturbance and surface change associated with trees can potentially be estimated using: cosmogenic nuclides, fallout nuclides, optically stimulated luminescence, among others.
- Ground-penetrating radar data has been shown to be effective for mapping root biomass, isotopic data could reveal where root systems derive their water and thus initiate disturbances.
- Mechanical sensors can be used to measure the loads that trees impose on bedrock fracture surfaces and soil masses.

d) What new measurements, models, experiments, or sensors are needed to move forward?

- Continuum models of rock weathering and soil production based on integrated measures of tree root action.
- Mechanical models of rock deformation using tree root systems as explicit load-generating elements
- Event-based soil transport and bedrock extrication from tree action based on empirical data and scaling relationships.

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DRAFT TEXT PUZZLER #4: How does lithology affect the distribution of trees and subsurface carbon?

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It is well known that lithology can drive patterns in forest community composition in ecosystems (Whitaker 1960; Aiba and Kitayama 1999; Hahm et al. 2014), although the mechanisms responsible for these patterns are often poorly understood. Lithology and related soil characteristics can also drive patterns in C pools and fluxes independent of tree species. For example, a survey of 50 conifer and hardwood forest stands in the Northwestern US found that parent material and the resulting soil types were better predictors of patterns in aboveground net primary productivity and nitrogen mineralization than forest type (Reich et al. 1997). Similarly, soils derived from parent materials that spanned over four million years of pedogenesis in Hawaii were dominated by the same tree species yet differed in net primary productivity (Vitousek and Farrington 1997), litter decomposition (Vitousek et al. 1994), and soil C pools (Torn et al. 1997), and P pools (Crews et al. 1995) among other things (Vitousek 2004).

The results from Hawaii raise important caveats related to parent material control on forest biogeochemistry because the underlying rock remains constant across the islands and it is soil weathering state and mineralogy that varies. Thus we must look more deeply into the mechanisms that control forest composition, structure and productivity. Most research exploring the interactions of lithology, plants, and C and biogeochemical dynamics has literally just scratched the surface—often only focusing on the top 10-30 cm of mineral soil. Here we begin to explore the relationships between lithology, the distribution of tree species, and C dynamics throughout the critical zone. Specifically we evaluate how differences in lithology and associated mineralogy drive relationships among nutrient availability, net primary productivity (NPP) and C storage throughout the soil profile.

The role lithology plays in determining forest structure, composition and biogeochemistry sometimes is evidenced mechanistically through the domain of other puzzlers such as water dynamics in rock fractures and the retention time of water within reach of forest ecosystems or through differences in soil residence time which in turn controls weathering and evolution of secondary minerals. Here we focus on how rock composition and structure affect biogeochemical properties of forest ecosystems. Lithologies differ in their mineralogical and elemental composition and therefore weathering releases differing suites of secondary products including those that create silicate clays and Fe, Al oxy(hydr)oxides and those that provide ecosystem nutrients. There is also an interplay between production of the secondary soil matrix and their ion retention properties, and the ongoing availability of ecosystem nutrients.

When considering the role of lithology on ecosystems one important unifying concept is that of the production of soil *skeleton* and *plasma* both of which make up the matrix of soil that determines water flow paths, rooting behavior, and nutrient retention (Brewer, 1964; Chadwick and Nettleton, 1990). Soil plasma is the fine-grained silicate or oxy(hydr)oxide clays and colloidal material that forms either directly from weathering reactions or from synthesis of ionic constituents in soil solution. In most instances organic matter (OM) can be included in the concept of plasma; here we keep it separate so we

can consider the role of plasma in stabilizing OM, but we need to remember that different plant species and communities can produce different organic compounds and that these are partly responsible for the fate of C in soil. By contrast with plasma, soil skeleton is the sand- and pebble-size particles that remain behind due to greater resistance to weathering. For instance, a mix of plagioclase and quartz mineral grains in a granitoid rock over time will weather to quartz-rich skeleton and plasma derived from neo-synthesis of the less soluble components from feldspar. The resulting plasma usually has negative charge, which retains the more soluble nutrient ions that are also released from the feldspar. In the early stages of soil development as soil that is inheriting both plagioclase and quartz from the parent rock will have a skeleton composed of both minerals but over time the skeleton will become dominated by quartz and with the loss of a reservoir of feldspar a soil can become depleted in ecosystem nutrients. As rocks weather they create a mix of skeleton and plasma depending on their initial mineral composition, the weathering environment, and the biota present.

To illustrate the role that lithology can play in determining critical zone functioning, imagine two rocks weathering in a humid forest: one a granite composed of quartz, feldspar (plagioclase and orthoclase), mica, and apatite, the other a basalt composed of olivine, plagioclase, apatite, and glass. In both cases, weathering of feldspar, mica, and apatite provide most of the nutrient ions and some of the components that are required for synthesis of plasma (Chadwick and Graham, 1999). The granite contains much more silicon (Si) than the basalt but much of it is tied up in quartz and therefore remains in the skeleton phase of the soil. By contrast since all the minerals in basalt are rapidly weatherable, a greater amount of Si is released by weathering and available to form soil plasma. The basalt is rich in “base” cations such as magnesium (Mg) and calcium (Ca) as well as the trivalent metals, iron (Fe) and aluminum (Al). Weathering in a humid environment means that soluble ions can be leached and when that happens the weathering matrix shrinks (collapses) which increases the concentration of less soluble elements such as Al, Fe, and in the case of granite, quartz sand. In drawing the contrast between granite and basalt, the role of quartz sand is important. In the former as weatherable minerals decay and solutes are removed the profile will collapse to the extent that sand will allow, but as the sand forms grain-to-grain contact with other sand grains collapse is minimized by the support of the skeleton. By contrast, in basalt all the minerals are quite weatherable and therefore the whole profile tends to collapse. Granite produces a clear morphology of weathering because profiles tend to deepen over time as acidic waters move deeper into the profile before encountering weatherable minerals. During basalt weathering there is no quartz skeleton (but see below) and therefore collapse is more directly related to primary mineral decay, secondary mineral synthesis and chemical denudation. In some instances, basalt weathering leads to similar rates of downward etching into fresh rock and soil collapse such that changes in thickness occur slowly. From a morphological perspective it is difficult to assess the weathering status of basalt soils because we do not have a macroscopic skeleton to observe, but we can use high field strength elements such as titanium (Ti), zirconium (Zr), or niobium (Nb) as elemental skeletons because they are minimally soluble and become concentrated in the plasma (Brimhall and Dietrich, 1987).

The differences in initial mineralogy, weathering and secondary mineral synthesis between granite and basalt can be used to evaluate end member behaviors in forest ecosystems. Soils forming on granite

have lower amounts of plasma, but more skeleton than basalt. Thus clay concentrations in granite soils often range from 10 – 20% compared with clay concentrations in basalt soils that range from 30 – 40% or more. The lack of skeleton in basalt soils means that though porosity is high and density is low, those soils do not transmit water very effectively. Thus there is greater soil-water through-flow in granite soils whereas there is more shallow lateral flow in basalt soils. Based on these properties we can hypothesize that basalt soils are more likely to develop anaerobic hotspots, and could potentially store more C throughout the profile in collapsed microsites. Materials can accumulate more readily in the basalt-derived soil, creating plasma rich in nutrients or Al, having differential impacts on plant growth (Chadwick et al., 2007; Vitousek and Chadwick, 2013). All else being equal, rooting depths should be greater in granite than in basalt soils, which could lead to greater C distribution through the soil profile, although this may be balanced by lower rates of C retention due to less plasma available for C-mineral interactions.

From a biogeochemical standpoint potential nutrient status is determined by the long-term interaction of atmospheric and biological acidity with rock minerals during weathering. Hydrogen ion is consumed during many weathering reactions that produce plasma and soluble cations, many of which serve as essential components of living organisms (Chadwick and Chorover, 2001). If we keep acid input constant and consider the density of mineral components that can neutralize that acidity it becomes clear that basalt soils have greater ability to neutralize acidity and to generate nutrient cations – quartz weathers slowly and releases no nutrient cations, by contrast volcanic glass weathers rapidly and releases a considerable amount of cations. Thus we expect that basaltic soils will have greater flow of cations into solution from weathering and that basaltic soils should resist acidification for longer than granitic soils (Chadwick and Graham, 1999). These results are subject to a positive feedback whereby the basaltic soils have more charged surface area (greater amount of plasma) and therefore can hold more cations as well. That increased surface area provides greater buffering so that it takes longer for leaching removal of cations even after most primary minerals in the rooting zone have decayed. Eventually however the primary mineral supply in both granite and basaltic soils will be exhausted and due to leaching the charged surface area will be subjected to acidification. Most acidification will be through an accumulation of Al and Al hydroxy ions on charged surfaces. Al ions are toxic to many organisms and it is likely that granitic soils will build Al toxicity more rapidly than basaltic soils. More specifically Ca, Mg, and potassium (K) are likely to support robust ecosystem function better and for longer on basaltic soils than on granitic soils, but comparisons of these behaviors across lithologies are only now being tackled. The same is probably true for phosphorus (P) as well but for somewhat different reasons. With increasing acidification, Fe and Al oxy(hydr)oxides become more reactive and sorb P tightly which protects P from leaching losses but it may be more difficult for roots to access it. However it is quite likely that root and microbial exudates can decompose those inorganic complexes to access P as needed, and/or that fluctuating redox conditions in denser, slow draining soils will release P through Fe reduction (Chacon et al. 2006). Basalt usually has more P and Fe than granite so there is greater build up of P in basaltic soils. These intercomparisons of P stocks vs fluxes on granite and basalt soils have not been completed and there are many uncertainties that need to be evaluated (Porder and Ramachandran, 2013).

The preceding discussion is based on relative balance among ionic inputs, storage and losses via leaching. There is however another important ecosystem function that counters this inexorable decline in nutrient status. Roots gather nutrient ions from a large volume of soil and later deposit them onto the soil surface (Porder and Chadwick, 2009). This biocycling serves to retard nutrient losses and to counter acidification (Vitousek and Chadwick, 2013). It is clear that base cations such as Ca and structural elements such as Si are biocycled and there is even some evidence that micronutrients such as Fe and barium (Ba) are preserved in profiles by this mechanism (Bullen and Chadwick, in review). Furthermore, organic matter produced by plants can coat mineral surfaces and impose negative charge, increasing nutrient retention and facilitating nutrient recycling.

Much of the reduced C added to soil as necromass is oxidized quickly but some remains as relatively intact plant matter for a period of time and a small amount is added to soil as plasma where it is interbonded with inorganic colloids and clays (Oades 1984). There are three aspects of C in soil that need to be considered: chemical composition, amount and turnover time (Sollins et al., 1996). Not all soil organic matter is the same. Differences in organic matter chemistry arising from initial chemical constituents of plants and from the reworking of that material by microbes can affect the reactivity of soil organic matter (Kögel-Knabner et al., 2008). Soils can contain large amounts of C but individual C atoms may be returned to the atmosphere quickly in which case turnover time is short and annual C input must be large. Alternatively small amounts of C may be added to soil annually and C stores may be maintained by stabilized atoms that are slowly released to the atmosphere. Fixed C must eventually be oxidized and returned to the atmosphere and the amount of C that funnels through soil is partly determined by the mechanism of return, which can be for instance fire, herbivore consumption, or microbial decay. Although there are many schemes for fractionating soil organic C into different components one often used way is using a density separation which partitions C into a light fraction (LF) that is largely composed of non-mineral bound C, an occluded fraction where the LF gets trapped in soil aggregates within the skeleton, and a heavy fraction (HF) that is composed on plasma associated C (von Lützow et al., 2007; Sollins et al., 2009).

The strength of binding of HF-C to inorganic plasma is a strong determinant of turn-over time in soil, which in turn relates to soil mineral composition, which is dependant on rock substrate mineralogy (Wattel-Koekoek et al., 2003; Sollins et al., 2009). Some of the longest C turnover times have been associated with the presence of short-range-order (SRO) minerals, which are metastable, nanocrystalline minerals that are composed of highly hydrated Si, Al, and Fe. SRO minerals can sorb hydrated C compounds and incorporate them into the growing plasma such that the HF-C is part of the plasma structure and protected from microbial decomposition. Organic matter – mineral interactions associated with crystalline minerals (1:1, 2:1 clays and Fe,Al oxy(hydr)oxides) are less strong and therefore they do not hold C for as long (Sollins et al., 2009). Of the more crystalline soil mineralogies, 2:1 clays sorb C most strongly followed by Fe oxides. The production of different soil minerals is controlled not only by the starting mineralogy but also by leaching intensity. Hence there is a strong climate by lithology control on the storage of HF-C. Basalts produce large quantities of SRO minerals and can produce substantial amounts of 2:1 clays and Fe oxides under different climate conditions. When

combined with fundamentally greater production of plasma, it is common for basalt soils to retain more C and retain it for longer than in a granitic soil under similar rainfall and forest conditions.

We have identified a list of preliminary questions to guide this exploration:

1. How do skeletons and plasmas differ across lithologies and how does this affect the composition and dynamics of vegetation?
2. Can plants overcome their lithologies by altering nutrient and water retention via C-mineral relationships?
3. How do tree species mediate nutrient availability and buffering capacity in the critical zone?
4. How does critical zone structure through effects of lithology, affect patterns in C storage?
5. How do water availability and drainage characteristics interact with tree species distributions and deep C storage?
6. How do atmospheric additions of nutrients alter tree-lithology-C relationships? Islands are likely to differ from interior mainlands (atmospheric inputs could provide new parent materials).

We expect that some of these questions might be initially explored using literature data from a range of sites with different lithologies but similar plant communities, and different plant communities across similar lithologies. However, few data are available for the subsoil, particularly for soil C. We envision field campaigns to sample the whole critical zone across lithologies with similar forest types and different lithologies (i.e. mid elevation tropical forests – Hawaii and Puerto Rico, both with a range of rock types); similar lithologies (granites?) with different forest types while controlling for mean annual rainfall and temperature (?) as much as possible. Key measurements would include rooting depth and biomass, soil C pools, C fractions, ¹⁴C age of the C fractions, mineralogy, nutrient stocks, DOC and potential soil C mineralization, O₂ or redox (?).

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