Third Annual Report for NSF EAR-0724958 entitled "Transformative Behavior of Water, Energy and Carbon in the Critical Zone II: Interaction Between Long- and Short-term Processes that Control Delivery of Critical Zone Services. July 23, 2016.

SCM-JRB CZO Team:

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A. Accomplishments

1. What are the major goals of the project?

The Catalina-Jemez (C-J) CZO project aims to improve our understanding of the mechanisms underlying quantitative relations between climatic forcing and critical zone evolution in water-limited systems by focusing on linkages between long time-scale climate/lithology interactions and short time-scale ecological/geological feedbacks, and how both affect CZ services.

This goal motivates the proposal's central thematic questions:

1) How do the long-term drivers of CZ structure and function (EEMT and tectonics) alter parent material to control current CZ structure and response to perturbation?
2) How is long-term CZ evolution affected by ecosystem process controls, including especially localized plant and microbial activities?
3) What is the impact of CZ structure on buffering climate- and disturbance-driven variability in water, soil and vegetation resources and how does this translate into changes in CZ services?

We postulate that the climatic forcing of subsurface CZ evolution is effectively predicted on the basis of effective energy and mass transfer (EEMT), which combines into a single climatic term the energy transferred to the CZ as effective precipitation (precipitation in excess of evapotranspiration) and reduced carbon (i.e., net primary production).

The CZO site focus is on the water-limited (semi-arid to sub-humid) southwestern US. A broader impact of our research is, therefore, to improve societal understanding of processes that govern water resource delivery and quality in this region. Mountain block and mountain front recharge processes serve as the principal source of all freshwater resources to human inhabitants in this part of the world, and hence our project focuses strongly on factors affecting the water cycle, including the partitioning of water delivered (as a result of orogenic forcing) to higher elevation catchments, and the influence of hydraulic throughput on CZ geochemical and geomorphic evolution. We are investigating how event-based partitioning feeds back to affect the development of hydrologic flow paths, landscape structure and (bio)geochemical heterogeneities.

Our approach involves a combination of field-based observational measurements, controlled experimentation, and conceptual/numerical modeling at each of two principal research sites in the water-limited southwestern US - Santa Catalina Mountains (SCM, AZ) and Jemez River Basin (JRB, NM). In year 3, of the CZO grant, we have initiated and completed several activities and made substantive progress in each of these areas.

Our transdisciplinary research approach interrogates CZ process dynamics and structure along four integrated lines of inquiry: (i) Ecohydrology and Hydrologic Partitioning; (ii) Subsurface Biogeochemistry; (iii) Surface Water Dynamics; and (iv) Landscape Evolution.
By building bridges across these four lines of inquiry, we address linkages between short time-scale (e.g., hydrologic) events and long time-scale (e.g., geomorphic) evolution of the CZ.
In addition to the goals we have for testing hypotheses given in the proposal, the Catalina-Jemez CZO is active in pursuit of CZO network goals. Transformative, network-level science findings should result from comparably quantified structural properties and process rates at multiple sites.

By doing so, we can, as a network, assess CZ parameter trends and test response hypotheses across the wider climate, lithology space afforded by the network. For these reasons, Chorover has led cross-CZO (X-CZO) development of "common measurements" conceptual frameworks for the CZO network, along with several collaborators.

2. What was accomplished under these goals?

Major Activities for Third Year of CZO

- Major activities in year 3 of the CZO grant in each of the six areas are described below, and the PIs and senior personnel that led efforts in each of these areas are referred to here by last name.

1. Ecohydrology and Hydrologic Partitioning (EHP):

- Installed a new flux tower site in unburned mixed conifer forest in the JRB (partially funded by DoE Ameriflux).
- Maintained a continuous record of carbon, water and energy exchange in three towers (situated in Ponderosa Pine and two in Mixed Conifer Forest [burned and unburned], respectively) in the JRB and one tower (situated at the interface of Ponderosa Pine and Mixed Conifer Forest) in the SCM (Litvak, Barron-Gafford et al.).
- Snow surveys were conducted in March 2015 to continue a time series assessment of snowfall inputs, including the impacts of topography, vegetation distribution, and fire (Brooks).

2. Subsurface Biogeochemistry (SSB):

- Deep line drilling was conducted in the mixed conifer ZOB (JRB). Three boreholes were excavated up to 50 m in depth with samples collected at 40 cm intervals for geochemical and microbial analysis, and wells installed for subsequent groundwater hydrology and chemistry assessments (McIntosh, Pelletier, Rasmussen, Chorover et al.).
- Instrumented pedons were installed in three locations in the new unburned mixed conifer site (JRB) to enable time series measurements of soil gas (CO_2 and O_2) concentrations, soil moisture, water potential, temperature, pore water chemistry, and redox potential, similar to ongoing in other JRB sites (Chorover, Schaap et al.)
- Depth resolved soil samples were collected from the unburned JRB mixed conifer site during installation of instrumented pedons (Chorover, Rasmussen et al.)
- Depth resolved soil samples were collected to characterize the catchment scale spatial variability associated with biogeochemical and microbial composition for year 3 postburn in the mixed conifer ZOB (JRB) (Gallery, Chorover, Rasmussen et al.).
- Pore water chemistry data were collected to continue the time series results for instrumented pedons in the SCM and JRB (Chorover et al.).
- Post-burn (JRB) assessment of microbial enzyme activities and their geo-spatial distribution at the ZOB scale (Gallery et al.)
- Incorporating to TIMS: (i) root dynamics in response to soil moisture, (ii) hydrologic controls on microbial enzyme activities and associated soil organic

matter (SOM) decomposition, and (iii) reactive transport controls on pedogenic weathering (Niu et al.)

- C-J CZO representation in multiple X-CZO activities related to SSB including (i) CZ biogeochemistry, (ii) organic matter, and (iii) redox processes working groups.
- Microbial communities transform the majority of carbon and other nutrients in soil and influence landscape scale biogeochemical cycling. While much work has been done to understand microbial community response to prescribed burn and wildfire, few studies have looked at the influence of depth and landscape position at the catchment scale post-fire disturbance. We hypothesize that areas of deposition within the landscape will increase microbial activity and act as areas of increased biogeochemical cycling and nutrient turnover relative to the surrounding soil matrix (i.e. 'hot spots'). To test this hypothesis we sampled 22 soil pits 18 days after the June 2013 Thompson Ridge Fire in the Jemez River Basin Critical Zone Observatory, across a gradient of burn severities in a mixed-conifer zero order basin. We subsampled six depth profiles through the surface soil profile and measured potential activities of seven hydrolytic enzymes using established fluorometric techniques. We then modeled potential enzyme activity across the landscape using digital soil mapping techniques to identify spatial variability across the landscape and localized areas of increased enzyme activity. To explore the mechanism for these results, incubation experiments will test the carbon use efficiency and substrate utilization of these communities.

3. Surface Water Dynamics (SWD):

- A continued record for time series of surface water hydrological and biogeochemical data were collected for streams in both the SCM (Marshall Gulch Weir, Granite ZOB, Schist ZOB, Oracle Ridge, B2 Desert Sites) and JRB (mixed conifer ZOB, La Jara stream, History Grove stream, Upper Jaramillo stream) (McIntosh, Chorover et al.).
- Physical hydrologic data included discharge, temperature.
- Aqueous geochemical data included major and trace elements (ICPMS), anions (IC), DOC, DIC and TN (TC/TN analyzer), pH and EC (by electrode), and stable water isotopes (stable isotope analyzer) (Chorover, McIntosh, Troch et al).
- Collection and analysis of age tracers of different water reservoirs in the Marshall Gulch Catchment (SCM) (Meixner, McIntosh, Ferre et al.)
- Sampling of water sources for U, Sr, and S isotopes across seasons in JRB (McIntosh, Chorover, Ma et al.)
- Combined CZO observations with downstream long-term records of stream flow and MODIS vegetation productivity to document how the JRB sites have responded to a long-term warming and drying trend (McIntosh, Brooks, Troch et al.)
- Assessment of wildfire impacts on catchment-scale C effluxes and spectroscopic properties pertaining to organic matter chemistry (Meixner, Chorover et al.)

- Combining data streams to interpret C/Q phenomena through improved CZO-derived hydrologic, biogeochemical and geomorphic understanding (Trostle et al.).
- Led X-CZO working group on concentration-discharge (C/Q) relations at UNH (organized by Chorover, McDowell and Derry). Workshop was very successful and led to a special section in Water Resources Research entitled "Concentration-Discharge Relations in the Critical Zone", with deadline for paper submissions Aug 31, 2016.

4. Landscape Evolution (LSE):

- Our CZO team collaborated with Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG) to complete a one-week detailed geophysical survey in the Mixed Conifer ZOB in JRB. This survey follows on a successful similar survey of the Bigelow ZOB in SCM last year. Surveys were designed to understand deeper CZ structure in our JRB instrumented catchment, and to extend to depth information collected in near surface (soil) surveys and instrumentation. Data are used, e.g., to model infiltration from soils to the deeper subsurface by combining soil and geophysical surveys, and to identify locations for deep borehole drilling that took place in June 2016 (Chorover, Ferre, et al.).
- Measured millenial-scale erosion rates at 10 watersheds across the full elevation/climate gradient of the SCM. This dataset allows us to test the hypothesis that erosion rates are controlled by soil production rates in weathering-limited environments (Pelletier et al.).
- Utilized the CyVerse platform (next generation of iPlant) to generate high resolution global maps of EEMT (Pelletier, Swetnam, Rasmussen et al.)
- Analyzed post-wildfire vegetation recovery and erosion in a high severity burn area of the JRB following the Thompson Ridge Wildfire of 2013 using terrestrial LiDAR and numerical modeling (Pelletier, Papuga et al.).
- Developed new methodology for quantifying the pedogenic impacts of long-term (time-integrated) EEMT to global landscapes (Rasmussen et al.).
- Participating in cross-CZO working group on the deep CZ (Suzanne Anderson, BC CZO, Pelletier, et al.)

5. Critical Zone Services (CZS):

- Field, Breshears et al. are leading the expansion of the conceptual framework of ecosystem services to assimilate the services of the critical zone, which provides, through long-term geological processes essential 'life' support. A recent perspective piece was published in EOS.
- Participating in a cross-CZO working group on CZ and ecosystem services, led by Bill McDowell (PI, Luquillo CZO).

6. Education and Public Outreach (EPO):

- Significant progress has been made on our Flandrau Science museum exhibit "Welcome to the Critical Zone"
- Writer and illustrator integrated into team and plan is for completion of exhibit by fall 2016 (Bill Plant)
- A series of Youtube videos on Critical Zone Science (from the Catalina-Jemez CZO) are now available from the Critical Zone series run as part of the Tucson public Science Café (Shipherd Reed).
- Continued website development and CZO data posting (Durcik).
- Participating in X-CZO team focused on EPO (Reed and Plant).

Specific Objectives for Third Year of CZO

Objectives for the complete CZO project are found in the funded proposal. Specific objectives for this third year of the Catalina-Jemez CZO were:

1. To conduct detailed geophysical characterizations of the Mixed Conifer ZOB in the JRB in preparation for borehole drilling and well installations.
2. To complete borehole drilling and well installations at three locations in the MC ZOB, including core sample extractions with minimal artefactual impacts for subsequent mineralogical, geochemical and microbial characterizations.
3. To develop high throughput methods for black carbon analysis in fire impacted soils.
4. To install a new tower site and instrumented pedons in unburned mixed conifer forest, JRB.
5. To initiate detailed studies of age tracer analyses of water sources in Marshall Gulch catchment (SCM).
6. To initiate novel isotopic studies (U, S, Sr) of water sources in the JRB.
7. To utilize CyVerse (next generation iPlant) for calculation of EEMT globally and at high spatial/temporal resolution.
8. To assess the mechanisms underlying concentration-discharge relations of multiple elements, including trace elements in CZO catchments.
9. To integrate Critical Zone Services into the better known Ecosystem Services context through community outreach.
10. To continue collection of time series data from our CZO instrumented catchments including: eddy covariance, soil CO2 exchange, phenocam continuous series, depth profiles of soil gas and solution phase concentrations, temperature and water content/potential, groundwater chemistry, and streamwater hydrologic flows and geochemical fluxes.

Significant Results

- **Key outcomes or other achievements**

Ecohydrology and Hydrologic Partitioning:

- Extensive snow surveys performed by the spring 2016 snow hydrology class at UU in collaboration with researchers at UA and LANL during March 2015 quantified the spatial distribution of snow cover at locations burned in the 2011 and 2013 fires in the Jemez mountains including revisiting locations surveyed in Harpold et al 2014, Gustafson et al. 2010, Musselman et al 2008, and Veatch et al. 2009. Initial analyses indicate that the patterns in post fire snow accumulation reported in Harpold et al 2014 persist three and five years post fire. Date from these survey will be used to evaluate models of hydrologic partitioning following forest disturbance.
- Building on the theme of forest disturbance impacts to hydrologic partitioning in the critical zone and mountain water resources, Biederman et al. (2015) published a cross CZO paper demonstrating that widespread tree mortality may not result in the increased water yield in western mountain catchments. These findings challenge the conventional wisdom of water resource management in the west and result from compensatory increases in evaporation associated with CZ structure including topography and vegetation distribution and demography. The mechanistic interactions were quantified first at SCJ and subsequently validated at BCO and other non CZO sites in earlier publications from our project.
- Moving from forest disturbance to climate change, Foster et al. (2016) used CZO results to develop a model simulation the independently evaluates the effects of the type of precipitation (a change from snow to rain) vs temperature (warming scenarios) on streamflow and water yield. These findings highlight that warming and the associated increase in ET have a larger negative impact on water yield than a change from snow to rain. These results have important implications for managing both the amount and timing of streamflow.
- In an invited contribution for the 50th anniversary issue of Water Resources, Research, SCJ researchers led a review paper that highlighted recent advances and outlined four challenges for Critical Zone Hydrology (Brooks et al. 2015). 1) Identify the interactions among terrain, lithology, vegetation, and water that control subsurface weathering and allow prediction of subsurface structure. This represents an ongoing, multidisciplinary effort to understand how and why structure develops. (2) Quantify the amount, residence time, and movement of subsurface water to better predict plant available water and stream flow generation. This work will utilize the growing knowledge on how CZ subsurface structure develops to reconcile ongoing disciplinary questions including partitioning of plant water sources and the rapid release of stored water. (3) Evaluate the role of terrain complexity in modifying microclimatic influences on water demand. Combined with improved understanding of where plants obtain water, this work will address when and where partitioning to vapor flux is under primary control of subsurface supply versus climatic demand. (4) Develop focused or targeted observations across a larger range of spatial scales to place site-specific work in regional context. These efforts will use the patterns associated with the rapidly increasing spatial and temporal data on CZ structure to predict dominant processes/controls and thereby sensitivity to change in the vast majority of locations that are not extensively instrumented and studies.

- Harpold et al. (2014) demonstrated that, in contrast to widely held expectations, increased sublimation following fire reduces net water input to the critical zone by increasing sublimation and evaporation from snow and soil surface. This paper was the result of a field survey conducted by students in a snow hydrology field class.
- Broxton et al. (2015) developed a snow energy balance model that operates at the scale of LiDAR forest and land cover that describes the dynamic balance between shading from solar radiation, wind, and interception that controls snow water input. This model is being implemented in forest management activities in Northern AZ.
- Biederman et al. (2014) extended the results form Harpold and Broxton papers (above) to demonstrate that widespread beetle mortality has an effect on snow accumulation, melt, vapor flux, and streamflow similar to the effects of fire.
- Harpold et al (2014b,c) presented LiDAR data from three western CZO's along with collocated ground and soil moisture observations to quantify the relationships between snow melt and soil moisture in western montane landscapes.
- Zapata-Rios et al. (2015a) combined CZO observations with downstream long term records of stream flow and MODIS vegetation productivity to document how the Jemez CZO sites have responded to a long term warming and drying trend.
- Zapata-Rios et al. (2015b) related mineral weathering to terrain attributes that control hydrologic partitioning and subsurface transit time in the Jemez CZO sites.

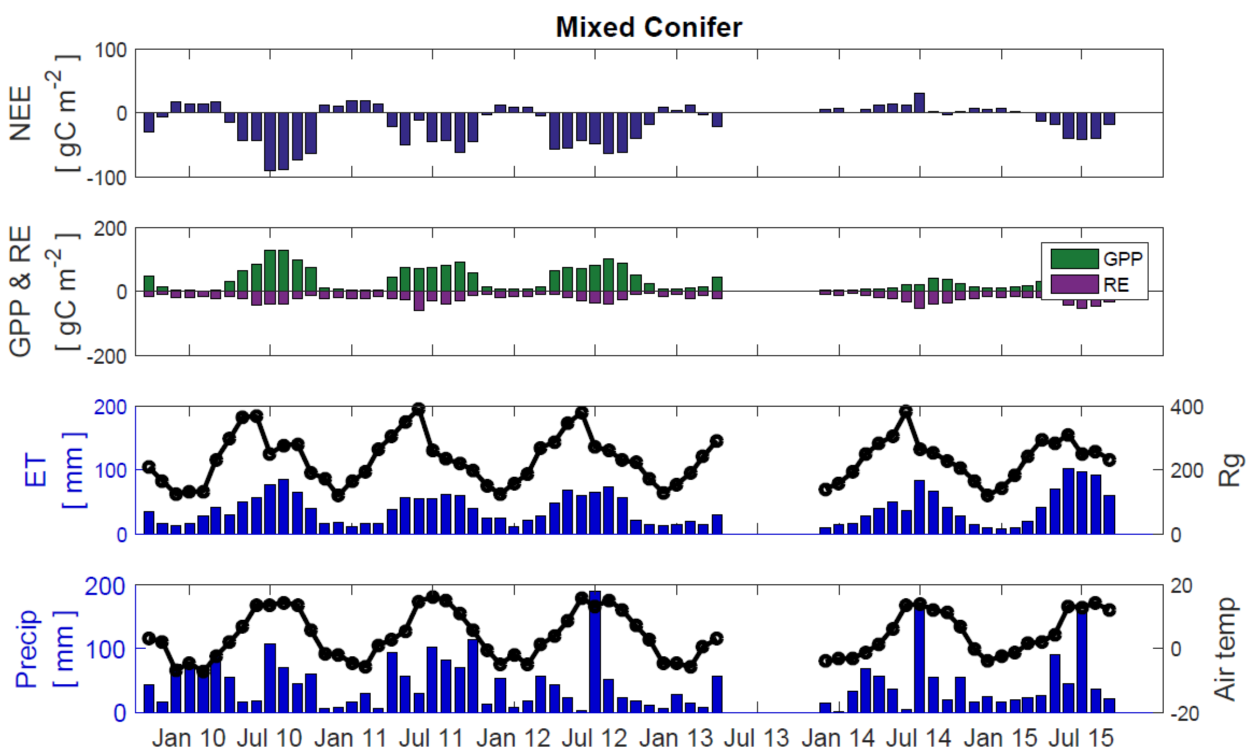


Figure 1a. Eddy flux data for the Mixed Conifer Site, JRB (Litvak et al.).

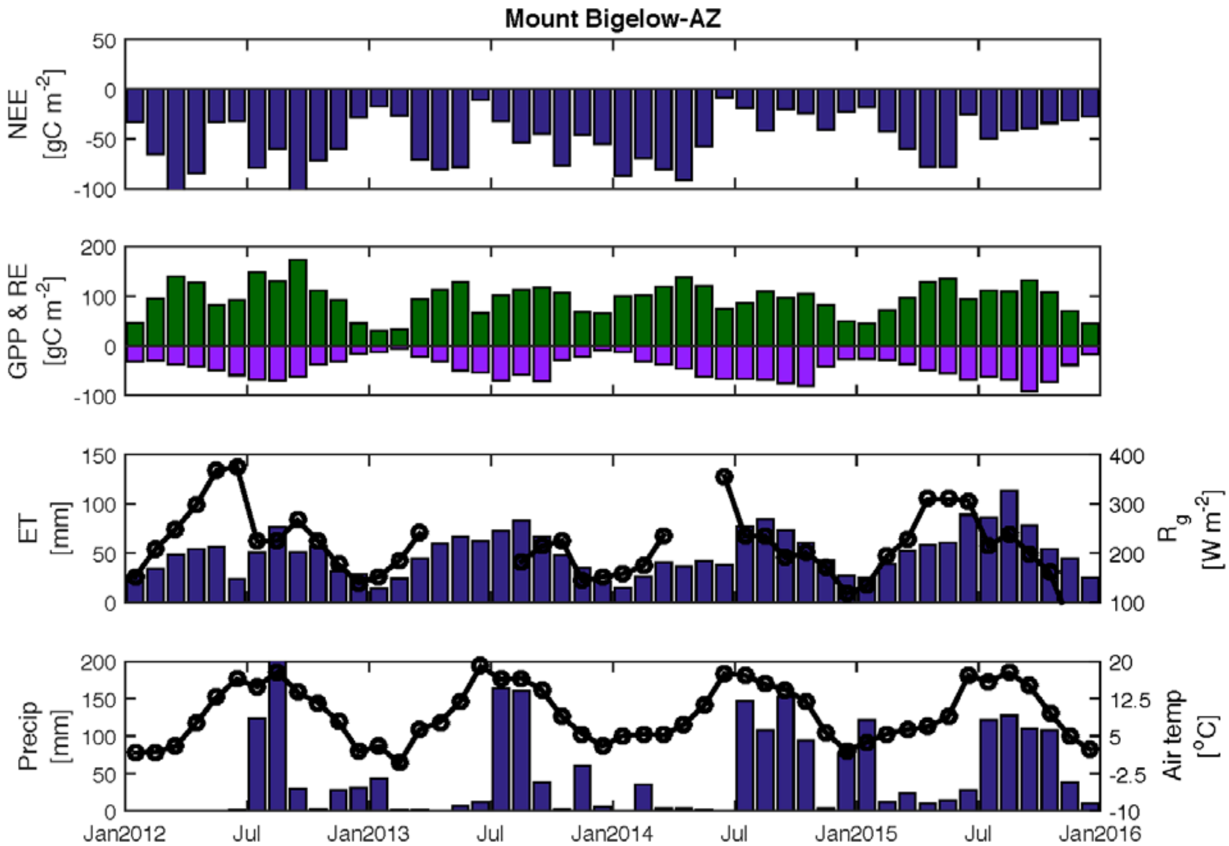


Figure 1b. Eddy flux data for the Bigelow Tower Site in SCM mixed conifer forest (Barron-Gafford et al).

- Net ecosystem exchange of CO_2 at the Mixed Conifer site in the JRB shows that the site returned to a net carbon sink by 2015, within two years after the wildfire that burned the forest in entirety (July 2013) (Litvak et al.).
- We have found that eddy covariance data suggest that the Bigelow ZOB in SCM is a constant sink for atmospheric CO_2 (Figure 1b). We believe that the classic means of separating measures of Net Ecosystem Exchange of CO_2 (NEE) are not capturing nighttime CO_2 efflux rates from the soil at night. To this end, we are developing a new flux partitioning scheme that utilizes our continuous CO_2 production data streams to improve estimates of ecosystem carbon balance.
- By examining measure leaf photosynthetic (A) responses to controlled variation in internal CO_2 concentration (C_i) we quantified phenological variation in A-C_i derived ecophysiological traits between ponderosa pine (*Pinus ponderosa*), southwestern white pine (*Pinus strobiformis*), and Douglas fir (*Pseudotsuga menziesii*) (Figure 2). Our species had similar, positive responses of net photosynthesis under ambient atmospheric conditions (A_{net}) to the onset of monsoonal precipitation but A_{net} varied strongly during the cooler portions of the year, representing differences in these co-occurring species performance. Maximum rates of carboxylation (V_{Cmax}) were greatest in *P. menziesii* for

much of the year, while *P. ponderosa* and *P. strobiformis* were similar (Figure 3). Investment in A_{net} relative to V_{Cmax} varied significantly among the three species—a pattern consistent with their relative shade tolerance and reflecting a trade-off between shade tolerance and photoinhibition. By quantifying seasonal variation ecophysiologial traits among co-occurring tree species in a Madrean mixed conifer forest, these results help link climate- and disturbance-mediated shifts in forest community composition and structure with ecosystem function. Results are described further in a manuscript in review at *Oecologia*.

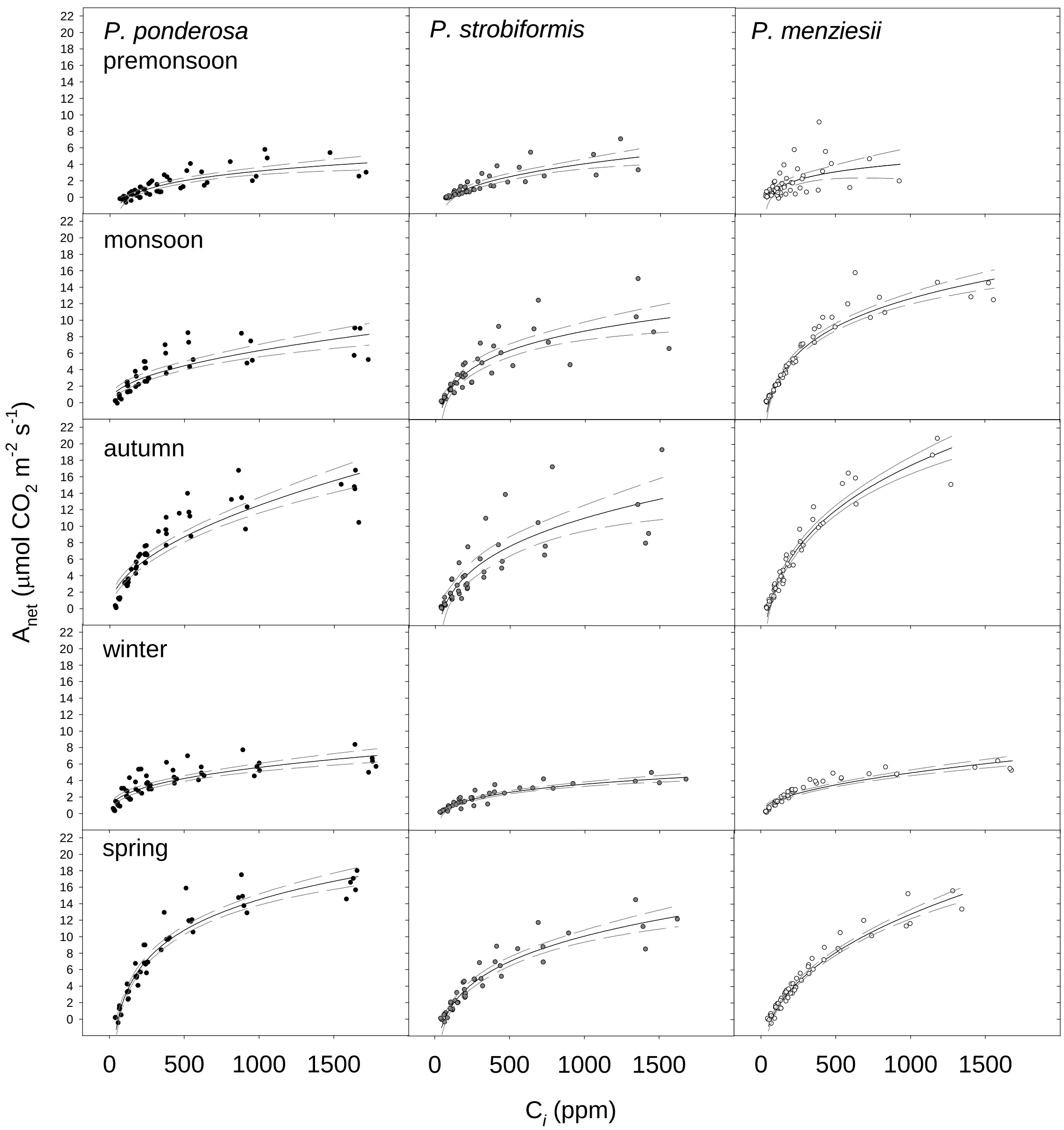


Figure 2. Leaf photosynthetic responses to controlled variation in internal CO_2 concentration for mixed conifer species in Bigelow ZOB (SCM).

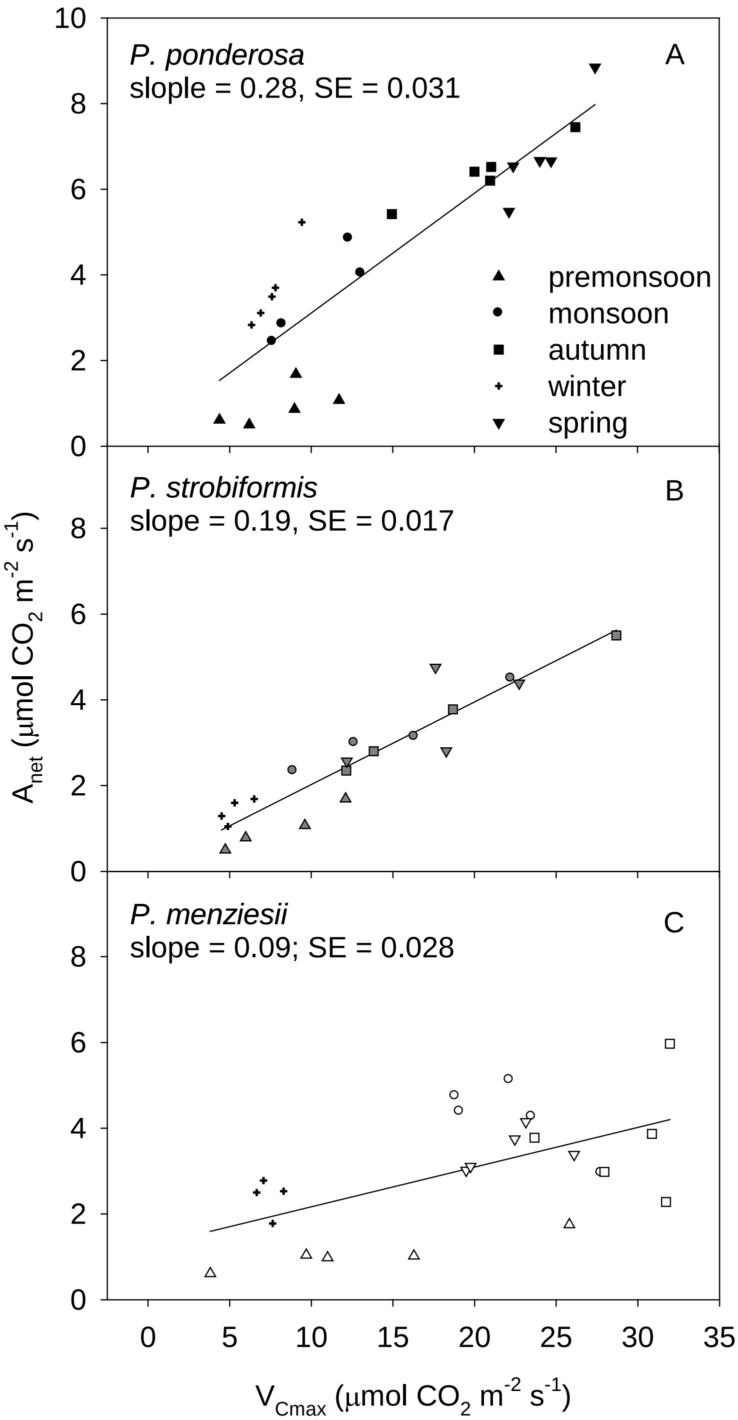


Figure 3. Maximum rates of carboxylation (V_{Cmax}) were greatest in *P. menziesii* for much of the year, while *P. ponderosa* and *P. strobiformis* were similar.

- We found that within our lowest elevation site that rates of CO_2 efflux were nearly twice as great on the South aspect, even during the dry season, and that individual rain pulses stimulated efflux on this South aspect for longer periods of time (Figure 4). This resulted in significantly (4X) greater cumulative CO_2 loss to the atmosphere for the same amount of water input based on aspect (Figure 5).

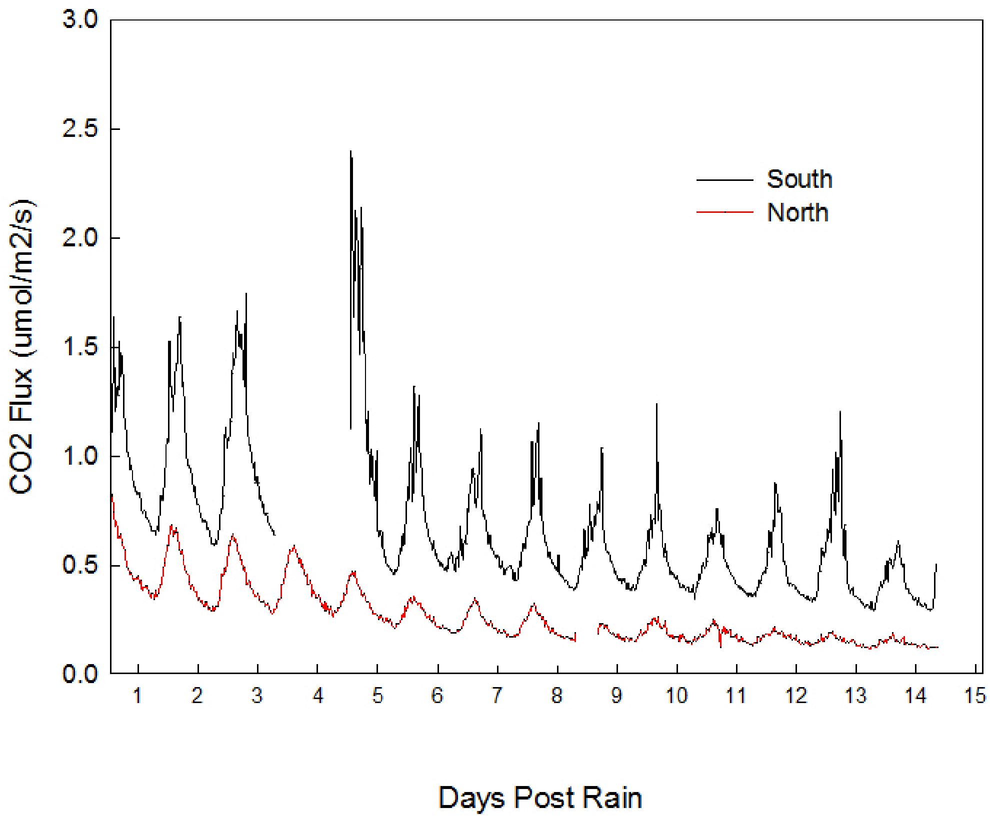


Figure 4. South versus north aspect response for CO_2 evolution following rainfall event (Barron-Gafford et al., in review).

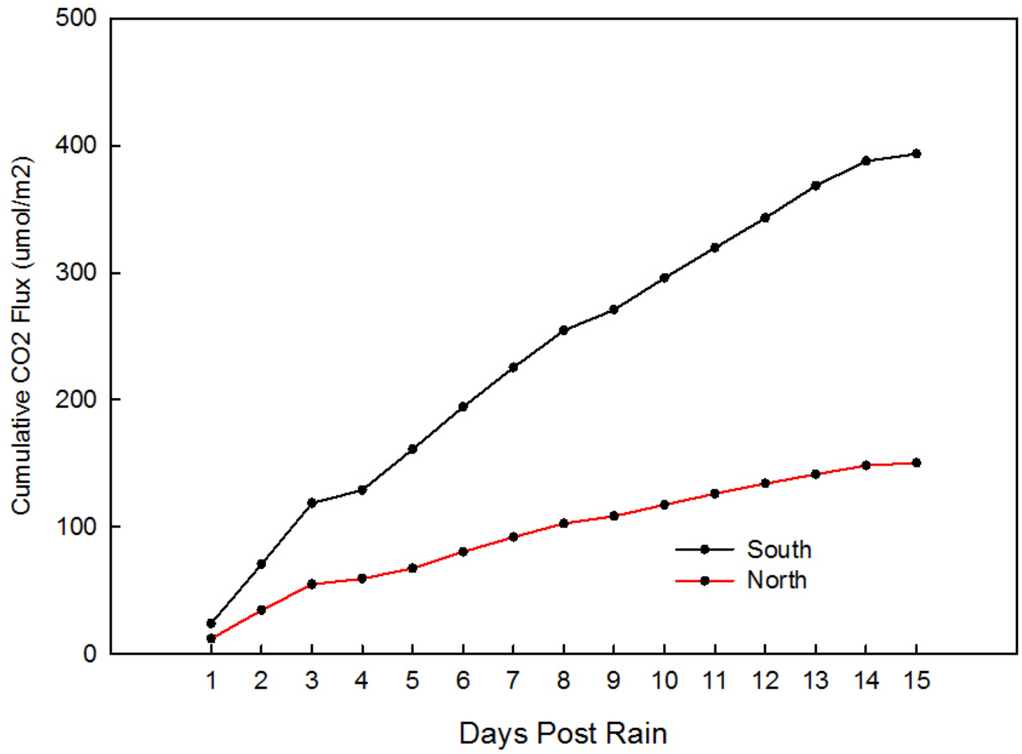


Figure 5. South versus north response for cumulative CO2 evolution following a single rainfall event (Barron-Gafford et al., in review).

- A book chapter (Breshears et al. 2016) is in press that links broad-scale vegetation change and its implications for biodiversity.
- A paper published in *Nature Climate Change* describes model assessments using regional-scale ecosystem models and global dynamic vegetation models both of which predicted broad-scale loss of conifers under warming within the model projected regions of each (McDowell et al. 2016).
- A paper was published in the journal *Water Resources Research* in which streamflow responses to beetle induced tree mortality were quantified (Biederman et al. 2016). This work suggests little differences to streamflow changes in most basins following beetle induced die-off which is likely a result of increased transpiration by surviving vegetation, increased snow sublimation, and increased subcanopy evaporation.
- An invited synthesis was commissioned and published for the *Centennial of the Ecological Society of America* on drought related tree mortality (Allen et al. 2015). This paper summarized key mortality-relevant findings, differentiating between those implying lesser versus greater levels of vulnerability. Global vulnerability drivers were identified that are known with high confidence: (1) droughts eventually occur everywhere; (2) warming produces hotter droughts; (3) atmospheric moisture demand increases nonlinearly with temperature during drought; (4) mortality can occur faster in hotter drought, consistent with fundamental physiology; (5) shorter droughts occur more frequently than longer droughts and can become lethal under warming, increasing the

frequency of lethal drought nonlinearly; and (6) mortality happens rapidly relative to growth intervals needed for forest recovery. These high-confidence drivers, in concert with research supporting greater vulnerability perspectives, support an overall viewpoint of greater forest vulnerability globally.

- A review of rangeland responses to increasing drought extremity (in press with *Rangelands*: Breshears et al. 2016), as expected with climate change, indicates that: (1) not all rangelands will be equally susceptible to extreme droughts – particularly with regard to their vulnerability to undergoing state changes; (2) the degree of woody plant abundance, and differences in mortality thresholds among growth forms, may be one attribute that helps explain differential vulnerability to state changes; and (3) management in an era of increasing climate variability needs to be in tune with forecasted changes in external drivers (e.g. drought) and the relative differences in vulnerability among rangeland ecosystems to these drivers.
- Developed new theory on change in vegetation structure as related to evapotranspiration partitioning. We have continued to collect data on microclimate as related to vegetation structure at the Mt. Bigelow flux tower. We have conducted preliminary analyses using data from this site and others to assess how changes in wind speed, relative humidity, and vapor pressure deficit relate to spatial patterns of vegetation structure, as estimated digitally through hemispherical photography analysis or LiDAR. Some significant correlations have been detected in preliminary analyses and we will expand these analyses to assess their robustness.

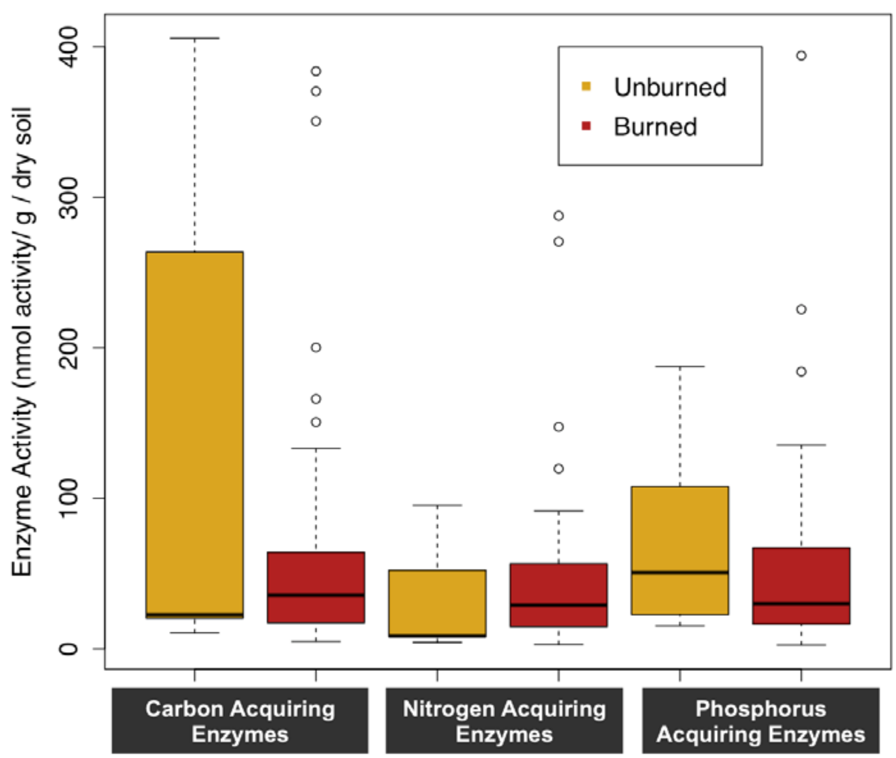
Subsurface Biogeochemistry:

- In a cross-CZO effort, Burns et al. (2016) build on the work from Perdrial et al. (2014) and Zapata-Rios et al. (2015) to demonstrating that fluorescent characteristic of DOM can be used to “fingerprint” spatial and temporal patterns in streamflow generation providing a biogeochemical tracer of coupled hydrological and biogeochemical processes.
- Two recent papers (Stielstra et al. 2015; Berryman et al. 2015) demonstrated how CZ topographic structure mediates soil carbon response to climate by regulating the importance of energy vs. moisture in soil respiration. These findings hold across sites in Santa Catalina, Jemez, and Boulder Creek CZO
- Francisco Balocchi’s thesis examined the interaction of snow cover and soil properties on soil freezing processes. These processes have the potential to strongly influence the hydrologic response of catchment systems to melt events. His results showed that fine textured soils were subject to more extensive and longer lasting soil frost.
- The accuracy with which passive capillary samplers (PCAPs) can estimate flux comes into question due to oversampling/undersampling dependent on the strength and duration of precipitation events and soil type. To explore the conditions that give rise to inaccurate sampling, extensive use of the HYDRUS2D/3D groundwater modeling software was used to simulate a 2-D axisymmetric flow model in a medium containing a PCAP in both steady-state and transient conditions through the application of various precipitation rates and periods across several soil textures. Results showed that the PCAP

does overestimate/underestimate flux with varying capture multipliers calculated from the ratio of simulated flux into the plate and the simulated flux from precipitation. Larger fluxes and longer time periods resulted in increased convergence of flux into the PCAP while smaller fluxes and shorter durations resulted in divergence of flux from the PCAP.

- Two recent papers from Vazquez-Ortega's Ph.D. research (Vazquez-Ortega 2015, 2016) highlight the use of the lanthanide series (rare earth elements, REE) as biogeochemical tracers in the critical zone. Fractionation of REE was found to be a function of bio-ligand concentrations and environmental redox status.
- In a geospatial analysis conducted at the catchment scale, we found that enzyme activity varied significantly with depth for certain carbon (C) and nitrogen (N) acquiring enzymes but not for hemicellulose, chitin, or phosphorus mineralizing enzymes. Higher activity was observed for areas of depositional convergence within the landscape for most enzymes sampled. Additionally, we looked at shifts in enzyme nutrient acquisition ratios that correspond with resource limitations relative to microbial stoichiometric demands. Results show a variance in resource acquisition potential with depth for C relative to N, with greater resources being allocated towards acquiring C at shallower depth. Conversely, greater resource acquisition potential was expended towards acquiring P relative to N and C at greater depths. Collectively, these results provide insight into the important role of microbial communities in soil C and nutrient cycling following fire and the application of digital soil mapping models to elucidate linkages of microbial activity and biogeochemistry at the sub-catchment scale.

Figure 6. Extracellular enzyme activity values for burned and unburned plots (2013 vs 2015 respectively) for surface 0-10 cm soils in MCZOB catchment and Sulphur springs control samples. (n=22 sites burned, n=3 unburned). Non-significant variations between burned unburned plots (p>0.05, t-test). (Fairbanks et al. in prep.)



	Burn		Depth		Burn/Depth Interaction	
	P	F	P	F	P	F
Biomass C	0.15	2.15	**0.0022**	10.75	**0.00097**	12.74
Biomass N	0.19	1.81	**0.00063**	1.38E+01	**0.0051**	8.79
TOC	0.22	1.52	**0.0012**	12.19	0.56	0.34
TN	0.22	1.53	**0.00012**	18.26	**0.22**	1.58
GWC (%)	0.099	2.86	0.48	0.52	0.95	0.0042
pH	**1.28E-07**	41.45	0.26	1.33	**0.003**	10.01
Nitrification	**0.0046**	9.03	0.51	0.43	0.26	1.29
Ammonification	**0.031**	5.02	0.76	0.093	**5.21E-05**	20.65
N-mineralization	**0.00042**	14.85	0.45	0.58	0.31	1.044
C:N	**0.0052**	8.75	0.13	2.39	**0.00065**	13.73

	Landscape Position		Depth		Landscape/Depth Interaction	
	P	F	P	F	P	F
Biomass C	0.3	1.13	0.059*	3.89	0.44	0.61
Biomass N	0.64	0.22	**0.037**	4.82	0.64	0.22
TOC	0.9	0.017	**0.00031**	17.24	0.065*	3.72
TN	0.093	3.038	**0.00073**	14.67	0.89	0.018
GWC (%)	**0.022**	5.94	0.75	0.11	0.71	0.14
pH	0.15	2.21	**0.0036**	10.25	0.44	0.61
Nitrification	0.31	1.068	0.21	1.65	0.99	0.0004
Ammonification	**0.032**	5.14	**0.027**	5.49	0.068*	3.62
N-mineralization	0.6	0.29	0.76	0.093	0.53	0.41
C:N	0.56	0.35	0.76	0.099	**0.048**	4.29

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Table 1. MANOVA results of individual and interacting effects of a) burn, soil depth, and burn with soil depth; b) landscape position, soil depth, and landscape position with depth. Bold values are statistically significant (P<0.05), asterisks indicate (P≥0.05-0.1).

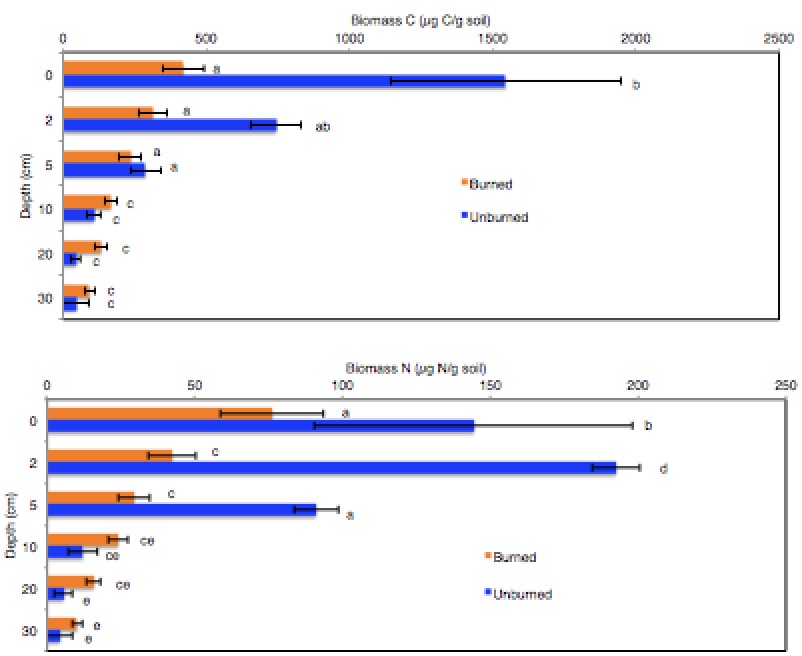

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Figure 7. Microbial biomass C (top) and N (bottom) with depth and between unburned (blue) and burned (orange) soils.

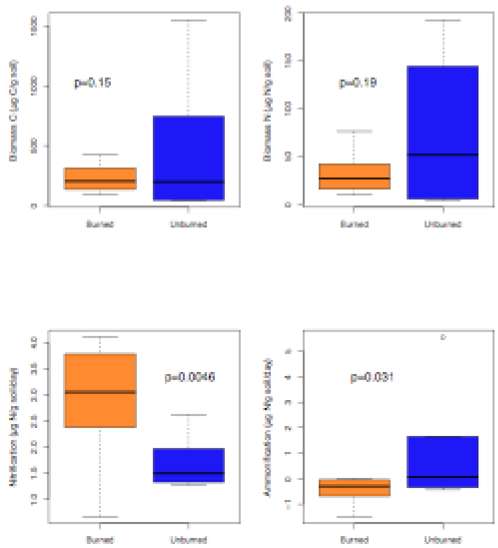

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Figure 8. Microbial biomass C and N (top) and N-cycling rates (bottom) between unburned (blue) and burned (orange) soils; P-values from MANOVA (Murphy et al., in prep.).

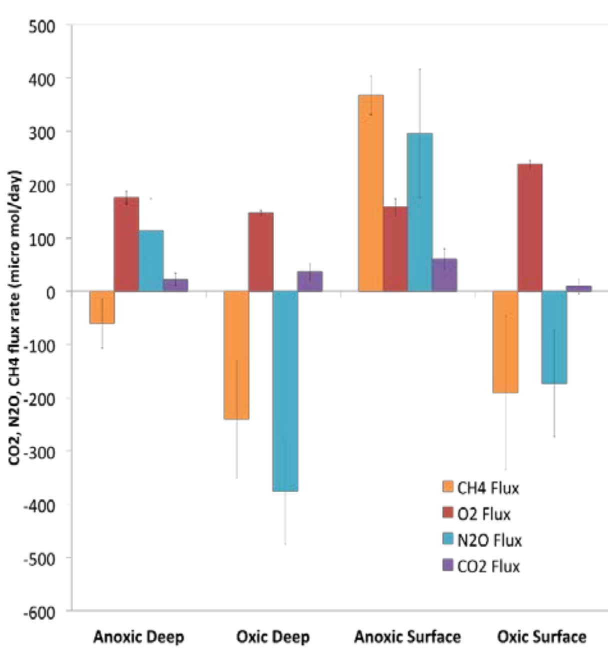

Figure 9. Gas flux rates for soils exposed to oxic vs. anoxic conditions in controlled soil incubation experiment from samples taken at 0-10 cm depth and 30-40 cm depth. Soil samples from the mixed conifer 2013 burned zob corresponding to six sensor instrumentations were flushed with oxygen and N2 gas to simulate fluctuating redox conditions. Data represents gas GC measurements from the two convergent sites (n=2) and four planar sites (n=4) in triplicate replicates for each treatment across both depths studied (i.e. 0-10 and 30-40 cm). Higher fluctuations in greenhouse gas production was observed in convergent vs. divergent sites in response to simulated conditions. Convergent sites show N_2O consumption, which is consistent with observations from anoxic soils and sediments rich in organic matter (Fairbanks et al, in prep).

Table 2. Solute weathering fluxes calculated from soil, soil water, and stream water samples

	Soil Age	Curvature	Water Flux (L/m^2)	TWI	EEMT ($MJ/m^2/yr$)	Na ($moles/m^2/yr$)	Si ($moles/m^2/yr$)
ZOB Soils							
Pedon 1	16900	Planar	54	9.61	25.07	0.06	1.57
Pedon 2	21200	Concave	101	10.84	24.97	0.07	1.70
Pedon 3	21000	Convex	48	8.38	24.67	0.07	1.72
Pedon 4	25400	Concave	39	10.35	25.15	0.05	1.15
Pedon 5	21000	Concave	108	10.42	24.91	0.08	1.97
Pedon 6	16800	Concave	85	9.23	25.11	0.07	1.70
Avg. All Pedons						**0.06**	**1.63**
ZOB Soil Water							
Pedon 5 (2011)						0.003	0.001
Pedon 5 (2012)						0.04	0.03
Avg. 2011-2012						**0.02**	**0.01**
La Jara Stream Water							
WY 2010						0.015	0.04
WY 2011						0.005	0.01
WY 2012						0.009	0.03
Avg. All WYs						**0.01**	**0.03**

*Water flux values through pedons are maximum values for WY 2012 measured from wick lysimeters
TWI = topographic wetness index; EEMT = Effective Energy and Mass Transfer

- Despite the JRB-CZO's semi-arid climate, the regolith thickness, long-term Na and Si mineral weathering rates, and solute concentrations are on par with other more humid environments, likely because of the young age and highly fractured nature of the volcanic bedrock (Table 2).
- The highest weathering rates and solute fluxes, and shallowest regolith and water table are seen in the convergent zones associated with the highest lateral water and DOC fluxes.
- Comparable Na weathering rates across timescales and substrates (i.e. solid vs. aqueous phases), suggests that Na is derived from primary mineral weathering, only limited by water flux, and transported relatively conservatively through the CZ. Previous studies (Zapata-Rios et al., 2015, WRR) confirm increasing Na concentrations with increasing water residence time in springs around Redondo Peak.
- Major differences in the Si weathering rates between pedogenic timescales (determined by chemical depletion profiles of soils) and more recent timescales (e.g. soil water and stream water fluxes), accompanied by saturation indices and Ge/Si relationships, suggests that Si released from primary mineral weathering is precipitated as secondary clays along flowpaths through the CZ.

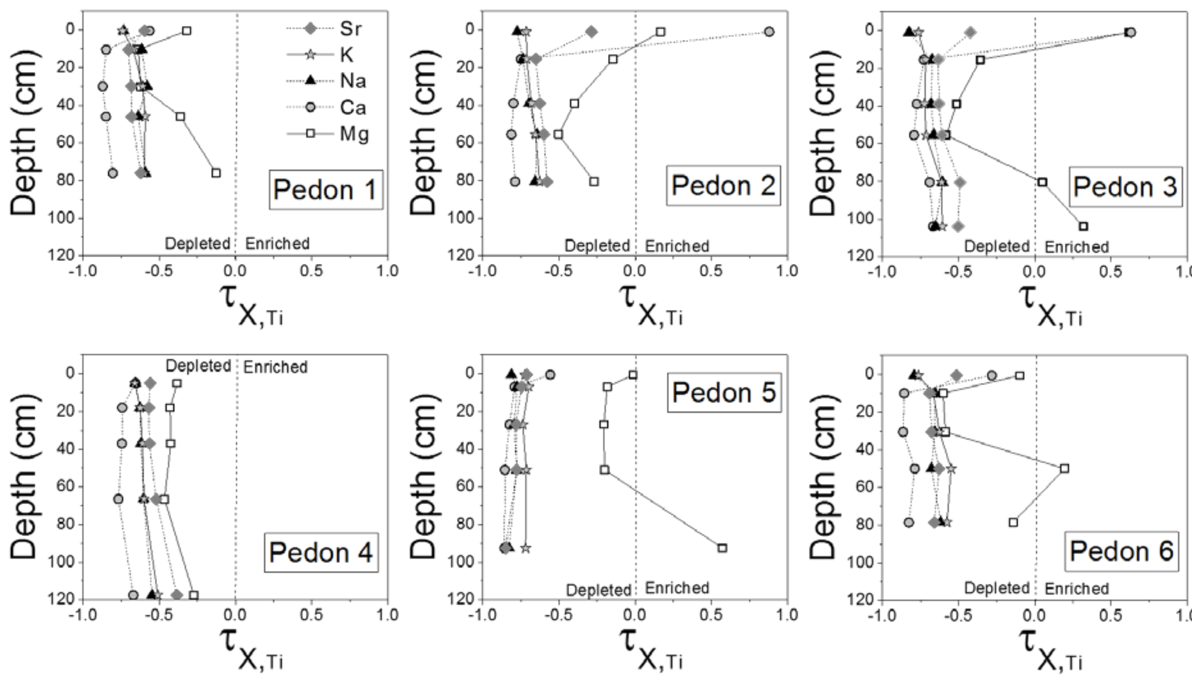

Figure 10. Elemental depletion profiles of major cations from the six pedons in the Mixed Conifer Zero Order Basin (MCZOB) in La Jara catchment. Positive tau (τ) values indicate the element is enriched compared to the bedrock, while negative τ values indicate depletion. Weighted average values of the two bedrock types in the MCZOB were used as the parent material for all of the soil pedons following the same method as Vázquez-Ortega et al. (2015).

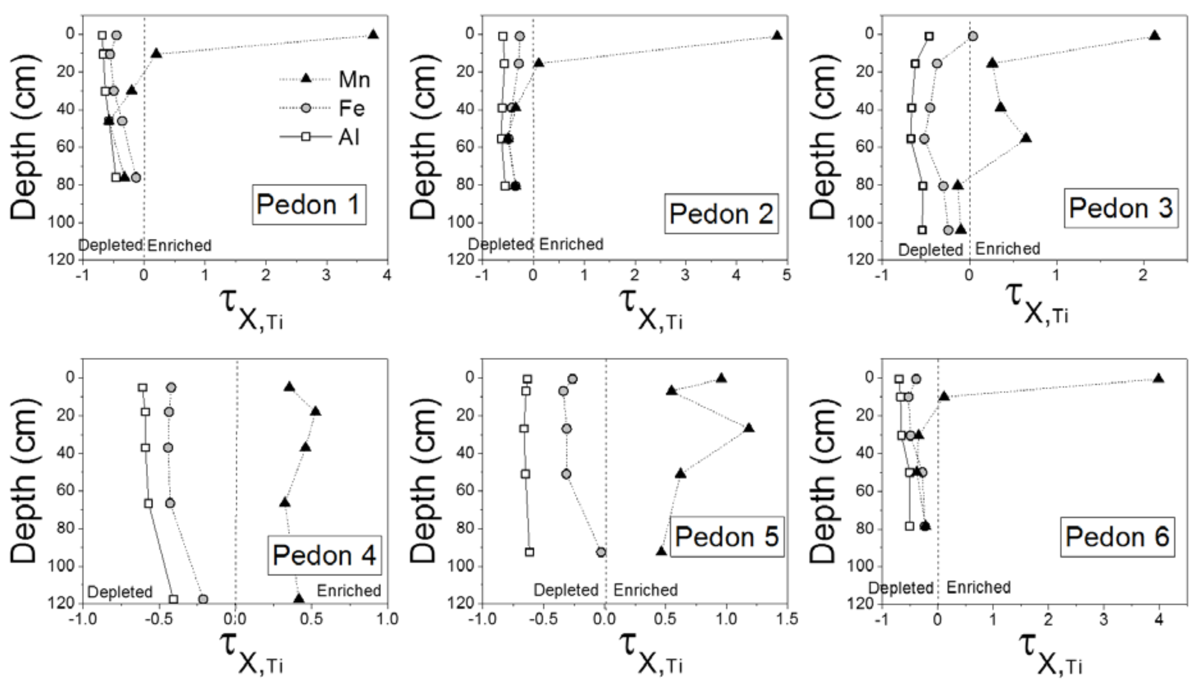

Figure 11. Elemental depletion profiles of redox sensitive elements (total Mn, Fe) and Al from the six pedons in the Mixed Conifer Zero Order Basin (MCZOB) in La Jara catchment.

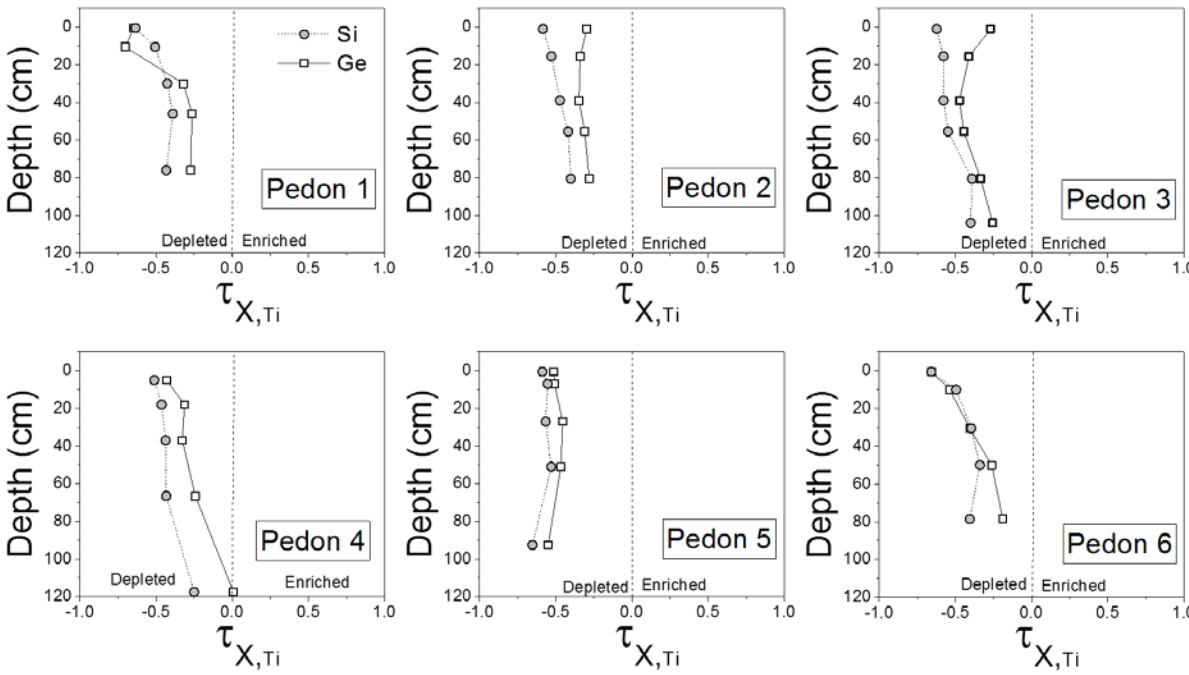

Figure 12. Elemental depletion profiles of Si and Ge from the six pedons in the Mixed Conifer Zero Order Basin (MCZOB) in La Jara catchment.

- Relatively consistent depletion of elements with depth through soil profiles in the MC-ZOB suggests deeper weathering fronts may exist in the regolith/bedrock. Recent geophysical survey results, which show regolith thicknesses up to 49±10 m depth, and visual inspection of core samples from the deep drilling project support this hypothesis.
- Enrichment of Mn, Ca, Mg and Sr in the O-horizon indicates important contributions of those solutes by dust and organic matter degradation/cycling into the upper boundary of the CZ.

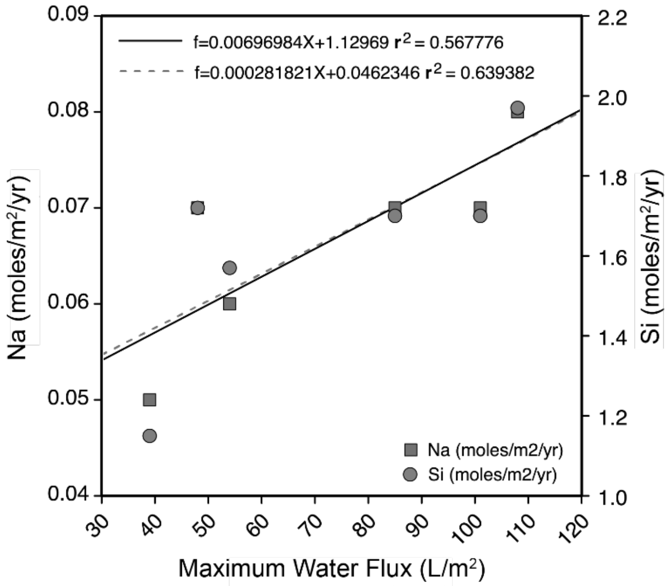

Figure 13. Na and Si weathering fluxes versus maximum water flux (measured in WY 2012) for the six soil pedons.

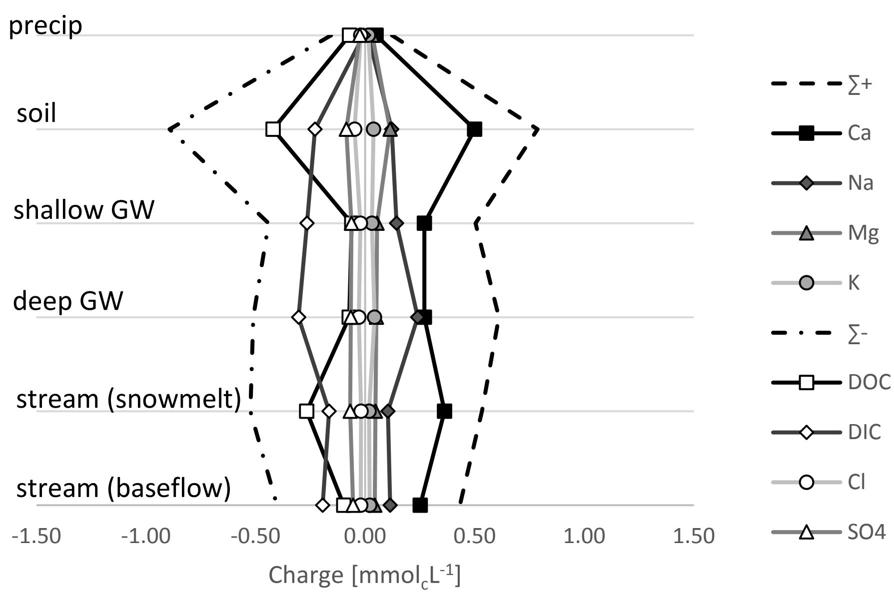

Figure 14. Geochemical evolution of waters through the CZ (shown in terms of charge balance for JRB-CZO samples). Shallow groundwater samples are from high elevation springs around Redondo Peak, while deep groundwater samples are from low elevation springs (Cowboy and Redondo Meadow springs) at the base of Redondo Peak. Dissolved organic carbon (DOC) was assumed to be the balance of leftover negative charge, with charges that varied from -0.3 and -0.5.

- All water types sampled in the La Jara catchment CZ, including precipitation, soil waters, shallow and deep groundwater, and stream water have similar pH values (6.8 average; 0.4 standard deviation) and major cation chemistry, dominated by Ca^{2+}, Na^{+}, and Si, which suggests a similar source of solutes and rock-buffering, likely from dissolution of plagioclase feldpars.
- Soil waters have the highest average concentrations of DOC, Ca^{2+}, Mg^{2+}, Sr^{2+}, Fe, and Al compared to the other water types (Fig. X), likely from evaporation, biologic inputs (e.g. degradation of organic matter) and cycling, and polyvalent cation complexation with organic carbon.
- Shallow and deep groundwater are enriched on average in Na^{+}, Si and DIC compared to soil water, stream water, and precipitation. The increase in Na^{+} and Si concentrations in groundwater with depth (highest value observed in the lowest elevation spring) suggests increased plagioclase weathering along deeper flowpaths with increasing water residence time. Microbial processing of DOC and mineral dissolution can account for the decrease in DOC and increase in DIC between soil water, shallow groundwater, and deeper groundwater.
- The increase in base cations, Si, and DIC with depth also supports the hypothesis that deeper weathering profiles and reaction fronts exist in the underlying regolith in the MC-ZOB than what is observed in the soil profiles, as seen in other CZOs. Borehole excavations in the MC-ZOB indicate visible silicate mineral weathering fronts that extent to more than 40 m in depth.

Surface Water Dynamics:

- Andres Sanchez-Romero's thesis work had two major findings. First, while groundwater is a consistently dominant source of sustained streamflow at the Valles Caldera its importance increases with deeper soils and more northern aspect. Second, the addition of additional source waters is needed to properly represent these more complex flow systems while they are unnecessary in the less complex catchment flow systems.
- Initial results from Brianna McClure's thesis work have allowed the following tentative conclusions. Post fire there is a brief period of increased FI, SUVA and HIX indices indicating an increase in humic substances in the post-fire environment.

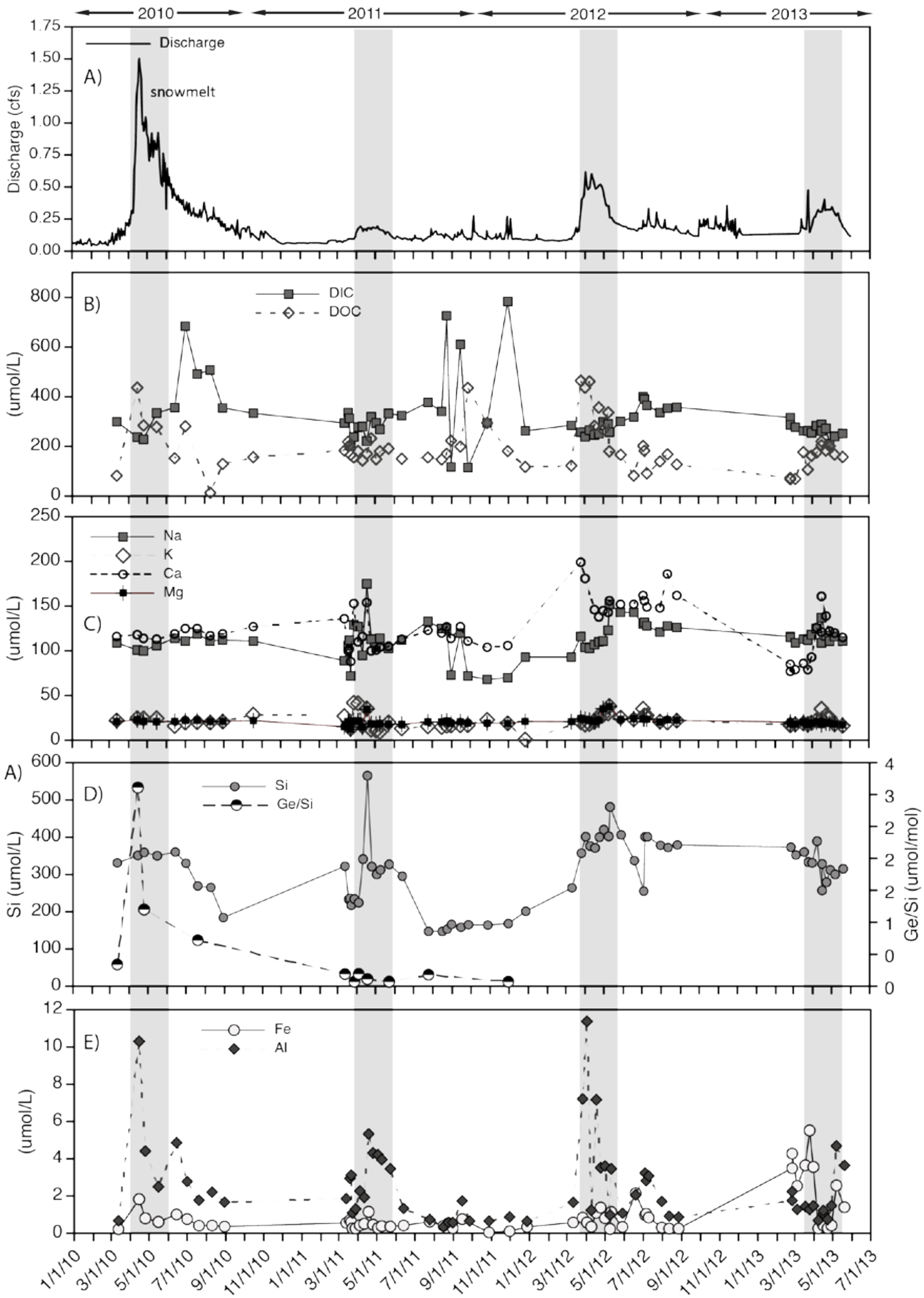

Figure 15. Time series of La Jara Creek discharge (daily) and chemistry prior to the Los Conchas fire in May 2013. Stream water samples were collected at higher frequency (~weekly during spring snowmelt and summer monsoons) starting in 2011 (McIntosh et al., in review).

- Time-series solute chemistry results from catchments draining Redondo Peak (La Jara Cr shown in Fig. 15) show major geochemical fluctuations in response to large shifts in precipitation patterns (i.e. amount and timing of snowpack accumulation) since 2009. Similar data has been collected following the Las Conchas fire (May 2013) and is being used to investigate the effects of fire on water and solute fluxes.
- Spikes in DOC, Al and Fe concentrations, Ca^{2+}, Mg^{2+}, K^{+} and Ge/Si ratios during relatively wet conditions in spring snowmelt in WY 2010 and 2012, and the North American Monsoon (NAM) in WY 2011, indicate periods of soil water flushing and connectivity of hillslopes to the stream. Higher Al concentrations compared to Fe may be attributed to greater degree of colloidal transport of Al. Lower, although detectable, spikes in Al and DOC, and no spike in Ge/Si were seen during spring snowmelt in WY 2011 and 2013, indicating less contributions of soil waters to stream flow during these drier winters with possibly frozen soils.
- Na, Si and DIC concentrations in La Jara Creek throughout the 4 WYs most closely resemble shallow groundwater, indicating it likely sustains stream baseflow throughout the year. Although soil waters contribute to streamflow during 'wet' periods, the stream water Na, Si and DIC concentrations do not change dramatically likely because soil water and shallow groundwater have similar Na, Si and DIC concentrations from weathering of primary minerals (e.g. plagioclase).
- Elevated stream water Si concentrations during snowmelt in WY 2011 and 2012, approaching values for deep groundwater, may indicate some contribution of deeper groundwater, although the Na concentrations in La Jara Creek never reach the high values observed in the low elevation springs (deep groundwater). This suggests that the regional ('deep') water table may not intersect or contribute significantly to La Jara Creek.
- These results suggest that very little snowmelt runs off directly into La Jara Creek; rather, the majority of snowmelt infiltrates and resides in the CZ for a period of time (at least ~12 years according to tritium-based transit times of spring waters; Zapata-Rios et al., 2015b), reacting with soils, regolith and bedrock, before discharging to the stream in subsequent years. Shallow groundwater may exist as perched aquifers in the fractured regolith that may be slowly draining from snowmelt recharge, and discharge laterally to La Jara Creek, as the isotopic composition of shallow groundwater and stream water represent snowmelt throughout the year (Liu et al., 2008a; Zapata-Rios et al., 2015b). Deeper groundwater, possibly from the regional water table, may be primarily disconnected from the stream (i.e., deeper than La Jara Creek). As snowmelt flushes soils on the hillslopes, and/or shallow groundwater flowpaths intersect soils near the stream, they pick up easily mobilized DOC, Fe, Al, Ge, and REY (Vázquez-Ortega et al., 2015). Greater soil flushing during spring snowmelt in WY 2010 and 2012 may be attributed to greater snowmelt infiltration from 'wetter' winters, more consistent snowpacks, and unfrozen soils.

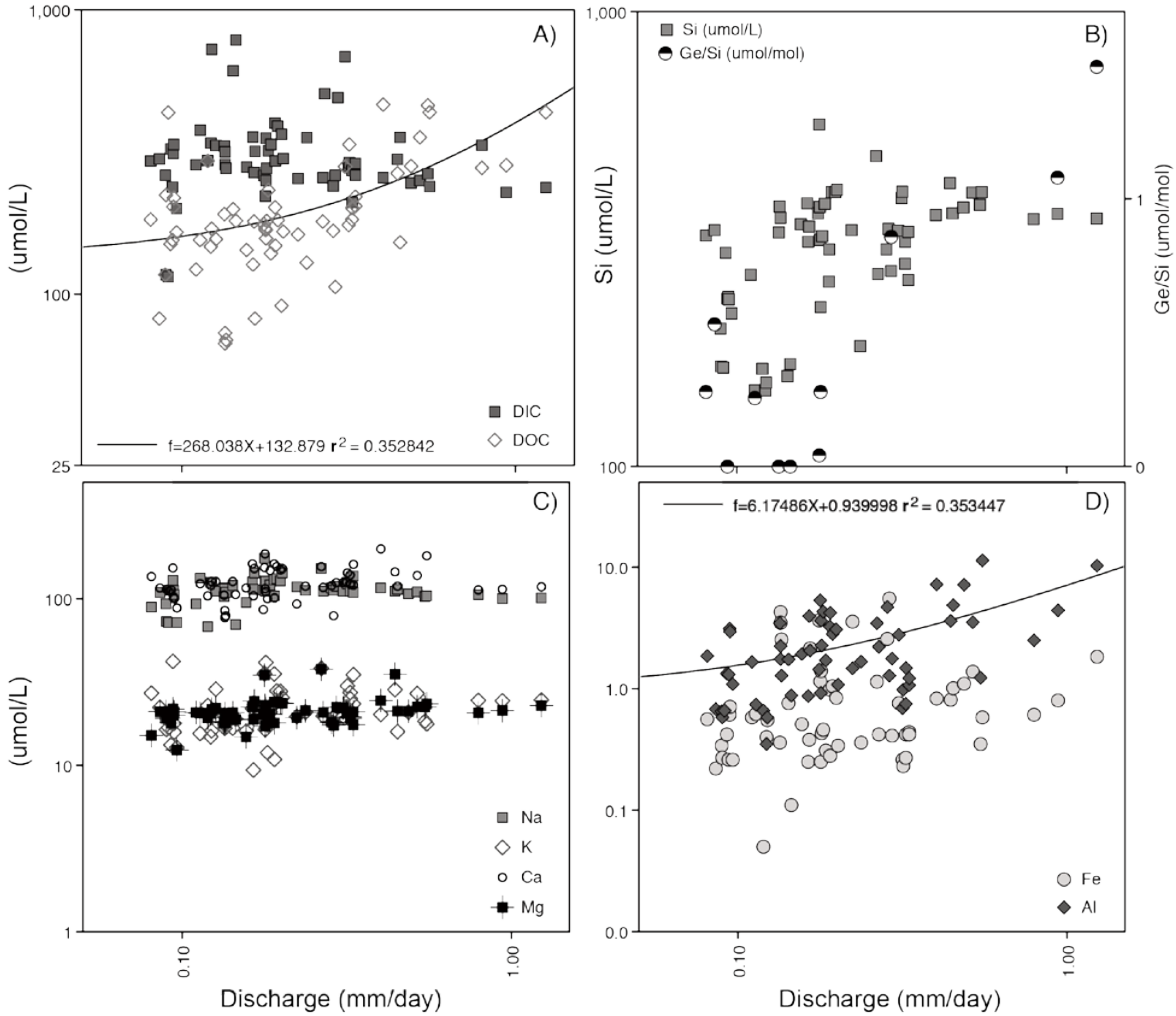

Figure 16. Concentration versus discharge relationships for La Jara Creek stream water on log-log scale. A) Dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) versus discharge; B) Si and Ge/Si versus discharge; C) Major cations versus discharge; and D) Fe and Al versus discharge. Linear regression curves are shown for DOC and Al with associated r^2 values (p values were both <0.05). There was no linear relationship (on log-log scale) for base cations, Fe or Si.

- Several different patterns are apparent in the C-Q relationships for La Jara Creek streamflow: 1) DIC, base cations and Fe are relatively constant; 2) Al, DOC, and Ge/Si ratios are positively correlated with increasing discharge; and 3) Si values are highly variable, except for the highest flow conditions (>0.79 mm/day), which were only seen in the relatively ‘wet’ winter of WY 2010. There is no dilution trend in La Jara Creek streamflow C-Q relationships, further confirming the lack of direct overland flow to the stream in this semi-arid climate, with well-drained soils.

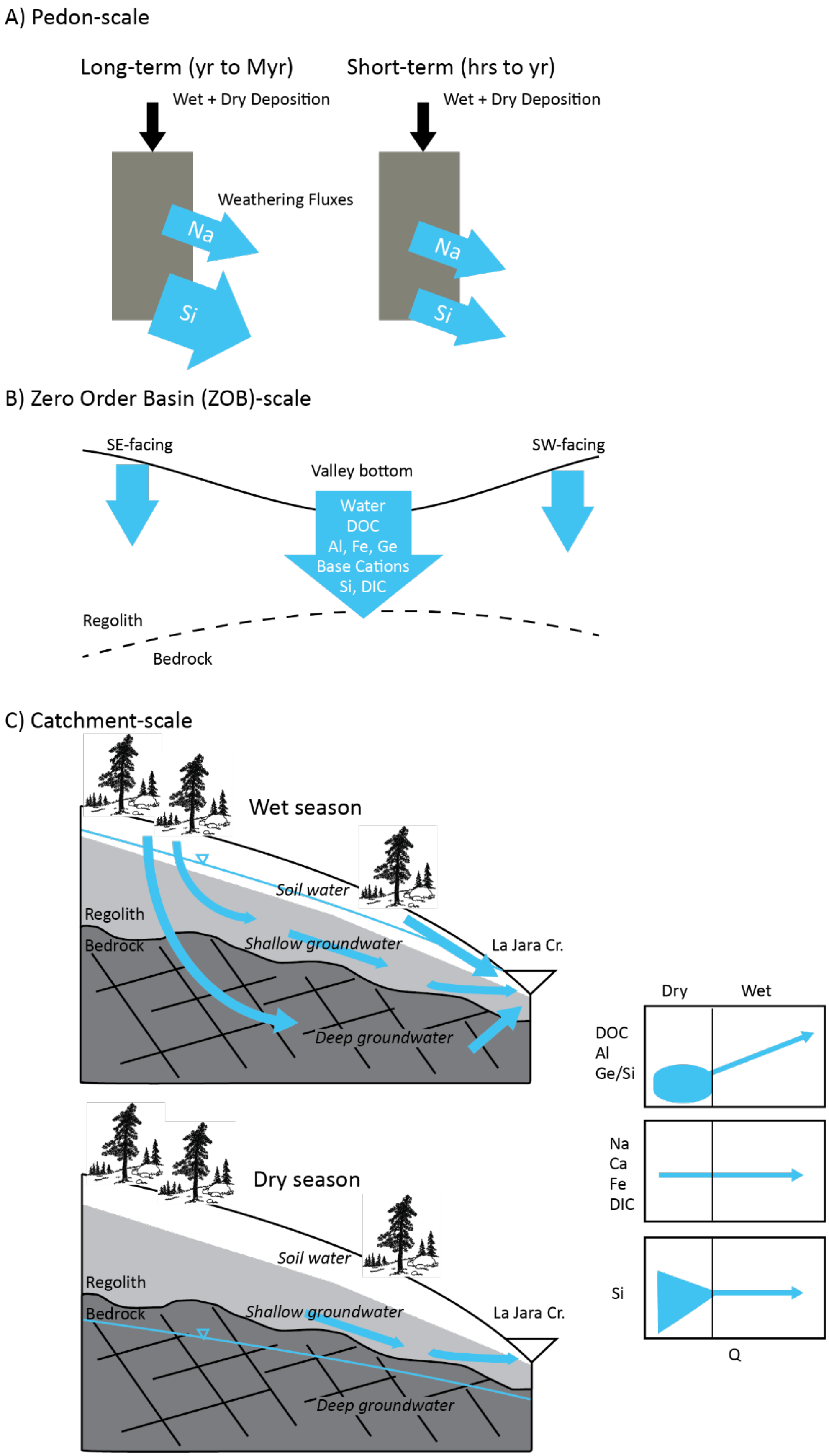

Figure 17. Conceptual model of CZ development, flowpaths, and solute fluxes controlling C/Q relationships across temporal and spatial scales.

- Comparable Na weathering rates between soils (geologic timescales), soil waters and stream waters (shorter timescales; Fig. 17a) suggest that wetting of soil, regolith and bedrock surfaces during spring snowmelt (in relatively wet years) promotes primary mineral dissolution and provides a constant supply of base cations and DIC to soil water and groundwater, only limited by the water flux. In contrast, Si weathering rates are 2 orders of magnitude higher over geologic timescales compared to recent fluxes; the difference in Si weathering rates over time, combined with solute chemistry and Ge/Si ratios suggests that interaction with secondary clay minerals controls Si-Q relationships in soil waters and stream flow.
- The highest base cation, Si, and DIC fluxes were observed in the valley bottom of the MC-ZOB where water and DOC fluxes are the highest (Fig. 17b). Flushing of these convergent zones likely controls C-Q relationships under high flow conditions.
- C-Q relationships in La Jara Creek for DOC, Al and Ge (impacted by colloidal transport and organic matter complexation), and Si vary with availability and routing of water (i.e. wet vs. dry seasons/water years) (Fig. 17c). In relatively wet conditions, DOC, Al and Ge are flushed from soils to the stream increasing their C with Q. Si and base cation concentrations remain constant likely due to production and flushing of rock-derived solutes from different reservoirs in the CZ and mixing in the near-stream environment. Under dry conditions, stream flow is primarily supplied by drainage of perched or shallow aquifers, and reaction with clay minerals likely leading to variable Si concentrations.

Landscape Evolution:

- Won a major high-performance computing grant from NSF-sponsored XSEDE to support the final development and community use (via OpenTopography.org) of a mapping tool that computes solar insolation and EEMT over large areas.
- Documented the predominance of post-wildfire erosion in the topographic evolution of the Valles Caldera (Orem and Pelletier, 2016).
- Documented the thickness of regolith in 7 areas of the Valles Caldera. Related the spatial variations in regolith thickness to aspect and topographic position (Olyphant et al., 2016).
- Documented dependence of slope aspect on topography in several SW US sites, and developed a theoretical model that explains the deviation of slope-aspect asymmetry from N-S to SW-NE (Pelletier and Swetnam, 2016).
- Leading XCZO slope aspect workshop to be held in Tucson, September.
- Troch et al. (2015) reviewed the concept of “Catchment coevolution: A useful framework for improving predictions of hydrologic change?” Water Resour. Res., doi: 10.1002/2015WR017032. Hydrologists have recently called for a more rigorous connection between emerging spatial patterns of landscape features and the hydrological response of catchments, and have termed this concept catchment coevolution. Empirical evidence of the interaction and feedback of landscape evolution and changes in hydrological response is presented. From this review it is clear that the independent drivers of catchment coevolution are climate, geology, and tectonics. Next, common currency that allows comparing the levels of activity of these independent drivers is

identified, such that, at least conceptually, we can quantify the rate of evolution or aging. Knowing the hydrologic age of a catchment by itself is not very meaningful without linking age to hydrologic response.

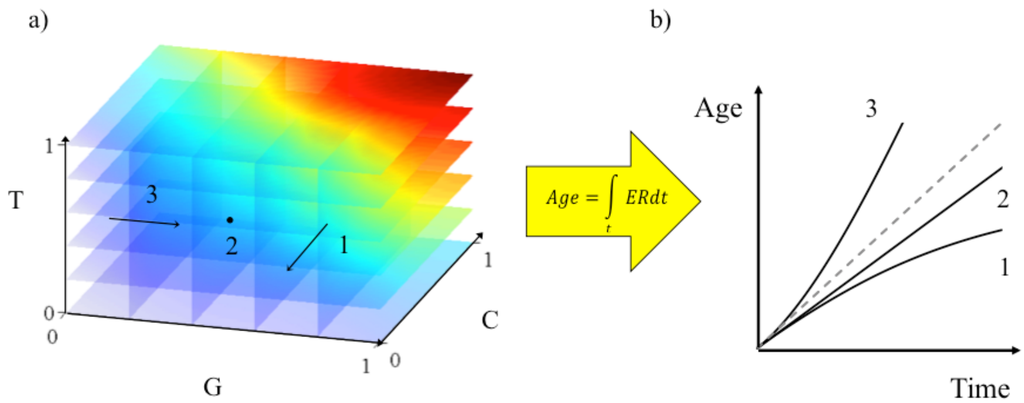

Figure 18. Conceptual diagram illustrating how different combinations of levels of activity of the catchment forming factors (climate (C), geology (G), and tectonics (T)) affect the evolution (age) of a catchment.

Critical Zone Services:

- We have developed a better understanding of ecosystem services using perspectives offered by geosciences (Field et al 2016). We specifically point out that the benefits society receives from ecosystems can be improved by including the spatial and temporal scales utilized by geoscientists.
- A literature review and model parameters are currently being developed to better describe post wildfire runoff and erosion using rainfall simulation. Results of this work will enhance CZO goods and services.
- An additional paper on CZ services has been outlined that will link the key insights from SCM-JRB CZO to date (synthesized for the most recent Virtual Site Visit) to their implications for CZ Services.

Education and Public Outreach:

- Hired undergraduates as Instructional Specialists to facilitate the Critical Zone Discovery (CZD) school field trip program that will begin in Fall 2016. This process engaged science students interested in outreach. The curriculum for the CZD is substantially developed and we will pilot test some of the learning activities during UA Fusion Camp science summer camp at Flandrau Science Center & Planetarium.
- Finalized design documentation for Critical Zone Science exhibit fabrication, hired contractors for exhibit writing, artwork, and construction. All aspects of the exhibit production are underway with “soft” opening planned for July 25.
- Developed and produced the “Mt. Lemmon Science Tour” app, a free smartphone audio tour for the drive/bike up the road from Tucson to the top of the Santa Catalina Mountains. The Tour debuted in November 2015 and has already been downloaded by

over 25,000 users. On the Tour, listeners learn about the fascinating science of Arizona's "Sky Islands Region" including the Critical Zone concept and integrated Earth Science related to the CZ.

- Produced the "Critical Zone Science Café Series" that took place in Fall 2015 as part of ongoing "Downtown Science Café" series. With an average attendance of 70 people per Café, the series of four cafes reached hundreds of people and introduced them to the concept of the Critical Zone and how hydrology, soil science, and geology relate to the CZ. The Cafes were recorded on video and are now available on the Flandrau Science Center's YouTube channel. https://www.youtube.com/watch?v=FsYhPxuhMTs
- Recorded photos and video of field instrumentation and research at UA CZO's Marshall Gulch and Mt. Bigelow research sites, including the Seismic Reflectivity research process. Recorded photos and video of the CZ Drilling Project at one of the Jemez Mountains research sites in New Mexico.
- Worked with soil science graduate student Chris Shepard to apply for a NASA Space Grant that would fund him to work collaboratively with Shipherd Reed and Bill Plant to help produce videos about CZ researchers, research tools, and key science topics. Shepard's grant was funded.
- In the process of producing videos with Chris Shepard about the Seismic Reflectivity research, the CZ Scientific Drilling Project, profiles of grad student and faculty researchers. Videos will go on YouTube and be posted on Social Media to help promote the upcoming exhibit "Welcome to the Critical Zone." Some videos will be included in the exhibit.
- A new Facebook page for the Santa Catlina Mountains/Jemez River Basin CZO at the University of Arizona will help disseminate CZ science and reach a broad public audience with updates on CZO science.

CZO Datasets

- More than 83 million data values are currently stored in the database.
- To present, 48 datasets have been published on the Catalina-Jemez website (http://criticalzone.org/catalina-jemez/data/). Published datasets contains 379 data files in the CZO data display format and GIS standard formats such as ArcGIS shapefile and GeoTIFF. All published datasets are periodically updated after data are processed and quality controlled.
- Seven (7) new datasets were added from 7/1/2015 to 6/30/2016 which includes Jemez EEMT-topo, three Bigelow site datasets and three topographic carbon storage datasets as joint products with the Boulder Creek CZO.
- 748 unique users downloaded 9656 data files from the Catalina-Jemez datasets published on the website for one year period from 7/1/2015 to 6/30/2016.
- To present, more than 17.7 million data values have been harvested to the CZO Central data and metadata depository hosted by the San Diego Supercomputer Center (SDSC). These data are available for download via the CUAHSI Water Data Center services (http://hiscentral.cuahsi.org/pub_services.aspx). These are direct links for 2 Catalina-

Jemez services: http://hiscentral.cuahsi.org/pub_network.aspx?n=158 and http://hiscentral.cuahsi.org/pub_network.aspx?n=177.

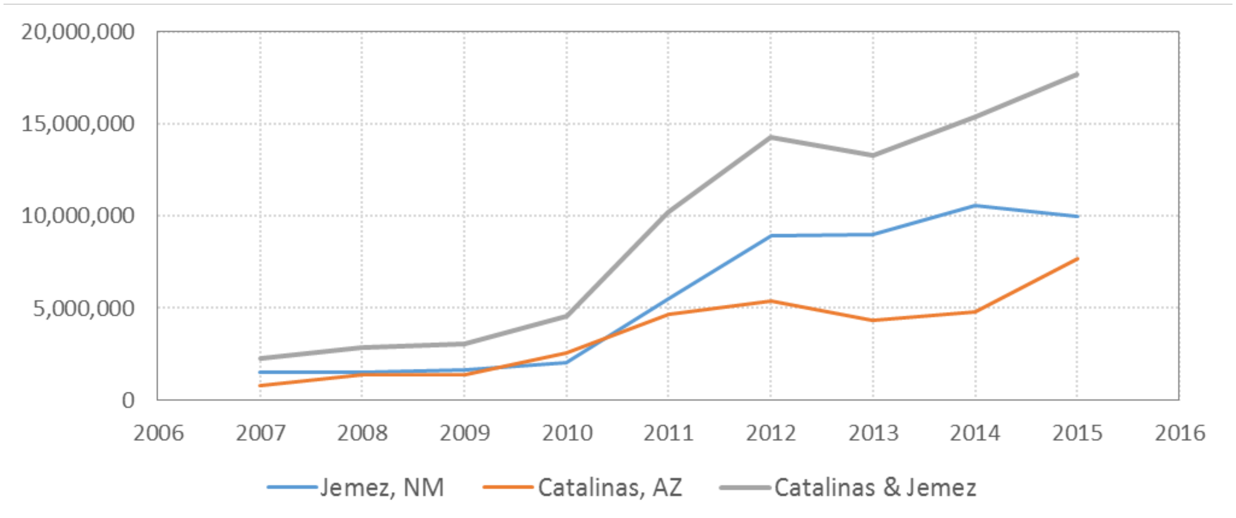

Figure 19. The number of data values collected and stored in the Catalina-Jemez database every year.

Website Usage

The CZO website (http://criticalzone.org/catalina-jemez/) had 5602 visits by 3681 users for one year period from 7/1/2015 to 6/30/2016. Users viewed 18297 pages. The number of new users was 3033 which is 82.4 % of all users and new users started 54.1 % of all website visits.

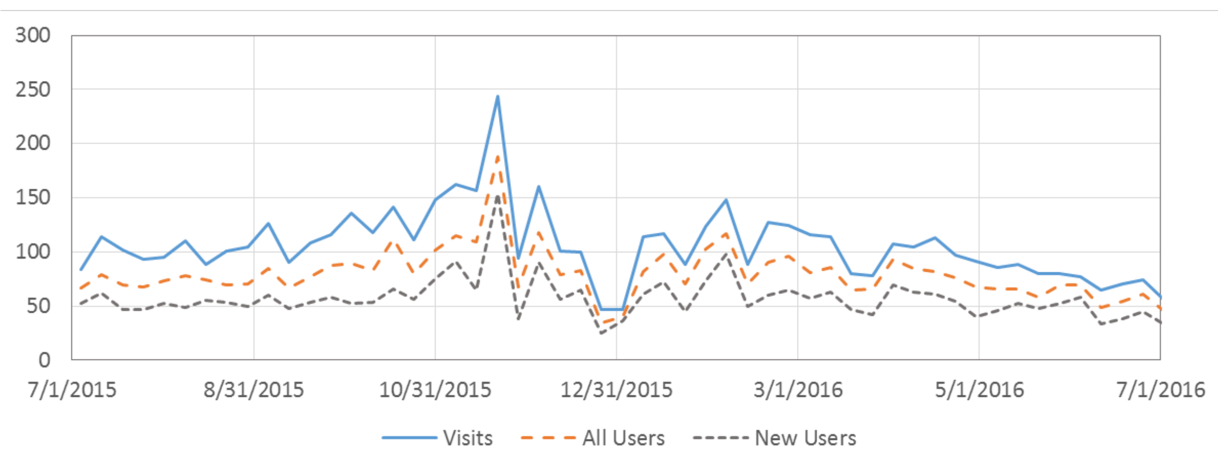

Figure 20. The number of weekly Catalina-Jemez CZO website visits, and new and all users.

3. What opportunities for training and professional development has the project provided?

· Describe significant activities related to student and post doc training and mentoring and report on progress of previously reported activities.

- New class on snowpack partitioning in western CZO's was developed at University of Utah
- The University of Arizona Field Hydrology course continued several specific activities that offered students training and provide data to the project. First, students conducted snow surveys near the Mount Bigelow eddy-flux tower that investigated the effect of vegetation and aspect on snow accumulation patterns. Second, the students investigated the variation in streamflow and chemical composition of the Sabino Creek USGS gauging site. The students also used geochemical data from the Marshall Gulch catchment and the Tucson basin to investigate the geochemical evolution of natural waters in this connected hydrologic system.
- Postdoc Tyson Swetnam co-taught a course with Prof. N. Merchant that developed a High-Performance Computing (HPC) workflow for the calculation of EEMT over large areas.
- Seven undergraduate students presented research posters at the University of Arizona Earth Week Student Symposium using CZO data.
- Barron-Gafford taught a graduate course on Biogeography, and the focus was on analyzing the similarities and differences among the means by which Critical Zone Science, Biogeography, and Ecology have approached integrated Earth Science. Through an extensive literature review and discussions, the class of soil science, ecology, dendrochronology, geography, and natural resource students produced a manuscript in revision at Global Ecology & Biogeography.
- Barron-Gafford mentored an undergraduate through an independent study, in which the student Leland Sutter quantified the influence of aspect on soil carbon efflux rates across dry and wet seasonal periods. The research included spatially distributed point measurements and near-continuous monitoring of CO_2 production in a subset of points on each aspect. The research was presented at an Arid Lands conference, and Sutter has since been accepted into a graduate position in the School of Geography at UA.
- We are training undergraduate students to deliver hands-on science education activities for the CZ Discovery program. We are working with graduate and undergraduate students to develop the CZD curriculum. The CZ Discovery program will launch in fall 2016.
- Post-doc Juan Villegas has built on his expertise in microclimate data collection and equipment installation at the Mt. Bigelow flux tower CZO site.
- Post-doc Jason Field has continued to introduce CZ concepts to high school students in the Project Yes! Program (http://www.tucsonurbanleague.org/what-we-do/project-yes). The 2015 cohort (~15) completed the program and the 2016 cohort (~15) has begun the program. Field also received mentoring on career opportunities and strategic ways to improve his CV.

- PhD student Mallory Barnes has received training on data collection at the Mt. Bigelow flux tower CZO site.
- The "Critical Zone Science Café Series" took place in Fall 2015 as part of ongoing "Downtown Science Café" series and reached hundreds of audience members.
- The "Mt. Lemmon Science Tour" (MLST) app, a free smartphone audio tour about the science of Arizona's "Sky Islands" mountains, provides a science narrative for the drive from Tucson to the top of the Santa Catalina Mountains. The Tour debuted in November 2015, and it has already been downloaded by over 25,000 users. The Tour focuses on integrated earth science and introduces the Critical Zone concept to the general public. Version 1.2 of the MLST will be completed this summer.
- Dawson Fairbanks participated in a training visit to the AquaDiva Collaborative Research Center in Jena, Germany to train on protocols developed to process core drill samples and extract microbial DNA from these oligotrophic environments. She also trained on water field sampling protocols that will be established at our Jemez CZO. This work was funded by the NSF SAVI International Scholars Program (2016).
- Dawson Fairbanks participated in an international Cross CZO Biogeochemistry Workshop focused on developing a paper highlighting the top ten biogeochemistry questions in the Critical Zone held September 2015 at UC Riverside.
- Dawson Fairbanks participated in the UA Carsons scholars program which provides communication training and professional development workshops to better improve scientific communication skills and allows engagement with a cross-department team of graduate students committed to climate change and interdisciplinary research. (January-December 2016)

Summarize the status and results of education activities supported by the CZO.

Collaboration with **UA Women in Science and Engineering (WISE)** organization to create CZ-themed hands-on K-12 science activities, and led 5 workshops disseminating them to **K-12 girls in Southern Arizona** in the Tucson metro area, Sahuarita, and beyond (Dawson Fairbanks and Maggie Murphy).

Tucson Magnet High School- Invited to speak at Tucson Magnet High School in a career development class on what it is like to be an environmental scientist. Graduate student described what it is like to be a critical zone scientist and described job opportunities to encourage young minorities in STEM fields in southern Arizona. (Dawson Fairbanks).

4. How have the results been disseminated to communities of interest?

· Describe progress towards meeting goals for engaging broader research community participation as described in the CZOMP.

- The “Introduction to the CZ” Public Science Café series held in Tucson, with presentations by Chorover, Rasmussen, Meixner, and Gallery) is now posted on Youtube.
- The McDowell et al. (2016) paper on tree mortality was covered in the press by *Science World, Albuquerque Journal, Biotech in Asia, Climate Wire, Counsel & Heal, Delaware First Media, Durango Herald, Eureka Alert – University of Delaware, Forbes, Grist, Huffington Post, LANL Press, Los Alamos Post, Los Alamos Monitor, Nature World News, NM Political Report, Noticias de Sciencias y la Technologia, Phys.org, Portland Press Herald, Public News Service, Science Codex, Scientific American, Summit County Citizen’s Voice, The Daily Caller, The Oregonian*, and *Washington Post* and received an Altmetric score for coverage including social media that was in the top 5% of all research outlets scored by Altmetric.
- The Biederman et al. (2015) paper on tree die-off effects on streamflow was highlighted in Eos (Strelich, Eos 97).
- The Allen et al. (2015) commissioned synthesis was covered in the media by *Science Blog, Spatial News, Web Wire, Click Green, Sierra Sun Times, Summit County Citizen, KYVZ, KUAZ*, and *La Gran Epoca*, and received an Altmetric score for coverage including social media that was in the top 5% of all research outlets scored by Altmetric.
- Brooks has joined the science advisory team for Healthy Headwaters Initiative and Carpe Diem West. This non-profit is a consortium of public utilities, natural resource managers, and NGO’s focused on improving resource management in western North America
- Results from Broxton et al. Harpold et al. and Zapata-Rios et al are being incorporated into forest management activities within the watersheds of the Salt River Project (SRP). The SRP is responsible for supplying water to the Phoenix metropolitan area, one of the most rapidly growing urban areas in the US.
- Three community white papers have been developed to engage the broader research community in CZ science and approaches. One paper is focused more on the ecological community (Field et al.), a second paper is focused on the unique LEO for coupled pedologic, hydrologic, and hydrochemical research, while the third paper is focused more on the hydrologic community (Brooks et al.)
- Barron-Gafford’s undergraduate/graduate course visited the upper elevation CZO sites as part of an experiential learning lab activity.
- We are training undergraduate students to deliver hands-on science education activities for the CZ Discovery program. We are working with graduate and undergraduate students to develop the CZD curriculum. The CZ Discovery program will launch in fall 2016 and will reach hundreds of students from underserved schools, grades 3 through 6.
- The nearly completed "Welcome to the Critical Zone" exhibit will be a compliment to the many school students visiting the "Critical Zone Discovery" program, offering an in depth, hands -on look at the critical zone science concepts. The exhibit will also serve as a great tool for engaging the local community, from school field trips to families as well as out of town visitors with the concept of the critical zone.

- The "Mt. Lemmon Science Tour" (MLST) app, a free smartphone audio tour about the science of Arizona's "Sky Islands" mountains, provides a science narrative for the drive from Tucson to the top of the Santa Catalina Mountains. The Tour debuted in November 2015, and it has already been downloaded by over 25,000 users. The Tour focuses on integrated earth science and introduces the Critical Zone concept to the general public. In April 2016, road signs connected to the Tour were installed by Pima County to alert users to key Tour points. Version 1.2 of the MLST will be completed this summer.
- Photos and Video of field instrumentation and research at UA CZO's Marshall Gulch and Mt. Bigelow research sites.
- **Member, Organizing Committee,** Cross-CZO SAVI Biogeochemistry Workshop, September 28-29, 2015, University of California, Riverside (R.E. Gallery)
- **Speaker**, CZO Microbial Ecology Intercomparison with Cyberinfrastructure-Enabled Data Synthesis Workshop, November 16-17, 2015, Argonne National Labs, Chicago, IL (R.E. Gallery)
- **Lead Convenor,** American Geophysical Union (AGU), Session ID# 9170: Microbial Controls of Biogeochemical Cycling. American Geophysical Union (AGU) Fall Meeting, 2015, Dec. 15, 2015, San Francisco, CA. (R.E. Gallery)
- **Invited Speaker,** Gallery, R.E., Soil ecology and community diversity from semi-arid to tropical forests. Department of Bacteriology, University of Wisconsin-Madison. February 17, 2016, Madison, WI
- **Scientific Advisory Board Member,** NEON Microbial Ecology Working Group, 2014-present, (R.E. Gallery)

· Summarize the status and results of outreach activities supported by the CZO.

CZO Discovery Program- Collaboration with the CZ Discovery Program on curriculum development to ensure activities meet K-12 science standards and tested activities through the WISE program. (Dawson Fairbanks).

American Association of University Women (AAUW), Tucson Branch, Invited Speaker, “Women in Science” April 9, 2016 (R.E. Gallery)

Science Cafe Series CZO, Invited Speakers, Chorover, Meixner, Rasmussen and Gallery.

5. What do you plan to do during the next reporting period to accomplish the goals?

- Mineralogical, geochemical and microbiological analyses of core material extracted during the drilling operation in the MC ZOB, JRB.
- Analysis of three year postburn soils data from MC ZOB (evaluation of black carbon distribution and burial).
- Collection and analysis of well hydrologic and hydrochemical data from JRB.
- Postdoc Swetnam and faculty research associate Nesbitt have been hired to expand empirical and modeling activities associated with terrain mediated energy, water, and carbon partitioning.
- A newly funded proposal from NSF-IOS is combining critical zone observatory data and approaches (terrain and geomorphic) with organismal approaches (plant-hydraulic and evolutionary) to understand resilience and resistance of western forests to widespread drought mortality.
- Working with graduate student Katherine Guns, PI Pelletier will perform lidar data analysis and landscape evolution modeling to quantify and understand controls on bedrock channel morphology and the generation of cliffs in the arid, low-elevation portion of SCM.
- The new exhibit about Critical Zone science and research, "Welcome to the Critical Zone," will open in August 2016.
- In August 2016, we will finish training our undergraduate Instructional Specialists to deliver the activities for the CZ Discovery program. We will promote the program to regional Title 1 schools, schedule school field trips, and deliver programming starting in September 2016.
- An upgraded version (1.2) of the "Mt. Lemmon Science Tour" (MLST) will be released.
- We will begin work on the "Critical Zone Tour" podcast that will build on the science concepts in the MLST app and provide a more complex look at CZ science for users with a higher level of education and interest.
- We will release and promote videos about CZO research and scientists on YouTube for the "CZO Journey" series, working with Chris Shepard. The production and release of new CZ videos will continue through 2017.
- Complete the literature review and model parameters that are currently being developed to better describe post wildfire runoff and erosion using rainfall simulation.
- Complete an additional paper on CZ services has been outlined that will link the key insights from SCM-JRB CZO to date (synthesized for the most recent Virtual Site Visit) to their implications for CZ Services.
- Complete data collection on microclimate change during a dry down on Mt. Bigelow and analyze for relationships with vegetation structure.
- Murphy (MS Student): Anticipated Aug 2016 complete thesis, 2016/2017 publication of thesis material.

- Fairbanks (PhD Student): August 2016 submit enzyme activity manuscript. Fall 2016 process core drilling samples. Fall 2016 complete processing seasonality and aspect experiment. Fall - Spring 2016 analyze DNA 16S and ITS community data for 2013-2015 year samples and seek training opportunities for other bioinformatics processing techniques.

B. Products

Papers published

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Elshall A.S., Ye M., Niu G-Y, and Barron-Gafford G.A. (In Revision) Relative Model Score: A Multi-Criteria Metric for Measuring Relative Predictive Performance of Multiple Models. Water Resources Research.

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Trostle, K. D., J. Ray Runyon, M. A. Pohlmann, S. E. Redfield, J. Pelletier, J. McIntosh, and J. Chorover. (In review) Colloids and organic matter complexation control trace metal concentration-discharge relationships in Marshall Gulch stream waters. Submitted to Water Resources Research.

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<u>Papers in Preparation</u>

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Mitra B., Papuga S.A., and Swetnam, T. (in prep) Observations of species-specific shifts from energy-limited to water-limited transpiration in subalpine mixed-conifer: a seasonal analysis. Water Resources Research.

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Wu, R.-J., G.-Y. Niu, K. M. Dontsova, P. A. Troch, and J. Chorover (2016) Developing a three-dimensional model of colloid transport in porous media in PFLOTRAN, Environmental Modelling & Software (in prep.)

Theses

Balocchi, F, 2016, "Soil behavior during freeze-thaw processes at a snow-dominated forest site simulated with the physically-based numerical water flow and heat transport Soil in Cold Regions Model (SCRM)", M.S. Thesis, Hydrology and Water Resources, University of Arizona

Murphy, M. August 2016. "Interaction of wildfire and landscape position on soil microbial community nitrogen cycling ". MS Thesis, Soil, Water and Environmental Science, University of Arizona.

Sanchez-Romero, A., 2016. "Understanding Process Information Using End-Members in the Critical Zone. Case Study: Valles Caldera, New Mexico." . M.S. Thesis, Hydrology and Water Resources, University of Arizona

White, A. 2015. "Examining the Impacts of Wildfire on Throughfall and Stemflow Chemistry and Flux at Plot and Catchment Scales". MS Thesis, Hydrology and Water Resources, University of Arizona.

Conference Talks or Proceedings

Barron-Gafford, G.A. (*Invited speaker*), Biogeography in the Critical Zone: Insights from the Mountain Tops and Valley Floor. UCLA Department of Geography Tod Spieker Colloquium Series, Nov. 2, 2015, Los Angeles, California.

Barron-Gafford, G.A. (*Invited speaker*), Ecohydrology in our Critical Zone: Insights from Semiarid Mountain Tops to the Valley Floor. School of Natural Resources & the Environment (SNRE) Colloquium, October, 2015, Tucson, Arizona.

Barron-Gafford, G.A. (*Invited speaker*), Examining ecosystem function in space and time within the critical zone through the lenses of ecology and biogeography. Department of Ecology & Evolutionary Biology Colloquium, September, 2015, Tucson, Arizona.

Barron-Gafford, G.A. (*Invited speaker*), Sensor Technologies and Unmanned Aerial Vehicles (drones) to Measure Ecosystem Processes in Semi-arid Environments. Research Insights in Semiarid Ecosystems (RISE) Symposium, October, 2015, Tucson, Arizona.

Begaye, G., T Meixner, and J. Chorover, Changes in DOM Quantity and Quality in a Southern Rockies Forested Catchment, In Abstracts, NGWA Conference - Hydrology and Water Quality in the Southwest, February 23-24, 2016, Albuquerque, NM USA.

Brooks, P.D. et al, Challenges and Opportunities in Managing Headwater Forests, Healthy Headwater Convening, June 2016, Salt Lake City, UT

Brooks, P.D. et al., Ecohydrology in the critical zone: vegetation response to spatial and temporal variability in available water, Annual meeting of the Ecological Society of America, August 2015, Baltimore, MD

Brooks, P.D. et al., Regional Sensitivity of Seasonal Snow Cover, Spring Runoff Conference Plenary, April 2016, Utah State University, Logan, UT

Brooks, P.D. et al., Scale-dependent interactions between vegetation, landscape, and climate: How critical zone structure influences ecohydrological resilience in a rapidly changing world, Fall Meeting of the American Geophysical Union, December 2015, San Francisco, CA

Brooks, P.D. et al., What happens to the rain? Linking advances in fundamental research to applied challenges in sustainable water resources, August 2015, Global Change and Sustainability Center, University of Utah

Chorover, J. What makes the global CZO network greater than the sum of its parts?" International CZO Workshop, Annual Meeting of the American Geophysical Union, December 13, 2015.

Chorover, J. Earth's critical zone: The layer that sustains life. Science Café Series, UA Science, Tucson AZ., September 22, 2015.

Colella, T., S.N. Mann, P. Murphy, J. Minor, J. Pearl, M. Barnes, R. Gallery, T. Swetnam, and G.A. Barron-Gafford, Critical Zone Science in the Anthropocene. Association of American Geographers Annual Meeting, April, 2016, San Francisco, CA.

Dwivedi, R, T Meixner, and P. A. Ferre, Effects of hydraulic conductivity and porosity on the groundwater age distribution in composite systems, In Abstracts – Arizona Hydrological Society Symposium, September 16-19, 2017, Phoenix, AZ USA.

Dwivedi, R, T Meixner, P. A. Ferre, J McIntosh, and J. Chorover, Impact of the projected climate change on the hydrologic functioning of mountain catchments with application to the Marshall Gulch Catchment, Tucson, Arizona, In Abstracts – El Dia del Agua Y Atmosfera, April 1st, 2016, Tucson, AZ USA.

Fairbanks D, Christopher D, Margretta M, Rasmussen C, Chorover J, Rich V, RE Gallery. Microbial ecology at the Jemez River Basin CZO. In Abstracts, SWESx Department Presentation 2016, Mar. 31-April 1, 2016, Tucson, Arizona.

Fairbanks D, K Green, M Murphy, C Shepard, J Chorover, RE Gallery, V Rich. Effects of redox fluctuations on microbial community ecology post-wildlfire in a high elevation mixed-conifer catchment in northern New Mexico. In Abstracts, American Geophysical Union Fall Meeting, 2015, Dec. 15, 2015, San Francisco, CA.

Fairbanks D, Murphy M, Frost G, Shepard C, Rasmussen C, Chorover J, Rich V, Gallery R. Topographic Controls On Soil Microbial Enzyme Activity Post-Fire in the Jemez River Basin Critical Zone Observatory. In Abstracts, Soil Ecology Society Biannual Meeting. June 2015, Colorado Springs, CO.

Fairbanks D, Shepard C, Murphy M, Rasmussen C, Chorover J, Rich V, Gallery R. Microbial biogeochemistry at the Jemez River Basin Critical Zone Observatory. Oral presentation at Department of Geomicrobiology, Friedrich-Schiller University. June 20, 2016. Jena, Germany.

Gallery, R.E., Biodiversity: New perspectives with observatory science. (Invited) Building Global Ecological Understanding (BGEU), University of Delaware, June 3, 2015, Delaware, MD.

Gallery, R.E., D. Fairbanks, V. Rich, M. Murphy, R. Lybrand, N. Trahan, D.J.P Moore. Microbial ecology in the high elevation mixed conifer critical zone. (Invited Symposium): Ecology in the Critical Zone. Ecological Society of America (ESA), 2015, August 9-14, 2015, Baltimore, MD.

Gallery, R.E., The unseen majority: what we know, and still need to know, about microorganisms. (Invited Symposium): IGNITE - When tiny things rule the world. Ecological Society of America (ESA), 2015, August 9-14, 2015, Baltimore, MD.

Hendryx. S, R.L. Minor, T. Colella, P. Murphy, E. Lee, R.L. Scott, P. Kumar, and G.A. Barron-Gafford, Impacts of hydraulic redistribution on plant and soil carbon and water fluxes in a dryland savanna. University of Arizona Arid Lands Poster Session, April, 2016, Tucson, AZ.

Lybrand, R.A., Gallery, R.E., Trahan, N.A., Dynes, E., and Moore, D.J. Disturbance- driven changes in soil exoenzyme activity and biogeochemistry of Colorado Forests. American Geophysical Union (AGU) Fall Meeting, 2015, Dec. 15, 2015, San Francisco, CA.

McClure, B., T Meixner, J. Chorover, A. Sanchez-Romero, and P. A. Ferre, Examining the Impacts of Wildfire on DOM Quantity and Quality in a Southern Rockies Forested Catchment, In Abstracts – El Dia del Agua Y Atmosfera, April 1st, 2016, Tucson, AZ USA.

Moore, D.J.P., Trahan, N., Dynes, E., Lybrand, R., & R.E. Gallery. Changes in soil function after fire and insect disturbance. Ecological Society of America (ESA), 2015, August 9-14, 2015, Baltimore, MD.

Murphy M, Fairbanks D, Boyer Cait J., Gallery R, Chorover J, Rich V, Dynamics of Soil Microbial Nitrogen Cycling in a Post-Wildfire Catchment. In Abstracts, SWESx Department Presentation 2016, Mar. 31-April 1, 2016, Tucson, Arizona.

Murphy M, Fairbanks D, Gallery R, Chorover J, Rich V., Soil Microbial Nitrogen Cycling Responses to Wildfire in a High Elevation Forested Catchment in Jemez Mountains, NM. In abstracts, American Geophysical Union Fall Meeting 2015. Microbial Controls of Biogeochemical Cycling Session, 2015 Dec 15, San Francisco, CA.

Murphy, P., R.L. Minor, D.L. Potts, and G.A. Barron-Gafford, Studying Topographic Controls on Primary Productivity. University of Arizona Arid Lands Poster Session, April, 2016, Tucson, AZ.

Neff, KL, T Meixner, Seasonality of Groundwater Recharge in the Basin and Range Province, Western North America, In Abstracts, 2015 Fall American Geophysical Union meeting, December 14-18, 2015, San Francisco, CA USA.

Niu G.-Y., Representing frozen soil and its effect on infiltration in Earth System Models, 2015 AGU Fall Meeting, 2015, San Francisco, US (Invited).

Sanchez-Cañete, E.P., G.A. Barron-Gafford, J. van Haren, and R.L. Scott, Accurate long-term soil respiration fluxes based on the gradient method in a semiarid ecosystem. University of Arizona Arid Lands Poster Session, April, 2016, Tucson, AZ.

Sanchez-Romero, A., T Meixner, J Mcintosh, J. Chorover. "Understanding Process Information Using End-Members in the Critical Zone. Case Study: Valles Caldera, New Mexico." . In Abstracts – El Dia del Agua Y Atmosfera, April 1st, 2016, Tucson, AZ USA.

Sutter, L., E.P. Sanchez-Cañete, and G.A. Barron-Gafford, An important aspect of soil carbon and water fluxes in desert environments. University of Arizona Arid Lands Poster Session, April, 2016, Tucson, AZ.

White, A., T. Swetnam, J. McIntosh, T. Meixner, P. Brooks, and J. Chorover, Examining the Impacts of Wildfire on Throughfall and Stemflow Chemistry and Flux at Plot and Catchment Scales. In Abstracts, American Geophysical Union Fall Meeting, December 2015, San Francisco, CA.

White, A.M., M. J. Taffet, Examining the Impacts of Wildfire on Throughfall and Stemflow Chemistry and Flux at Plot and Catchment Scales, In Abstracts, 2015 Fall American Geophysical Union meeting, December 14-18, 2015, San Francisco, CA USA.

2. Technologies or Techniques

- Development of a coupled sensor methodology for pore water sampling that triggers tension samplers upon reaching a threshold soil moisture content. Tested and validated in laboratory column studies.
- Near completion of the development of a mapping tool (hosted on OpenTopography.org) that computes solar insolation and EEMT in complex landscapes for any time range over the past 30 years, or as a long-term average. Will provide a measure of energy driving critical zone processes for any landscape at any spatial resolution. The user needs only to specify his/her area of interest. For more information on this effort see the video at http://www.cyverse.org/news/critical-technology-changing-world

C. Participants

2. What other organizations have been involved as partners?

Coronado National Forest, AZ

Valles Caldera National Preserve, NM

University of New Mexico

US Geological Survey (Hanna Coy)

USDA-ARS (Joel Biederman)

University of Utah

Department of Aquatic Geomicrobiology, Friedrich-Schiller University, Jena, Germany

Max Plank Institute for Biogeochemistry, Jena, Germany

USDA-ARS, Southwest Watershed Research Center, Tucson, AZ

Buffalo State University of New York

NSF XSEDE, OpenTopography

Regional Center for Mapping of Resources for Development (RCMRD) in Nairobi, Kenya (the Eastern and Southern Africa hub of the SERVIR Program of NASA and USAID)

3. Have other collaborators or contacts been involved?

- Salt River Project
- Carpe Diem West
- Healthy Headwaters Initiative
- Juan Valdes (University of Arizona)
- Aleix Serrat-Capdevila (The World Bank Group)
- Faith Mitheu and Michael Ngugi Kimani (RCMRD, Kenya)
- Martina Herrmann, Coordinator, Department of Aquatic Geomicrobiology, Friedrich-Schiller University, Jena, Germany. Cross-CZO Training Collaboration.
- Kirsten Kusel, Professor, Department of Aquatic Geomicrobiology, Friedrich-Schiller University, Jena, Germany. Cross-CZO Training Collaboration.
- Susan Trumbore, Professor, Max Planck Institute for Biogeochemistry, Friedrich-Schiller University, Jena, Germany. Cross-CZO Training Collaboration
- Praveen Kumar, Professor, Department of Civil and Environmental Engineering, University of Illinois, Champagne-Urbana

D. Impact

Be sure to discuss impacts of CZO activities including local community engagement and impacts to public policy. Impacts related to activities across multiple CZO sites should be included where appropriate.

1. What is the impact on the development of the principal discipline(s) of the project?

CZ Services: The advances we have developed in providing an expanded framework for CZ services (Field et al. 2016) enables direct applications within CZ disciplines and applicability across the CZ network and beyond.

Environmental Disturbances and Species Shifts within the CZ: Understanding of tree mortality processes, risks and impacts was substantially advanced (Allen et al. 2015, McDowell et al. 2016, Biederman et al. 2015, Breshears et al. 2016, Breshears et al. in press)

2. What is the impact on other disciplines?

CZ Services: The advances we have developed in providing an expanded framework for CZ services (Field et al. 2016) bridges CZ researchers to a separate group of researchers that has been focused on Ecosystem Goods and Services, as outlined in the Millennium Ecosystem Assessment report.

Environmental Disturbances and Species Shifts within the CZ: Understanding of tree mortality processes, risks and impacts (Allen et al. 2015, McDowell et al. 2016, Biederman et al. 2015, Breshears et al. 2016, Breshears et al. in press) reached a broad ecological and environmental science community

3. What is the impact on the development of human resources?

Student training for underrepresented groups.

CZO Micro Team: training 1 MS student (Murphy), 1 PhD student (Fairbanks), 6 undergraduate researchers (Green, Boyer, Kobida, Herndon, Cook, Moreno). All these trainees are women, one is a veteran, and 2 span other under-represented STEM groups.

4. What is the impact on physical resources that form infrastructure?

Developing capabilities to analyze deep subsurface microbiology by extracting DNA from core rock material obtained during summer 2016 drilling campaign.

5. What is the impact on institutional resources that form infrastructure?

6. What is the impact on information resources that form infrastructure?

7. What is the impact on technology transfer?

8. What is the impact on society beyond science and technology?

- The CZ Discovery program will introduce elementary school kids, many of them from underserved (Title 1) schools, to the concept of the Critical Zone, how cycles and systems interact in the CZ to support terrestrial life, and how the CZ provides clean air and water for people and agriculture.

- The "Mt. Lemmon Science Tour" free smartphone audio guide has introduced the general public (over 25,000 downloads and counting) to the concept of the Critical Zone, and to integrated Earth Science like the cycles, systems, layers, and time scales that are part of CZ processes and CZ services.

- **CZ Services:** The advances we have developed in providing an expanded framework for CZ services (Field et al. 2016) enables direct applications of CZ research from across the CZ network not only within the scientific community but to society at large.

E. Changes/Problems

Describe any unanticipated collaborations, research projects, and other endeavors enabled or stimulated by the CZO.

1. Changes in approach and reasons for change

2. Actual or anticipated problems or delays and actions or plans to resolve them

3. Changes that have significant impact on expenditures

4. Significant changes in use or care of human subjects

5. Significant changes in use or care of vertebrate animals

6. Significant changes in use or care of biohazards