Second Annual Report for NSF EAR-0724958 entitled "Transformative Behavior of Water, Energy and Carbon in the Critical Zone: An Observatory to Quantify Linkages among Ecohydrology, Biogeochemistry, and Landscape Evolution" (The JRB-SCM CZO). August 31, 2011.

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Information included in the first annual report is either not repeated or is briefly summarized here. The purpose of the current report is to provide an update on the more recent activities and findings during Year 2 of the Jemez-Santa Catalina CZO project. Some information in this report was included in an interim report submitted to NSF in March 2011, prior to the CZO program review.

<u>1. Major Research and Education Activities.</u> Project funding was initiated in September 2009. The UA portion of the CZO team, comprising 12 faculty, 4 postdoctoral scientists, 16 affiliated graduate students, and a data management specialist, derive from five departments at the University of Arizona. This group meets weekly to discuss research and education progress toward building a CZO that has two observatory locations: The Jemez River Basin NM (JRB) and the Santa Catalina Mountains AZ (SCM).

We hypothesize that *effective energy and mass transfer* (EEMT, MJ m^{-2} y^{-1}) quantifies climatic forcings that shape the co-evolution of vegetation, soils and landscapes in the critical zone (Rasmussen et al., 2010). Testing of this hypothesis occurs across EEMT gradients in the JRB-SCM CZO that also span granite, rhyolite and schist rock types. We expect that gradients in EEMT and lithology will predict key aspects of CZ structure formation from molecular to grain to pedon to watershed scales.

EEMT was calculated across the JRB and SCM CZO surfaces using PRISM data on precipitation and temperature, along with a 10 m DEM and the MODerate-resolution Imaging Spectroradiometer (MODIS) BRDF/Albedo Product data (MCD43A3) (whole CZO image included in our October 2010 report). Resulting data have been incorporated as a layer in a larger CZO geographic information system (GIS) to help identify sites for field campaigns and long term sensor and sampler installations (Fig. 2) (Chorover et al., 2011). For initial sensor and sampler installations, we are focusing on zero order basins (ZOBs) where we make concurrent measurements of ecohydrologic, biogeochemical and geomorphic processes with an interest in determining couplings between them. These couplings scale up to higher order river basins, and down to carbon/water/weathering reactions at mineral surfaces.

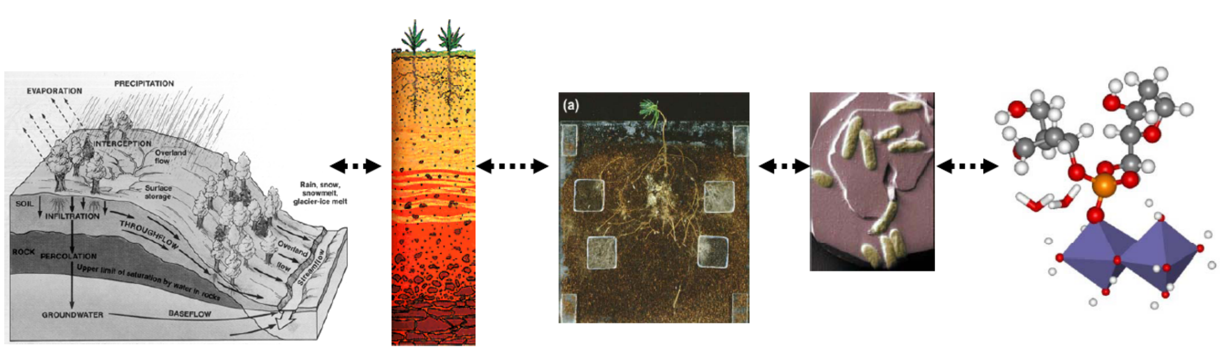


Figure 1. [after http://www.caes.uga.edu/Publications/displayHTML.cfm?pk_id=7173, Banwart et al (Aberdeen), Dohnolkova (PNNL), Omoike et al. (UA)]

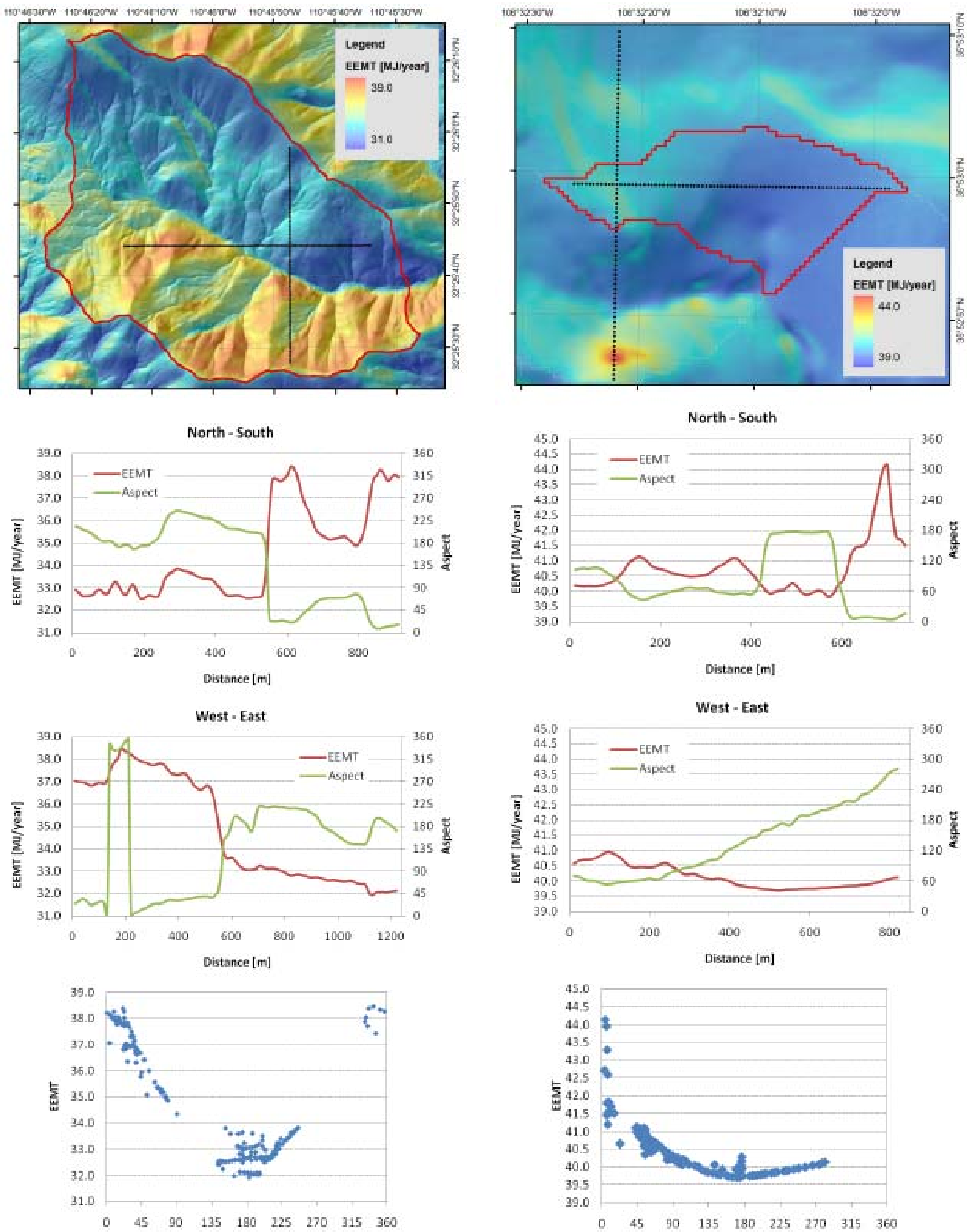


Figure 2. EEMT (MJ m^{-2} yr^{-1}) at the catchment scale all for mixed conifer catchments in the SCM (left, 1.55 x 10^6 m^2) and JRB (right, 1.35 x 10^5 m^2) that are the subject of intensive instrumentation and study. Graphs below show EEMT (MJ m^{-2} yr^{-1}) and aspect values for N-S and E-W transects through the catchments.

Rock types include granite and schist in SCM, and rhyolite in JRB). In the SCM, instrumented ZOBs have been installed at low (ca. 1100 m) intermediate (ca. 2100 m) and high (ca. 2400 m) elevations. In the JRB, a high elevation ZOB (ca. 3000 m) was instrumented in spring, summer and fall of 2010. A mid-elevation site targeted for instrumentation has been located in Cerro La Jara, a resurgent dome in the Valles Grande, and initial installations will occur there in fall 2011. Instrumentation across sites includes selected sites for Eddy flux towers, meteorological stations, precipitation collectors, soil moisture, potential and temperature probes, soil solution samplers, piezometers, flumes, pressure transducers and ISCO samplers.

1.1 Las Conchas Wildfire in Jemez River Basin CZO

An important recent development in our CZO was the Las Conchas wildfire – the largest wildfire in New Mexico state history – that impacted a large portion of the Jemez CZO in June-July 2011 (**Figures 3-6**), and has introduced unique opportunities for interdisciplinary CZ studies of this disturbance effect. The fire was ignited on June 26, 2011, when high winds toppled an aspen tree into a powerline on private land adjacent to the Valles Caldera National Preserve (VCNP). The fire spread extremely quickly after ignition, burning on average an acre of forest every 1.17 seconds for 14 consecutive hours, and it continued to grow for the next five weeks. Approximately 630 km^2 were burned, mostly in the first week of the fire. CZO resources are being allocated to mobilize quickly on an opportunity for collaborative study of burn effects, including instrumentation of a mixed conifer ZOB that contains burned and unburned forest patches, in order to monitor impacts and recovery. Our group considers this an important priority because wildfire is arguably the most important form of disturbance to affect step changes in critical zone structure and function in forested montane landscapes of the Southwestern US.

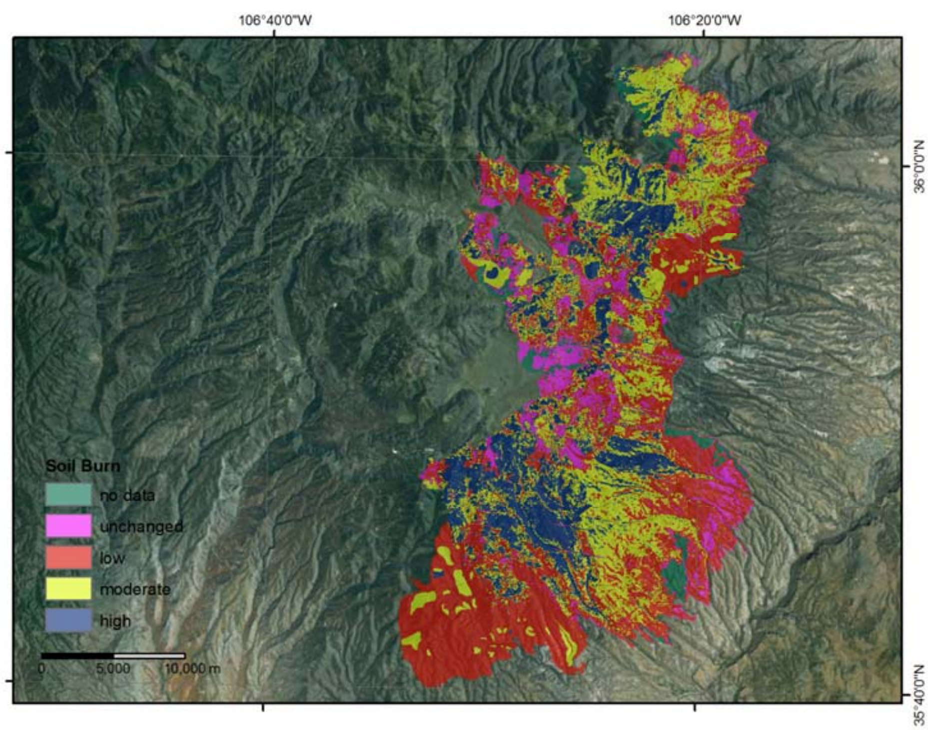


Figure 3. Preliminary assessment of soil burn classes resulting from the summer 2011 (June-July) Las Conchas wildfire in the Valles Caldera National Preserve (VCNP), Jemez River Basin CZO. Data derived from remote sensing, are provided courtesy of John Swigart, GIS specialist at the VCNP.

Figure 4. Spatial variation in fire intensity resulted in a patchy distribution ecosystem impacts. Top image shows understory burn in forest near Valle Grande trailhead off Highway 4. In this location, fire burned only understory grasses and litter on the forest floor. Bottom image shows high severity burn in forest stand on Cerro del Medio. All trees were killed in this patch, and forest floor was transformed to a deep ash layer. (Photos courtesy of Bob Parmenter, Chief Scientist, VCNP.)

Figure 5. Flash flood emerging from Indios Canyon and crossing the VC14 road in Valle Toledo on July 29th. Sediment, ash and charred logs were carried down stream by the flood waters (Photos courtesy of Bob Parmenter, Chief Scientist, VCNP.)

Figure 6 illustrates an example of the extreme geomorphic response following the Las Conchas fire and subsequent rainfall events of the 2011 monsoon season. Prior to the fire, this piedmont had no active channels and was entirely grass-covered. A single thunderstorm on August 5, 2011 formed a 1 km-long gravel-dominated distributary-channel system that transported boulders up to 1 m in diameter (see inset photo). In the weeks following the fire, Co-PI Jon Pelletier and Ph.D. student Caitlin Orem have documented similar extreme erosion and deposition in five fire-affected drainage basins. Interestingly, much of the sediment removed from the steep hillslopes of fire-affected drainage basins is not being transported to piedmonts like that illustrated in **Figure 6**. In the tributary drainage basins upstream from many piedmonts, we have observed deposition and channel avulsions at many tributary junctions, suggesting that the sediment deposited on the piedmont represents only a fraction of the total sediment being removed from hillslopes (the rest is stored at multiple places within the basin). A spatially-complete map of erosion/deposition is needed to properly quantify the sediment budget and geomorphic change caused by the fire and the subsequent monsoon rainfall events.

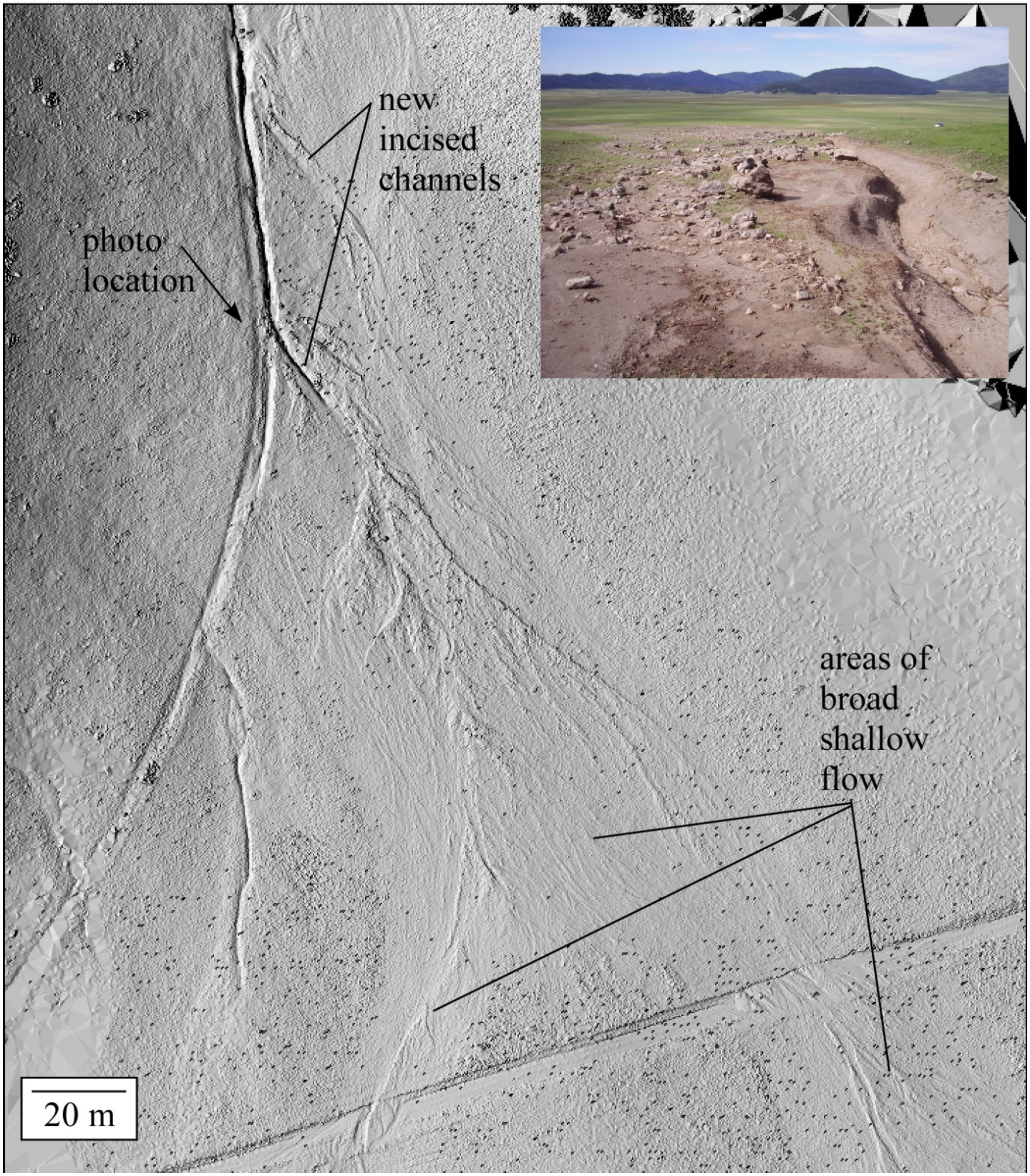


Figure 6. Shaded-relief map (acquired by ground-based LiDAR) of a piedmont downstream from a fire-affected area in the Jemez River basin (Pelletier and Orem, unpubl. data).

1.2 Equipment Installations

Installations that have been completed since the submission of our First annual report (October 2010) include the JRB mixed conifer ZOB and the SCM Oracle Ridge site. Details on instrumentation installed in the JRB MC ZOB were included in our first annual report to NSF, and those pertaining to the SCM Oracle Ridge site are given below. In addition to Oracle Ridge installations, we have proceeded with selected additions to the instrumentation array in the Marshall Gulch and Biosphere 2 desert sites in SCM. Installations to occur in the upcoming fall 2011 season included the JRB burned MC ZOB and initiation of the Cerro La Jara site.

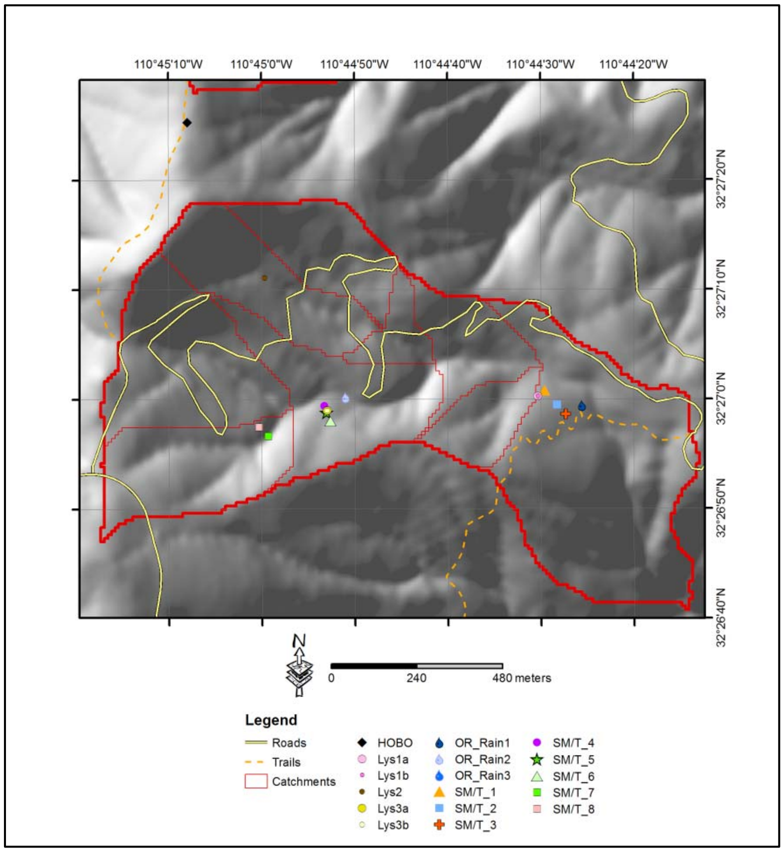


Figure 7. Location of instrumentation at the Oracle Ridge field site.

1.2.1 Installation of the Santa Catalina Mountains CZO-Oracle Ridge Field Site:

The Oracle Ridge site was chosen as a mid-elevation field site for the Santa Catalina Mountains CZO to complement the high elevation Marshall Gulch mixed conifer field site at 2400 m and the lower elevation Biosphere 2 Sonoran Desert field site at 1100 m. The site consists of an upper, middle, and lower sub-site which range from 2000-2300 m. The vegetation transition seen across this site include the pinyon-juniper-oak to ponderosa pine transition. Each sub-site is equipped with soil moisture and temperature data loggers which are co-located with 2-3 soil solution samplers installed at various depths (**Figure 7**). These data loggers and solution samplers are installed in both flow convergent and divergent zones, as they are in all of the SCM CZO sites. Bulk precipitation samplers are installed near rain gauges at each sub-site and are collected after storm events (**Figure 8)**. Surface water, soil water, and rain water samples are analyzed for major cations, anions, trace elements, nutrients, organic and inorganic carbon species, and stable water isotopes. A weather station was installed on Oracle Ridge in September 2010 to measure temperature, rainfall, barometric pressure, and relative humidity. Instrumentation throughout the Oracle Ridge field site was installed between September 2010 and February 2011. Future plans include installing an ISCO for daily and event based surface water sampling as well as establishing a stage discharge relationship at the lower sub-site using a high resolution pressure transducer. Weekly sampling has occurred since January 2011 and will continue perhaps bi-weekly through the winter rainfall and summer monsoon seasons at all SCM sites.

Figure 8. Rain Gauge (OR1) and bulk precipitation samplers at the lower field site at Oracle Ridge.

1.2.2 Santa Catalina Mountains CZO - Marshall Gulch field site new installations:

In an effort to better understand the water budget in our upper elevation ZOBs in Marshall Gulch we installed 9" Parshall Flumes in both the granite and schist catchments. In addition we installed sap flux sensors at each site. Both the schist and granite sites are north facing. The sap flux sensors were instrumented along east-west transects at each site (**Figure 9**) to investigate how aspect, soil moisture, net radiation as well as vapor pressure deficit (VPD) affects transpiration rates at each site. Eight trees in both sites were randomly selected for sap flux measurements with diameter at breast height (DBH) well represented. Tree transpiration was estimated from sap flux velocity (*V*), measured continuously using thermal dissipation probes (TDP) manufactured from Dynamax, Inc. (Houston, Texas). In the schist site sensors were installed in four white fir (*Abies concolor*) and four maple (*Acer pseudoplatanus*) trees while in the granite site sensors were installed in four white fir (*Abies concolor*) and four douglass fir (*Pseudotsuga menziesii)* trees. One sensor was installed in a dead tree in the schist site for background correction. All the probes were installed on the north side of each tree at approximately 1.4 m above the ground. Soil moisture probes were installed at 15, 30 and 55 cm depth while soil temperature probes were installed at 10 and 30 cm. The probes were installed on both the east and west facing slopes in both the sites.

Ongoing and future work in both the sites will involve installation of temperature and relative humidity sensors as well as net radiation sensors. In both the sites, DBH and sapwood depth will be recorded for up to ten individuals for each of the dominant tree species. Sap flux sensors will be installed on twelve more trees on both the north and south side of each tree. Tree cores from all representative tree species will also be collected to extract stable water isotopes.

1.2.3 Biosphere 2 Sonoran Desert Field Site in SCM:

Sampling soil solution chemistry and isotopic composition in the low elevation, Sonoran Desert field site in the SCM has been difficult when we have used tension samplers such as those installed in the higher elevation field sites. This is likely attributable to the low precipitation rates occurring at this elevation, and the rapid soil drainage rates that accompany infrequent precipitation. To address the "flashiness" of these soils, in June 2011 we installed zero tension soil solution samplers (**Figure 10**) which have enabled us to gather soil water samples during the 2011 monsoon season. These soil solution samplers are co-located with soil moisture and temperature dataloggers throughout our desert field site. This will allow us to better compare our three SCM field sites through precipitation, soil water and surface water samples.

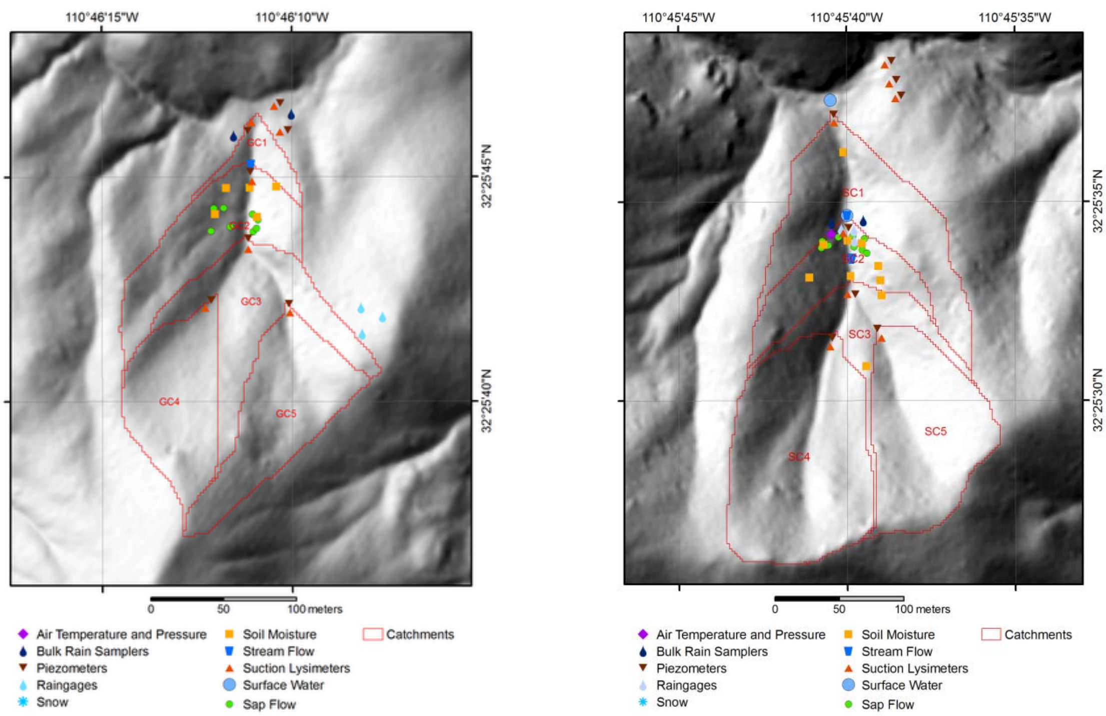
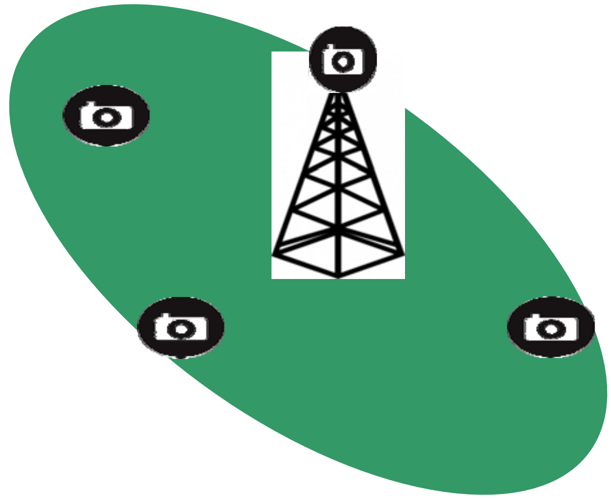


Figure 9. Shaded-relief map of the schist and granite ZOBs within the Marshall Gulch catchment indicating location of instrumentation installations, including new sap flow sensors.

Figure 10. Zero tension soil solution samplers were designed following the procedure outlined by Dr. Eve Hinckley at the Boulder Creek CZO, and installed in the B2 desert site, where infrequent precipitation events and rapid water drainage from sandy soils precludes the use of slow sampling tension samplers.



1.2.4 Installation of Digital Cameras for Time-Lapse Photographic Monitoring

Four cameras were installed at each of the mixed conifer sites in SCM and JRB above 2500 m, within the footprint of the eddy covariance towers. One overstory camera was mounted near the top of each tower just above the LiCor 7500, oriented into the principal direction of wind. All four cameras record images hourly. Images can be analyzed alongside flux and meteorological data from the tower.

1.3 Activities in each of the JRB-SCM Science Themes.

The JRB-SCM CZO is designed to quantify contemporary fluxes of energy, water, and carbon in the CZ in order to better predict long term CZ evolution and structure in semi-arid southwestern environments. Research is conducted in conjunction with the four, cross-cutting scientific “themes” of EHP, SSB, SWD and LSE.

1. ***Ecohydrology and Hydrologic Partitioning*** (EHP)
2. ***Subsurface Biogeochemistry*** (SSB)
3. ***Surface Water Dynamics*** (SWD)
4. ***Landscape Evolution*** (LSE)

Focus on these themes enhances our collaborative progress along complementary CZO research lines to probe common ground with a range of disciplines and techniques. For example, while our LSE theme investigates how long term EEMT forcing of rock weathering and ecosystem change drives soil production and erosion over millennia, EHP, SSB and SWD have the goal of quantifying contemporary rates of water-, carbon- and weathering-driven processes. Contemporary rates of carbon, water and weathering flux will constrain an evolving LSE model that strives for a predictive understanding of their long term effects on landscape evolution (Pelletier et al., 2010, AGU Abstract EP42A-03).

Since single locations (e.g., vegetation stands, hillslopes, ZOBs) within the CZO represent narrow windows in geologic time and EEMT space, they are ideal locations for detailed studies of coupled processes as they occur at their current stage of CZ evolution. These processes are being probed through sensor and sampler installations. To expand the EEMT and geologic parameter space that might otherwise not be explored, we are focusing our installations on small basins that occur along a gradient in climate and on three rock types. By focusing on ZOBs situated in a range of climates within a common larger river basin, we are (i) quantifying climate effects on CZO process coupling (via collocation of measurements of EHP, SSB, SWD and LSE), and (ii) scaling up process-level understanding to resolve the dynamics of catchment aggregates and larger watershed systems (e.g., Santa Cruz and Jemez River Basins). These river basins – that capture essential water resources for growing human populations in the Southwest and that are expected to become hotter and drier with climate change – are likely to be dramatically affected by up-gradient changes in climate forcing.

1.3.1 Ecohydrology and Hydrologic Partitioning Theme

The EHP group works closely with the other thematic groups (LSE, SWD, SSB), via weekly meetings, to address the following **three hypotheses**:

Energy: Hydrologic partitioning is uniquely related to effective energy;

Water: Vegetation controls pedon-scale water transit time; geomorphology controls catchment-scale water transit time;

Carbon: Hydrologic partitioning and water transit time control DOC and DIC input to subsurface.

EHP research efforts are focused on **two overarching questions** that guide installations and observations.

(i) How do ***temporal changes in vegetation structure and activity (e.g., mortality, phenology, seasonality****) affect hydrologic partitioning and the resultant transfer of water and carbon to subsurface and streamflow?*

(ii) How does spatial variability in ***vegetation structure*** *reflect or control patterns in* ***hydrologic partitioning*** *over the last 1 – 100 yrs?*

Recent activities pursued by the EHP group to address these questions:

- The first question is being largely addressed in instrumented ZOBs with measurements co-located with those from other themes.

- Addressing the second question relies primarily on distributed observations. This latter research is closely related to work in the ZOBs, but is required to scale sub-catchment and catchment-scale observations to larger areas. Distributed observations also take advantage of ongoing related work in the region.

- Installation of phenocams and meteorological stations in both SCM and JRB ZOBs, most recently in Oracle Ridge site (SCM) and the La Jara mixed conifer ZOB (JRB) to permit continuous data acquisition and visual observation (Nelson and Kurc, AGU Abstract B23G-0468**)**.

- Measuring net ecosystem exchange (NEE) of water and carbon to assess inputs to CZ processing in both JRB and SCM (John et al., 2010, AGU Abstract H33C-1154).

- Installation of sap flow sensors in association with SSB instrumentation in the JRB MC and Marshall Gulch ZOBs.

- Ground-truthing of vegetation and snowpack to assist with interpretation of new LiDAR data acquisitions during (March 2010) and minimum (July 2010) snowpack.

- LiDAR data analysis has been performed to assess relations between snowpack and vegetation distribution in CZO landscape positions.

- Modeling transition of spatial controls on distributed soil moisture and runoff at multiple model resolutions. (Mahmood and Vivoni, AGU Abstract H41F-1133).

1.3.2 Subsurface Biogeochemistry Theme

The SSB group works closely with the other thematic groups via weekly meetings to address the following **three hypotheses**:

Energy: Mineral weathering rate/transformation increases with EEMT resulting in concurrent changes in soil C stabilization.

Water: Ratio of inorganic carbon to organic carbon flux increases with increasing water transit time.

Carbon: Wet/dry cycles promote CO_2 production, enhancing mineral weathering and thereby promoting greater soil C stabilization.

The SSB research efforts focus on **two overarching questions**:

(i) How does the critical zone partition total rock weathering into components of:
(a) chemical denudation (elemental mass loss at pedon/hillslope scales);
(b) primary to secondary mineral transformation (element retention in thermodynamically stable forms).
(ii) *In the subsurface, how is net ecosystem exchange partitioned into:*
(i) DOC/POC, DIC export;
(ii) stable soil C pools;
(iii) physical erosion of soil C.

We developed a field design to address these questions and hypotheses across both the JRB and SCM CZO locations. Work in the present reporting period has focused on:

- Instrumenting the JRB La Jara mixed conifer (MC) ZOB with meteorological station, soil solution samplers, soil moisture, temperature and water potential sensors, piezometers, and streamwater discharge flume.

- Monitoring ZOB sensors and collecting samples generated during and following installation.

- Measuring gaseous CO_2 and aqueous DOC effluxes from CZO surface soils.

- Establishing within each ZOB "catena" or hillslope transects that run perpendicular to the ZOB - from ridge to hollow to ridge. Along these transects, locations are chosen for soil sampling, in situ monitoring of soil water content and temperature, and soil solution collection.

- Establishing instrumented ZOB transects in the mixed woodland to ponderosa pine vegetation types of the Oracle Ridge site, thereby providing a site with climate intermediate to the desert scrub (lower elevation, hotter and drier) and mixed conifer (higher elevation, cooler and wetter) ecosystems on granitic and metamorphic parent materials.

- Charactering soil biogeochemical and mineralogical properties and collecting soil moisture, temperature and solution samples on the JRB and SCM ZOBs (Lybrand et al., GES Abstract, 2011; Chorover et al., 2011).

- Completing isotopic analysis on collected surface soil samples from various aspects and landscape positions to begin to quantify variation in soil C and DOC content and quality.

- Conducting laboratory-based experiments on reactive transport of CZO-derived dissolved organic matter in soil columns (Vazquez-Ortega et al., AGU Abstract B13D-0503).

1.3.3 Surface Water Dynamics Theme

The SWD group works closely with the other thematic groups (LSE, EHP, SSB), via weekly meetings, to address the following set of research questions as part of our CZO efforts:

(i) How does carbon and nutrient cycling vary as a function of EEMT, bedrock lithology, and water transit times?
(ii) How do chemical denudation rates vary as a function of EEMT, bedrock lithology, and water transit times?

These broad questions are promoting cross-site comparisons between the Santa Catalina Mountains and Jemez River Basin, as well as with other CZO sites. We are starting with EEMT observations and moving towards more process-based hypotheses/understanding. Research intends to interpret catchment-scale dynamics in terms of nested instrumentation at the pedon to hillslope-scale. Our research questions place emphasis on determining water transit times, flowpaths, carbon systematics, nutrient dynamics and chemical denudation rates, which are now key foci of the SWD group. Overarching goals of this research are to understand sources and transformations of carbon from catchments and riparian areas to streams, closely linking with results on carbon, nutrients, solutes (i.e. dissipative products of chemical denudation) and water processing from the EHP and SSB groups. In addition, we aim to determine how chemical denudation rates vary as a function of water transit times, which will hopefully provide insight into why natural versus laboratory weathering rates are orders of magnitude different. We hope to better constrain hydrologic partitioning in mountain catchments and mountain block recharge, which has important implications for groundwater resources in adjacent alluvial basins.

The SWD group conducted multiple field campaigns in 2010-2011, and installed new instrumentation to begin to address these questions:

- Surface waters and springs have been sampled from catchments draining Redondo Peak (including the La Jara ZOB), and the Valles Grande in the Valles Caldera Preserve in the Jemez Mountains every 2-4 weeks from March to October, starting in 2009. Higher frequency sampling was conducted in spring and summer 2011, with the aid of autosamplers (ISCOs) installed on select streams (Upper Jaramillo, La Jara) and the ZOB outlet, to better capture daily snowmelt and monsoon dynamics.

- A second JRB CZO snow survey was conducted mid-March (2011) to measure snow water equivalence (to couple with recent LIDAR data), in addition to solute and isotope chemistry (to couple with stream water and soil water data). Daily snowmelt samples were also collected for isotope and solute chemistry from two autosamplers (ISCOs) installed on west and east facing slopes in the ZOB.

- New flumes were installed at the La Jara ZOB outlet, and near the outlet of La Jara Creek to better capture stream flow. Several rainwater collectors were also installed within the ZOB, and near the La Jara and Upper Jaramillo flumes to investigate variations in rainwater solute (without mineral oil) and isotope (with mineral oil) chemistry (**Figure 11**). ISCOs were attached to the two rainwater collectors in La Jara and Upper Jaramillo to capture events (**Figure 12**). Dust collectors were also installed to measure dry deposition.

- Hydrometric and hydrochemical data have been collected from summer 2006 onwards in two ZOBs located at the high elevation site (Marshall Gulch) in the SCM. Initial funding came from SAHRA (startup funding Peter Troch) and State of Arizona (Water Sustainability Program; Peter Troch and Jon Chorover). Stable water isotope concentrations in rainfall, snow melt, soil water and stream water were determined using a Los Gatos DLT-100 laser spectrometer. On average, weekly sampling took place during most of the year when sites were accessible (during winter snow pack soil water lysimeters could not be accessed). These data are being used to test a novel method to quantify the time varying nature of water transit times at ZOB and catchment scales (Heidebuchel et al, 2010, AGU Abstract H11C-0813).

- Surface and soil water samples are beginning to be collected at the newly installed mid-elevation ZOB (Oracle Ridge) in the Santa Catalina Mountains.

- All water samples were analyzed for major cations, anions, trace and rare earth elements, nutrients, organic and inorganic carbon species, and stable (^{18}O, ^{2}H) isotopes. Select samples have been analyzed for carbon and strontium isotopes. Sample aliquots were preserved for additional analyses (Ray et al., 2010; AGU Abstract Abstract B21D-0340, Perdrial et al., 2010, AGU Abstract B12A-05).

- Several manuscripts (listed in the publications section) have been submitted, or are in prep on results from the first two years of water sampling. We also continue to synthesize results, and refine our research questions and approach for next years sampling efforts.

Figure 11. Bulk rain collectors: a) La Jara flume, b) Upper Jaramillo flume, c) ZOB meteorological station.

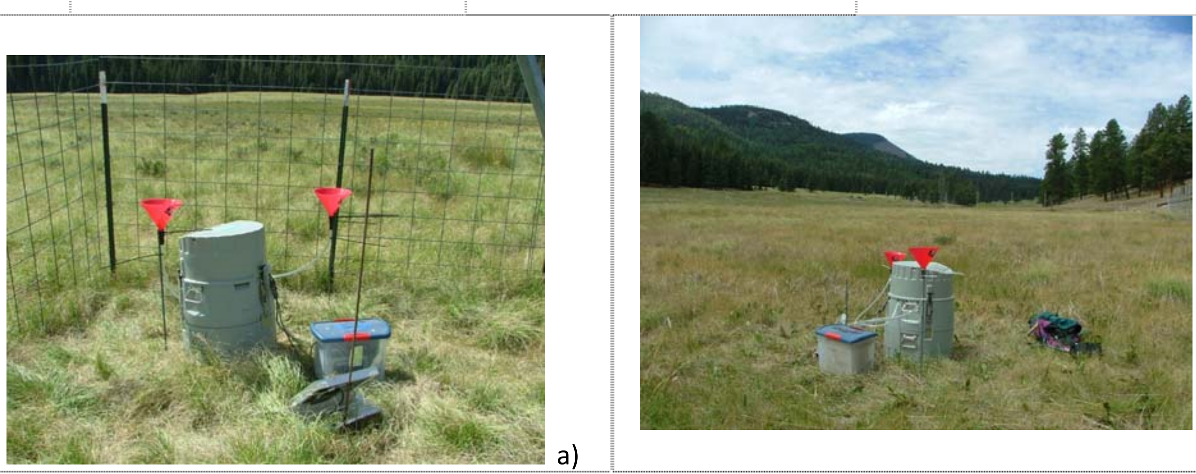


Figure 12. ISCO rain autosamplers: a) VCNP headquarters station, b) Upper Jaramillo protected area

1.3.4 Landscape Evolution Theme

The landscape evolution theme within the JRB-SCM CZO project seeks to understand and quantify how topographic measures (e.g. hillslope relief, valley density) and rates of fluvial and hillslope erosion are controlled by climate/EEMT and rock type/structure. Landscape evolution involves feedbacks over long time scales with pedology, hydrology, and ecology, hence there are natural overlaps between LSE activities and those of all other project subthemes.

Principal activities during the current reporting period include:

- A graduate course taught by Jon Pelletier conducted an extensive field data collection campaign in Banco Bonito (JRB) to assess controls over soil depth as a function of topographic position (Pelletier et al., *in press*).

- Development of a reduced complexity numerical model to describe the co-evolution of topography, hydrology, soil development, and vegetation in sky islands of the southwestern United States such as those characterized by the JRB-SCM CZO (Pelletier et al., AGU Abstract EP42A-03, and *in prep*.).

- Post-fire ground-based LiDAR data collection in the JRB to quantify sediment transport associated with summer monsoon rains following the Las Conchas wildfire.

2. Major Findings from Research and Education Activities (Current Reporting Period)

2.1 Ecohydrology and Hydrologic Partitioning Theme.

LiDAR Data Analysis. A critical control on the partitioning of water and carbon within the critical zone is the structure and composition of vegetation at the land surface. LiDAR data obtained during the summer of 2010 has been used develop distributed vegetation structure throughout our CZO sites. Ground truth data from 48 randomly-selected 38-m diameter plots quantified the height, diameter at breast height (DBH), species, and condition of every tree. These data are being compared to LiDAR-derived estimates of NDVI, above-ground biomass, and species composition and also provide the foundation for future LiDAR flights to assess changes in tree condition over time. Using these data we will map canopy height, LAI, above ground biomass, dominant species, condition, and disturbance throughout the CZO (**Figure 13**.).

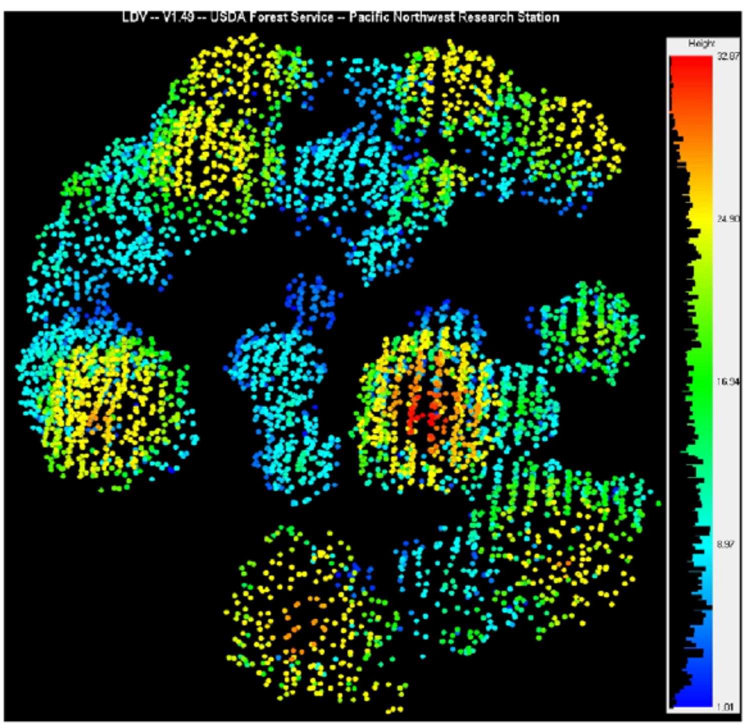


Figure 13. LiDAR derived canopy structure within the JRB CZO.

<u>*Snow depth and water equivalent.*</u> Precipitation inputs to the CZ represent a key forcing that controls subsequent processing toward CZ structure formation. In snow-dominated systems such as the upper elevations of the JRB, a large fraction of incoming precipitation occurs as snow, which can undergo sublimation prior to surface runoff, soil infiltration and/or plant uptake. We have found that variation in snow water equivalent (SWE) correlates with solar forcing (**Figure 14**).

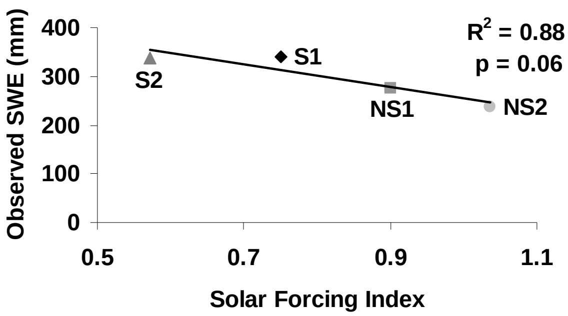


Figure 14. The observed variability in SWE (snow water equivalent) at maximum accumulation correlates well with solar forcing index at sites with similar total winter snowfall. More than 25% of winter snowpack sublimates at locations with high solar energy input, and thus never enters soil to be partitioned among runoff, recharge, or plant water use. (J. R. Gustafson, P. D. Brooks*, N. P. Molotch, and W. C. Veatch *Water Resour. Res*., 46, W12511, doi:10.1029/2009WR009060.)

Within our highest elevation (MC) ZOB, vegetation structure interacts with topography to control the partitioning of incoming precipitation as snow. These controls affect spatial patterns in maximum snow accumulation and occur before the growing season begins and as such are in addition to transpiration fluxes. For example, LIDAR coverage the JRB MC ZOB (**Figure 15**) shows that the seasonal snow pack before melt stores much more water on the shaded north side of vegetation stands than in either open areas or the south side of vegetation. Our LiDAR data therefore confirms the results of Gustafson (above) and provides a mechanism to spatially distribute net ecosystem water input across our CZO sites.

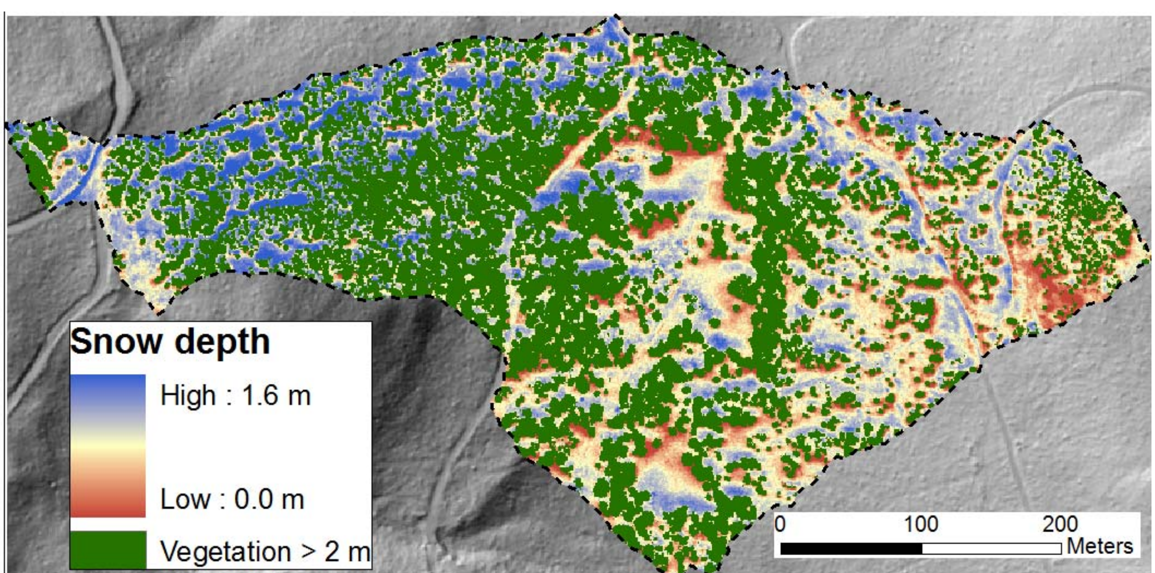


Figure 15. Snow depth at maximum accumulation within the JRB-SCM CZO upper elevation ZOB during the spring of 2010 derived from LIDAR data (Harpold et al., unpubl. data).

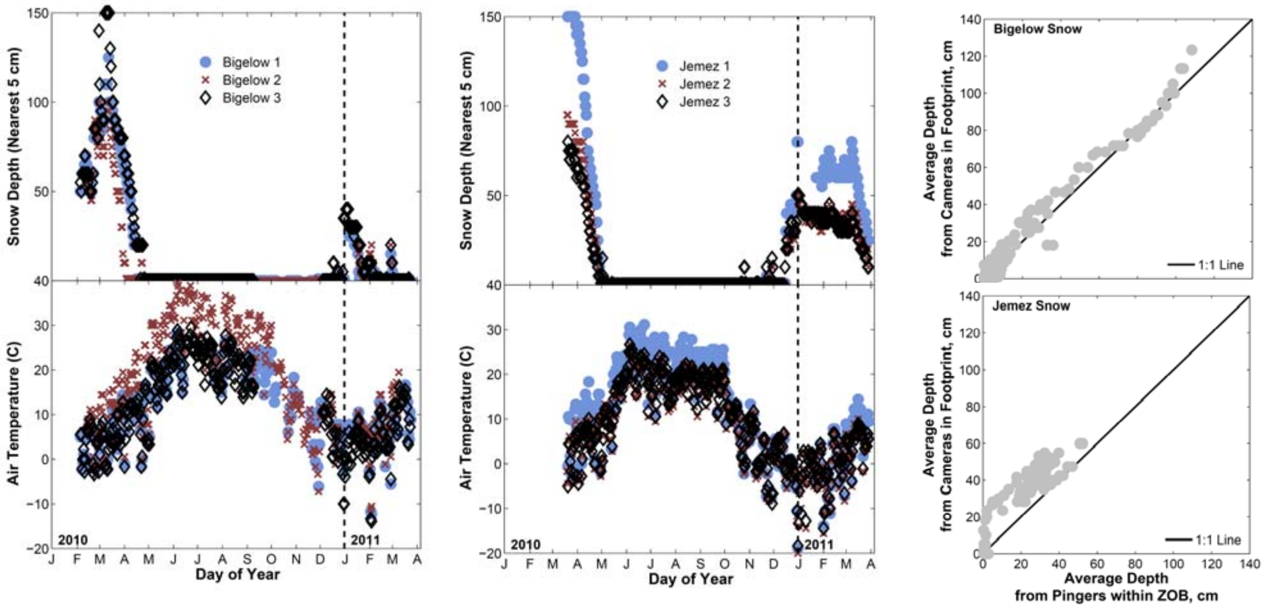


Figure 16. Interannual variability of snow cover and temperature is captured using the understory digital cameras co-located with thermocouples that were installed at each of the eddy covariance tower locations. Site to site differences are evident. At Bigelow tower (SCM), camera in warmest location indicates lowest snow depth, whereas at MC tower (JRB) warmest camera indicates greatest snow depth. Since cameras and snow depth “pingers” are co-located at Bigelow (SCM) and nearby eachother in MC (JRB), results can be compared as shown in right panels (Papuga et al., unpubl. data).

Greenness in the Understory. We selected a region of interest (ROI) for each camera and analyzed them for greenness throughout the year using Greenness Index = 2G - (R+B) (Kurc and Benton 2010 and Richardson et al. 2007).

Figure 17. Photographs from three cameras from the JRB MC site show spring (top) and summer (bottom) greenness that is digitally quantified according to the greenness index and plotted as a function of time in Figure 18 (Nelson, Papuga et al., unpubl. data).

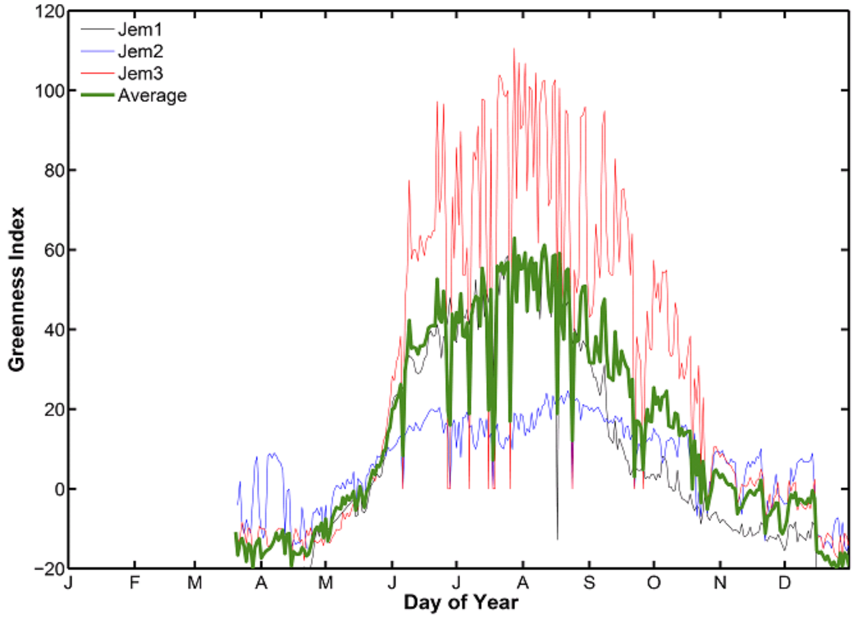


Figure 18. Time series of preliminary calculated values of "greenness index" for 2010 as determined from photographs shown in Figure 17. Results provide direct observations of understory greening in the footprint of the JRB mixed conifer eddy covariance tower, and can be related directly to independently measured values of net ecosystem exchange of water and carbon (Figure 20a,c), as well as to sap flux results (Figure 19) (Nelson, Papuga et al., unpubl. data).

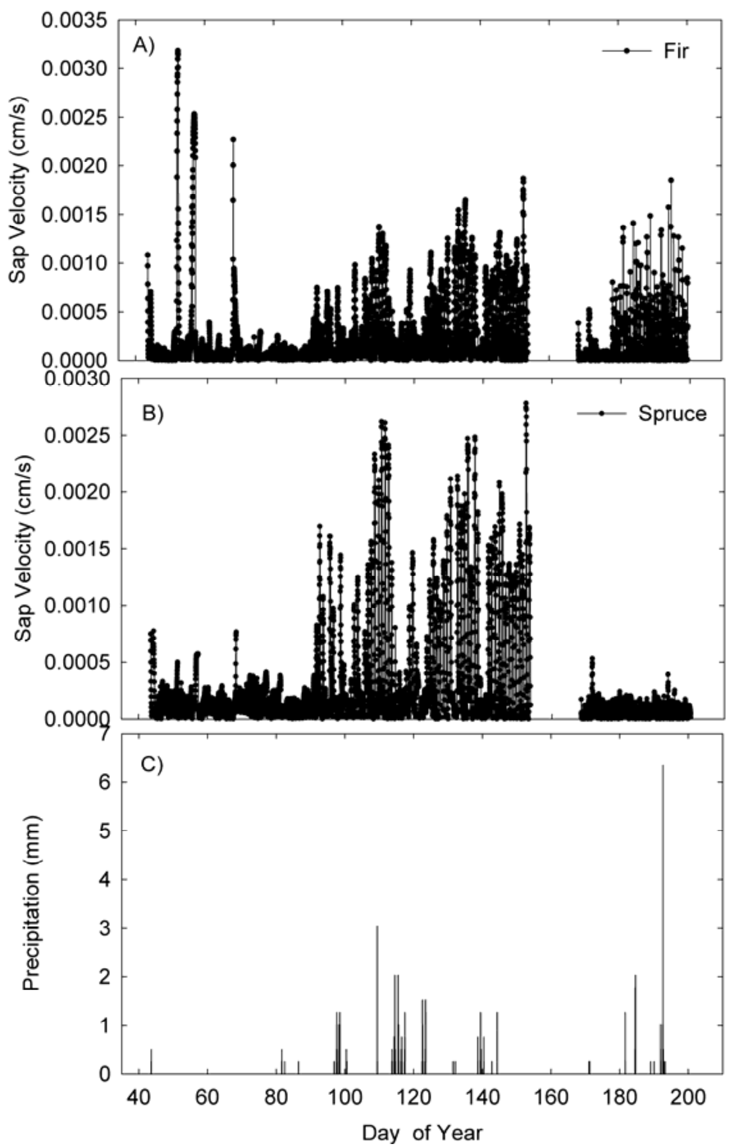


Figure 19. Time series of sap velocity of (A) fir and (B) spruce trees present in the JRB mixed conifer ZOB from February through July 2011. Also shown is (C) precipitation data for the corresponding period as determined by the adjacent meteorological station (Nelson, Papuga et al., unpubl. data).

Net ecosystem exchange in JRB and SCM: Mixed Conifer and Ponderosa Pine forests: Companion eddy covariance towers in conifer dominated ecosystems within the JRB and SCM portions of the CZO have monitored ecosystem scale carbon (Net Ecosystem Exchange of carbon; NEE) and water (evapotranspiration, ET) flux for multiple years. Paired plots of NEE illustrate variation in the patterns of seasonal carbon dynamics and substantial differences in cumulative CO_2 uptake among the sites and between years within each site. Data deriving from the Mixed Conifer and Ponderosa Pine towers in JRB are shown in **Figure 20**. Both mixed conifer and ponderosa pine forests in the JRB exhibit relatively high annual levels of net carbon uptake (**Figure 20**). Significant differences between the sites are apparent in the inter-annual variability, which is greater for the Ponderosa Pine site. Diminished precipitation in the 2010-2011 water year resulted in diminished carbon uptake in the Ponderosa Pine site, whereas the mixed conifer site appears more strongly buffered against such effect.

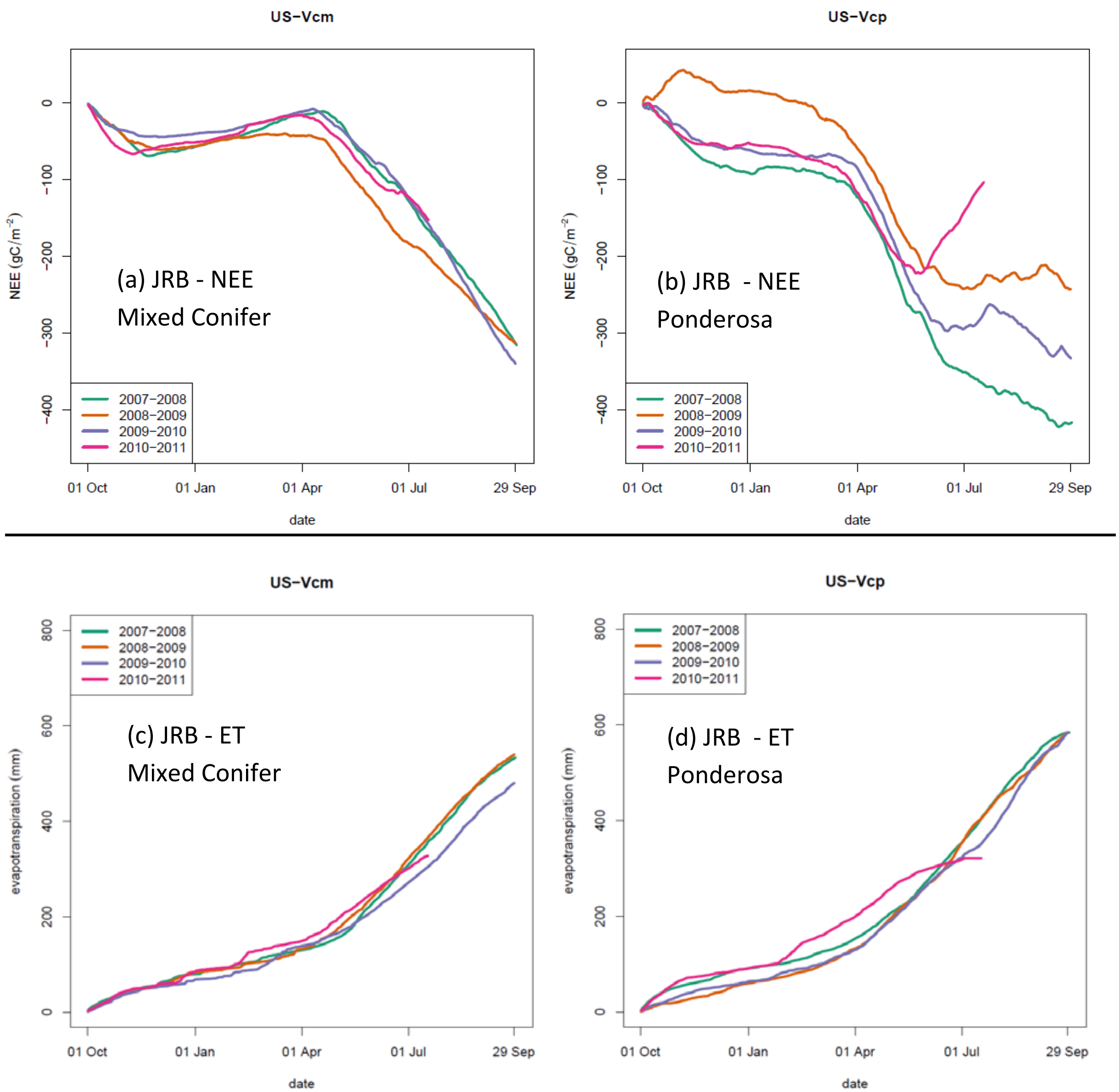


Figure 20. Net ecosystem exchange of carbon (top) and evapotranspiration (bottom) deriving from eddy flux tower data in the Jemez River Basin mixed conifer site (left) and Ponderosa Pine site (right) (Litvak et al, unpubl. data).

It is noteworthy that the steep decline in NEE to increasingly negative values begins in late April/early May for the JRB mixed conifer site (**Figure 20a**) and that this coincides with the steep increase in cumulative evapotranspiration (**Figure 20c**), as well as with significant understory greening (i.e., onset of photosynthetic activity in the understory) (**Figure 18**).

Similarly, within the SCM, the 2009-2010 hydrologic year was characterized by high snow inputs that lasted longer into the winter, while the site received very little snow in the 2010-2011 year. Significantly higher NEE values are measured at the Bigelow tower site (**Figure 21**) relative to the JRB mixed conifer site (**Figure 20a**). The Bigelow tower site is situated in mixed conifer forest at an elevation similar to that of Marshall Gulch.

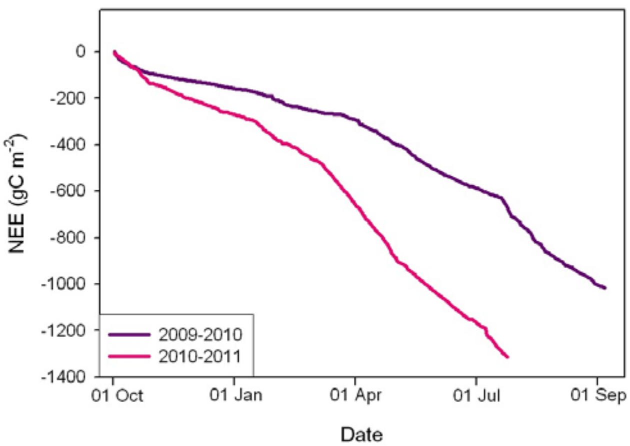


Figure 21. Net ecosystem exchange of carbon measured at the Bigelow tower site, SCM for the water years 2009-10, and 2010-11 (Barron-Gafford et al., unpubl. data).

The SCM mixed conifer flux tower site is characterized by relatively complex terrain, and there is substantial potential for cold air advective drainage. This surface topography could result in soil respired CO_2 draining from the footprint area prior to reaching the tower's instrumentation, which could be one explanation for the very high (negative) NEE values measured for this site. We have begun addressing this inherent challenge of western montane ecosystem-scale research by (i) establishing a CO_2 profile measurement system and (ii) establishing a 40-point array of soil respiration measurement collars to fully characterize soil respiration within this system. These measurements were initiated by Barron-Gafford and an REU student (Cynthia Wright) in July 2010 and have been conducted every two-weeks since that point when there was not snow present (**Figures 22-23**).

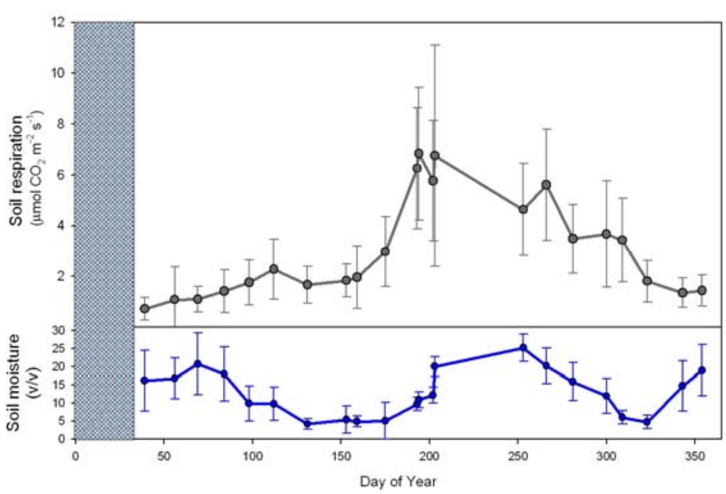


Figure 22. The complete time series on a calendar year that has been completed within the Bigelow ZOB. This plot combines all of the data from 40+ collar locations. (Wright, Barron-Gafford et al., unpubl. data).

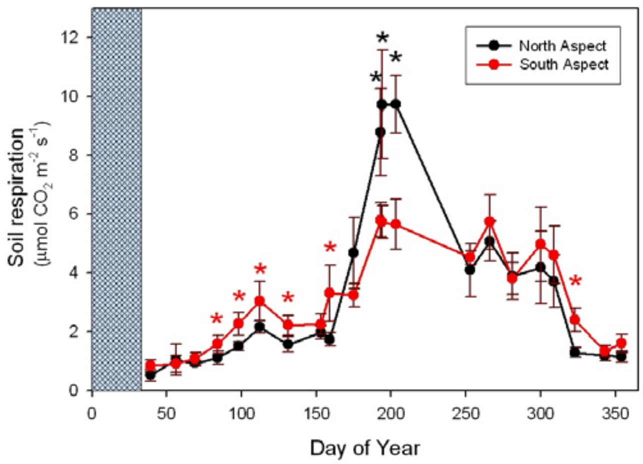


Figure 23. (a) Effects of aspect on soil CO_2 respiration in the Bigelow ZOB (Wright, Barron-Gafford et al., unpubl. data). (b) Photograph of spring snowmelt in the Bigelow ZOB showing faster snowmelt on S facing versus N facing slopes.

Soil respiration measurements within the SCM Bigelow Tower ZOB illustrate the importance of aspect in determining spatial patterns of soil respiration in this complex topography (**Figure 23a**). South-facing aspects had significantly greater rates of soil respiration during spring thaw and fall cooling, attributable to warmer temperatures, and correlated rates of snowmelt (**Figure 23b**). Evidently, aspect-driven differences in effective energy apparently drive rates and timing of snow melt. These surface hydrology processes, in turn, influence patterns of soil respiration and evaporation and localized phenology. We found a significant temperature sensitivity of soil respiration during these seasonal periods, but not in the summer. During the wet summer, north-facing aspects had significantly greater rates of soil respiration, attributable in part to wetter conditions due to reduced insolation, and therefore reduced soil evaporation.

2.2 Subsurface Biogeochemistry Theme

Variability in carbon partitioning by parent material in the SCM Mixed Conifer ZOB: Parent rock type effects on soil development may be expected to affect how ecosystem exchange (NEE) is partitioned to soil (root and heterotrophic) respiration and dissolved organic carbon (DOC). Seasonal variation in soil CO_2 and DOC efflux was quantified over winter snow melt and the summer monsoon of 2010 in the SCM mixed conifer ZOB for both granite and schist parent materials. The data indicate generally greater respiration in the schist relative to the granite locations (**Figure 24**). The very high CO_2 efflux in the schist site for July likely records a hot spot / hot moment captured during the summer monsoon. The data also indicated generally greater DOC export from the granite relative to the schist site. Greater DOC retention in the schist site corresponds with the schist soils being deeper and of finer texture than those in the granite locations. The combined data thus suggest predictable variation in gaseous vs. dissolved carbon loss from the two locations with greater DOC retention and its subsequent respiration in the schist locations.

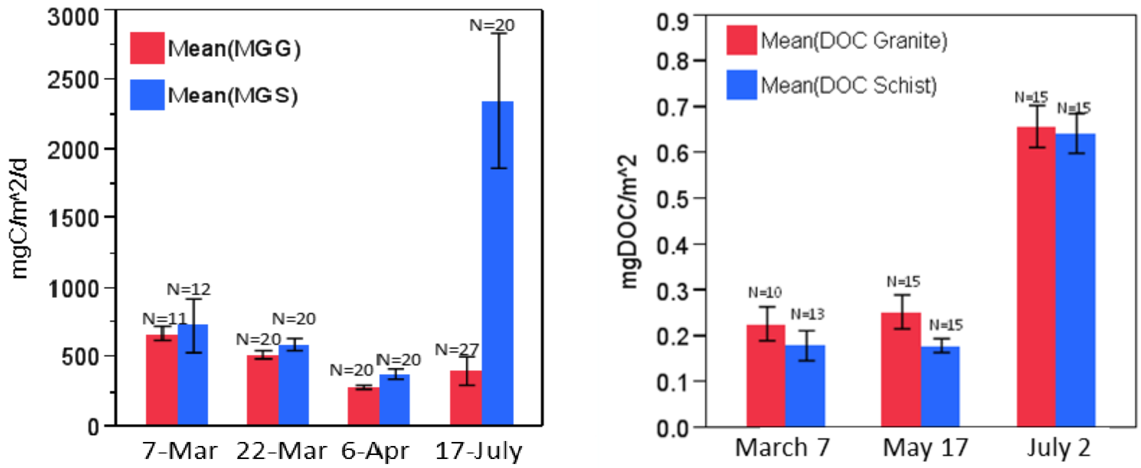


Figure 24. (a) Mean efflux of $CO_{2(g)}$ from a soil surface derived from granite and schist parent materials. (b) Mean water extractable dissolved organic carbon (DI DOC) from granite and schist derived soils (Stielstra et al.).

Depth dependent trends in dissolved organic matter composition in JRB Mixed Conifer ZOB: The coupling of pedogenesis with soluble organic matter driven weathering and flux is being investigated through the use of in situ soil solution samplers (both capillary wick and Prenart type tension samplers have been installed as a function of depth in six MC ZOB pits). Samples extracted during instrumentation of the soil pits have been studied via aqueous extraction in the lab to assess water extractable DOC concentrations and fluorescence excitation-emission matrices. Results are shown for extractable DOC and two indices of fluorescence EEM data (fluorescence index, FI and humification index, HIX) in **Figure 25**. Soil DOC concentrations are bracketed between those measured for water extracts of two forest canopy types and stream water DOC. Consistent trends in fluorescence data are observed for the two pits.

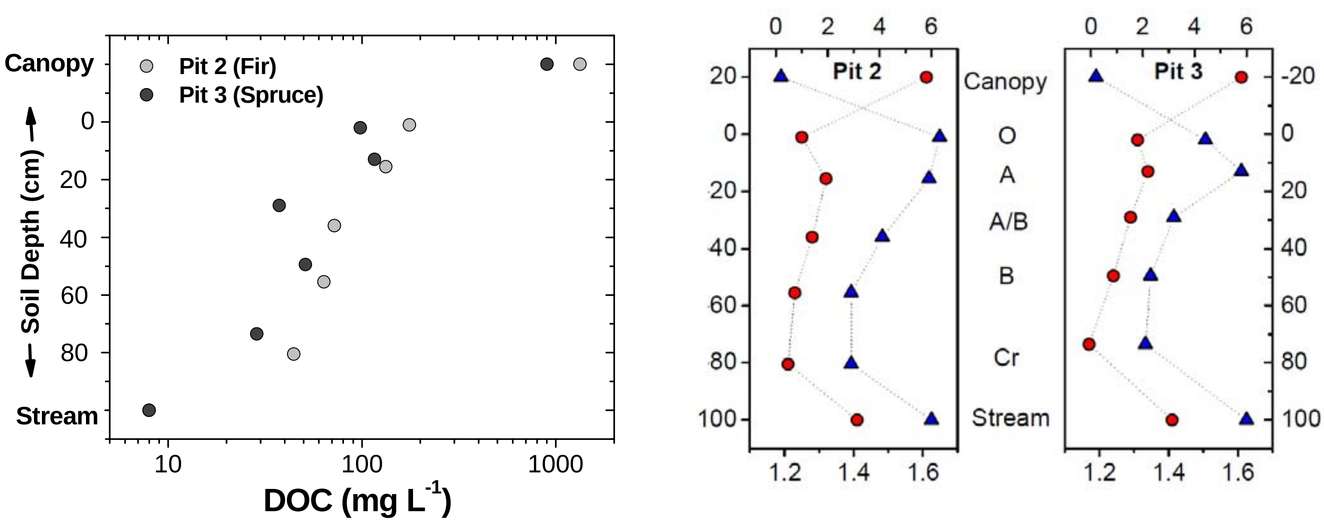


Figure 25. (a) Variation in water extractable dissolved organic carbon concentration as a function of vertical CZ location from forest canopy through soil profile to stream for fir and spruce vegetated pedons. (b) Fluorescence Index (FI, red symbols, bottom X axes) and humification index (HIX, blue symbols, top X axes) as determined from fluorescence excitation-emission matrices (EEMs) for same two locations in the JRB MC ZOB (from Chorover et al., 2011).

<u>*Impacts of DOM on pore water aqueous geochemistry:*</u> We hypothesize that DOM generated during solubilization and microbial degradation of ecosystem photosynthate has a significant impact on pedogenic weathering processes. In particular, we postulate that DOM mobilization in soil profiles contributes to landscape chemical denudation processes by mobilizing otherwise relatively immobile lithogenic metals (e.g., Al, Fe). **Figure 26** shows solution charge balance plots for two pedons from the JRB mixed conifer ZOB and some similar patterns are observed. In both plots, organic acids (OA) are important constituents of the charge balance throughout the pedon depth. In addition, organic acids balance the charge on cationic Ca in the surface and Al in the deeper subsurface, likely affecting porewater removal of these mineral weathering products, and their catchment mobilization during periods when flow paths intersect these horizons.

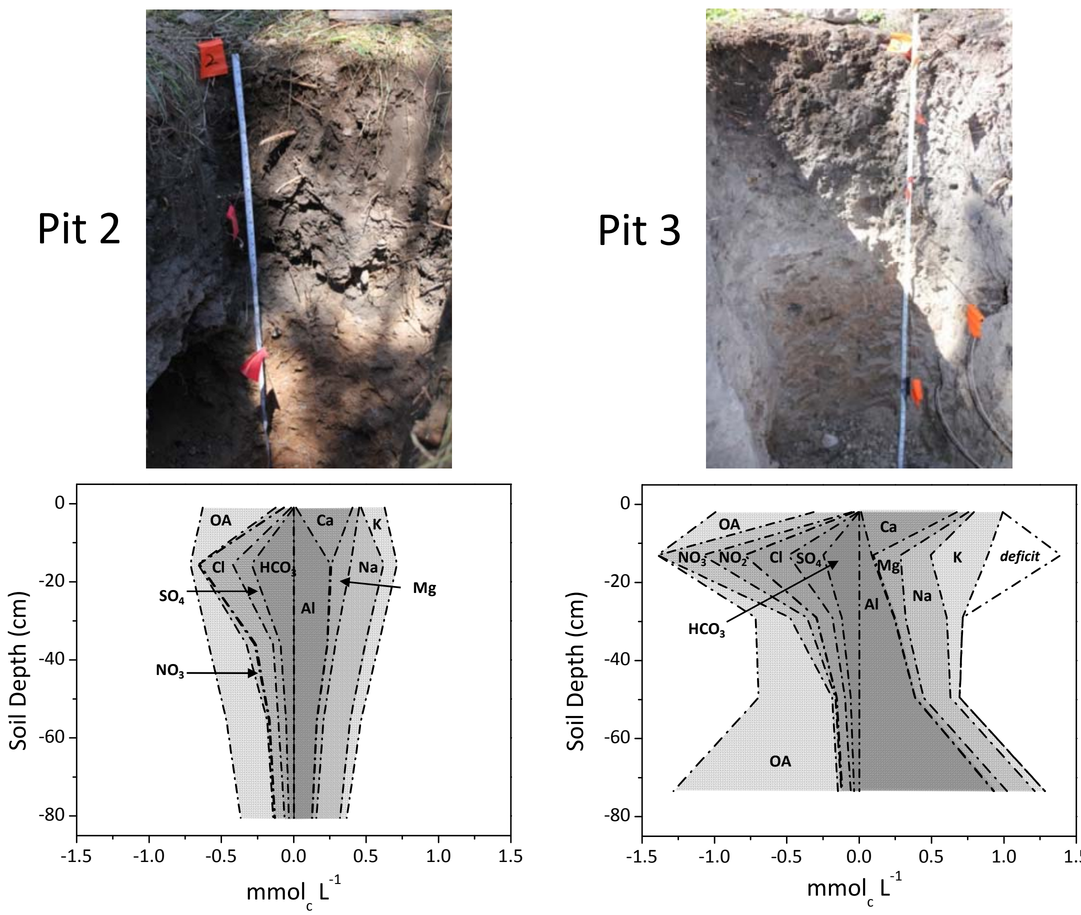


Figure 26. Soil solution ion charge balance plots for two instrumented soil pits in the JRB mixed conifer ZOB. Data are derived from aqueous extracts of sampled soil solids and will be compared to *in situ* solution sampler data that is now being analyzed (From Chorover et al. 2011).

<u>*Landscape position controls on soil depth and mineral assemblage in SCM:*</u> The time-integrated effects of aqueous geochemical weathering processes (as measured in pore water solution chemistry and flux) and erosion (as measured by sediment transport) governs the long-term formation of regolith. This is reflected in the depth of weathering profiles distributed in the landscape and their mineralogical and organic matter composition. Since we expect that hydrologic flow paths exert strong controls over pedogenic processes, we quantified variation in soil depth, bulk soil mineral abundance, and clay mineralogy for divergent and convergent landscape positions on granitic parent materials across seven elevations in the SCM with a focus on granite and schist parent material comparisons in the desert scrub and mixed conifer ecosystems of the SCM CZO. Soil depth generally increased with elevation for both divergent and convergent landscape positions (**Figure 27**).

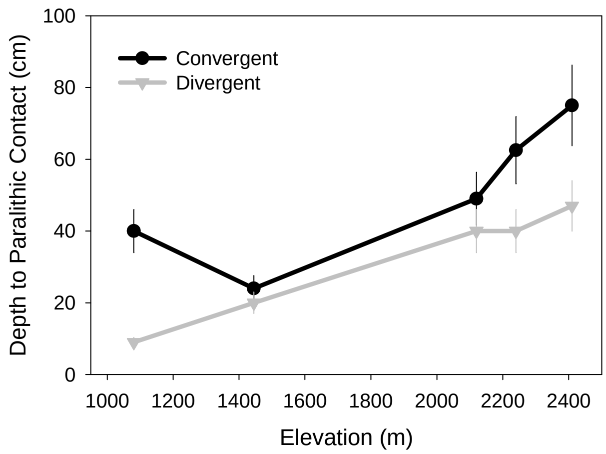


Figure 27. Dept to paralithic contact for granite derived convergent and divergent landscape positions across the SCM-CZO climate and elevation gradient (Rasmussen et al., unpubl. data).

Interestingly, soil depth was relatively deep in convergent zones for both the desert scrub and mixed conifer locations. This pattern closely mirrors rates of soil production and erosion quantified using cosmogenic nuclides in the Rincon Mountains adjacent to SCM (Rasmussen, *In Prep*.), that demonstrated relatively rapid erosion of divergent landscape position in both desert scrub and mixed conifer ecosystems. The variation in erosion across the gradient is likely tied directly to variation in landcover and the dominant erosion mechanism, *i.e.*, surface wash relative to bioturbation. These results thus indicate strong couplings among soil depth, erosion rates and ecosystem type across the SCM gradient.

Substantial variation in soil mineral assemblage (from x-ray diffraction) was observed with soil depth (**Figure 28**) and between landscape positions across the gradient, as well as between parent materials in the mixed conifer ecosystem. In the mixed conifer ecosystem, granite profiles were less chemically weathered than schist profiles. The mineral assemblage of both granite profiles was dominated by quartz and feldspar, with a lesser amount of mica and other accessory minerals. Granite weathering reactions appear to be dominated by the transformation of feldspar to kaolinite, and more specifically the pseudomorphic transformation of plagioclase feldspar to kaolinite. The schist profiles were dominated by a mix of primary minerals such as quartz, orthoclase and plagioclase feldspar, biotite, and hornblende, in addition to secondary 2:1 and 1:1 phyllosilicates. The general weathering reactions appear to be dominated by transformation of biotite to a secondary 2:1 mineral, and the transformation of plagioclase to kaolinite.

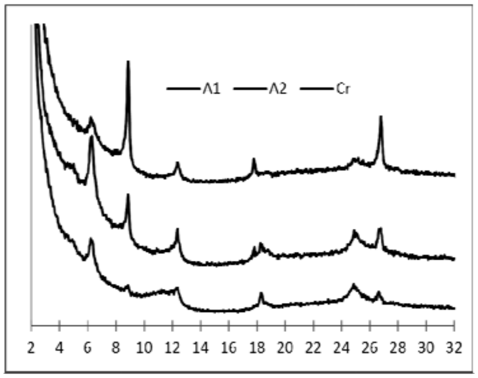


Figure 28. X-ray diffractograms of clay fractions from the mixed conifer divergent landscape position indicating distinct vertical variation in clay mineral assemblages as detected for A1, A2 and Cr genetic soil horizons (Medding et al., unpubl. data).

In terms of landscape position effects, the divergent hillslope positions from each parent material exhibited a greater degree of primary mineral weathering relative to convergent positions as indicated by greater Quartz-to-Plagioclase mass ratio in bulk soil mineral assemblage (**Figure 29**). Greater weathering in divergent positions suggests sufficient water input and mean residence time to drive weathering reactions, and sufficient water through flux to remove weathering products from the profile. In contrast, the convergent profiles exhibited very little primary mineral weathering in either parent material, but in general a greater abundance of clay-sized material. We postulate that the lack of primary mineral weathering in this landscape position likely corresponds to collection in convergent zones of solute rich waters effluent solutions from upslope divergent landscapes that diminish the rate of *in situ* primary mineral dissolution reactions. Furthermore, convergent landscape data suggest the clay fractions in theses profiles may be dominated by neogenic clays, such as smectite, suggesting precipitation from solute-rich soil waters. Hence, spatial distribution of soil mineral composition appears consistent with contemporaneous solute fluxes measured by lysimetry, suggesting a heterogeneous distribution of weathering intensity that is governed by hillslope hydrologic flux.

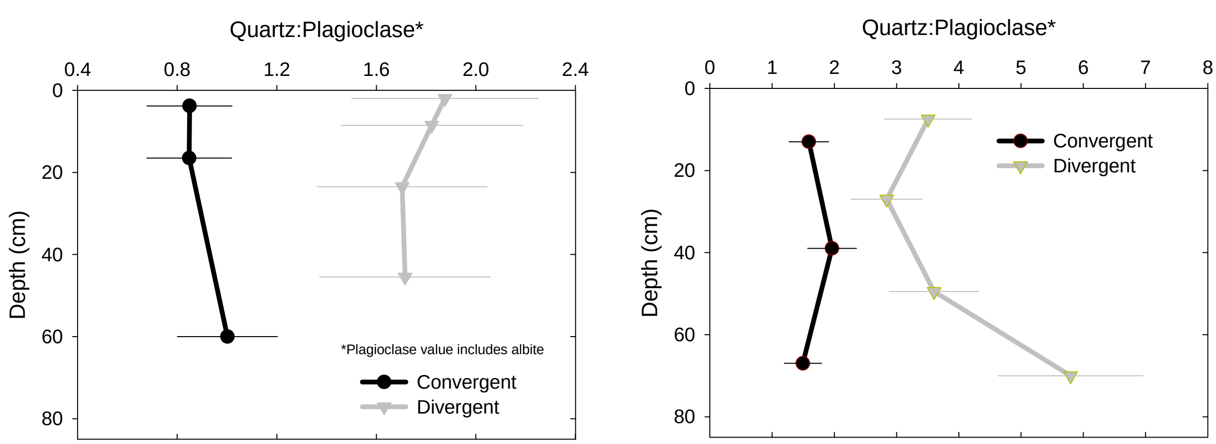


Figure 29. Quartz-to-Plagioclase ratios for (a) granite and (b) schist derived soils for convergent and divergent landscape positions in the mixed conifer ZOB and the SCM-CZO. Greater ratios indicate greater relative loss of plagioclase feldspar to chemical weathering (Lybrand et al.).

Pedon Morphology in the JRB-CZO Mixed Conifer ZOB: Soil formation from rhyolitic parent materials is being investigated through detailed mineralogical, geochemical and organic matter characterizations of six distributed soil pits in the JRB-CZO La Jara mixed conifer ZOB. Initial results (**Figure 30**) indicate both input of dust in the uppermost horizon (evidenced from sharp accumulation of illite in the near surface) and a shift from colluvium and mixed volcanic ash to rhyolitic tuff in the subsurface at 50 cm depth.

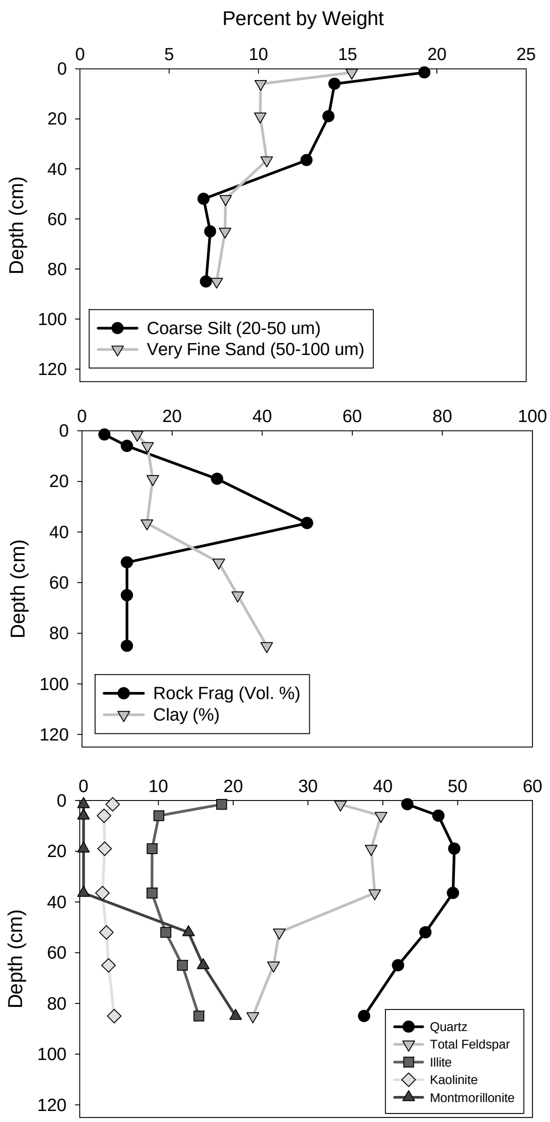


Figure 30. Variation in particle size and mineral composition by depth for one mid-slope soil profile in the JRB-CZO mixed conifer ZOB. Data in (a) include coarse silt and very fine sands and in (b) clay and rock fragment content that indicate both input of dust in the uppermost horizon and change from colluvium and mixed volcanic ash to rhyolitic tuff in the subsurface at 50 cm. Mineralogical data in (c) also indicate abrupt change in mineral composition at 50 cm with decrease in total feldspar and increase in montmorillonite; the increased abundance of illite in surface horizons suggest a strong imprint of dust on mineral composition (Medding et al.).

2.3 Surface Water Dynamics Theme

SCM Water Transit Time Distributions: A guiding hypothesis of the Jemez-Santa Catalina CZO is that regolith formation, driven by biotic and abiotic processes, and as characterized by depth to bedrock (e.g., **Figure 27**) and soil structure formation, influence hydrologic flow paths and associated catchment water transit time distributions and hydrologic response functions. Transit time distributions were determined for two paired catchments in Marshall Gulch in the SCM to test hypotheses about lithologic controls (granite vs. schist) on water transit times, and address the question of how to best characterize dynamic hydrologic response behavior on the catchment scale. Both hillslopes have similar climate, aspects (north-facing), gradients (28-30^o), and size (3-4.9 ha). The granite hillslope has thinner soils (40-90 cm) and coniferous forest cover, while the schist hillslope has thicker soils (80-120 cm) and mixed forest cover.

Results show that in general mean transit times of water draining the granite hillslope (9 days) is significantly faster than the schist hillslope (76 days), likely due to the slower weathering rates, shallower soils, and lower clay content in the granite vs. schist hillslopes, which may lead to reduced storage and a higher fraction of quick overland flow (Heidbuechel et al., *in review and in prep*). However, these mean values do not account for the variation in transit time that likely occurs throughout the year in semi-arid climates subjected to dynamic and episodic precipitation events.

To address this need, variable hydrologic response functions (HRF) and transit time distributions (TTD) were tracked with water volume fluxes (HRF) and fluxes of stable water isotopes (TTD); impulse inputs were converted to continuous output functions using a transfer function and convolution method. A moving window approach allowed transfer functions to vary in time (Heidbuechel et al., 2010, AGU Abstract H11C-0813). Information from each time step was integrated into a master distribution that captures the general response behavior by weighting individual time distributions by volume (HRF) and mass (TTD), superposition of weighted individual time distributions, and summation and normalization.

Individual TTDs for specific events (**Figure 31**) and master TTD for catchment characterization (**Figure 32**) are illustrated below.

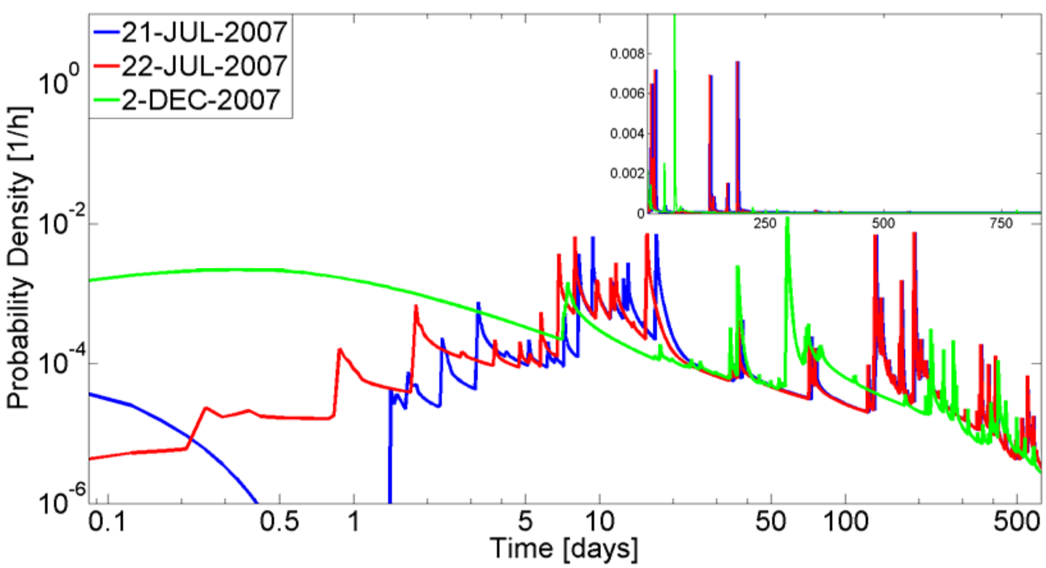


Figure 31: Three event TTDs for three individual precipitation events (21 July 2007, 22 July 2007 and 2 December 2007) in Marshall Gulch. Note the time shift between the TTDs of the two consecutive events. Each spike in the TTDs represents an activation of water out of the near-stream storage (Heidbuechel et al., *in review*).

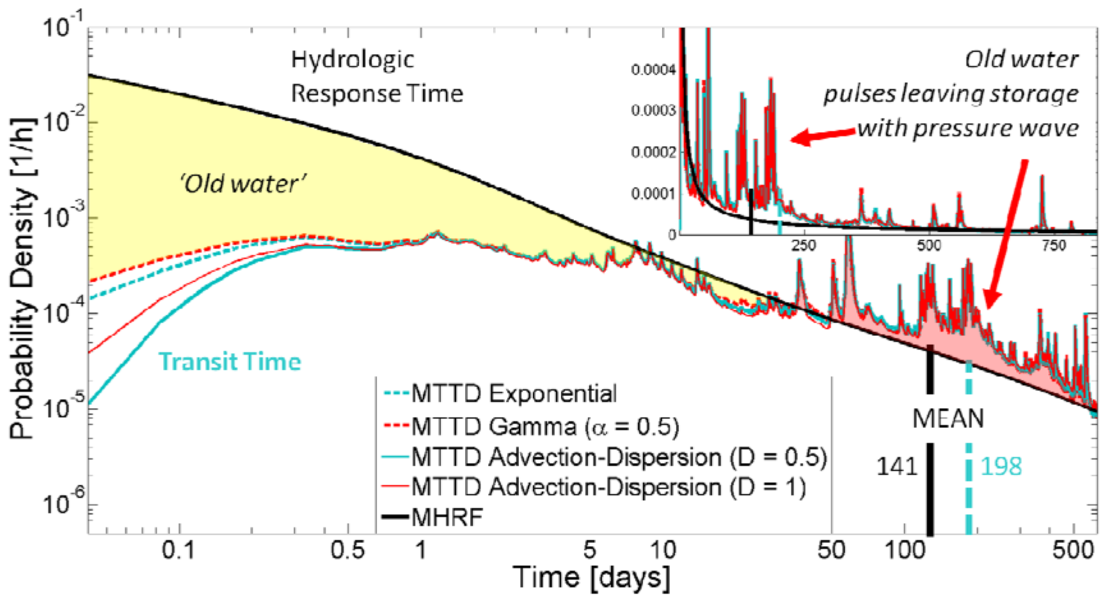


Figure 32: Master transit time distributions (MTTD) for four different transfer function models and master hydrologic response function (MHRF) for Marshall Gulch. Distribution means are indicated by vertical lines (Heidbuechel et al., *in review*).

JRB Water balance for headwater catchments: Water partitioning in headwater catchments around Redondo Peak may vary as a function of EEMT – something we are investigating using a water balance approach. Catchment characteristics have been defined for La Jara, History Grove, Upper Jaramillo and Upper Redondo creeks (**Table 1**). Precipitation was distributed throughout the catchments using four different methods: monthly lapse rates, seasonal lapse rates, thiessen polygons, and inverse distance interpolation (**Figure 33**). Discharge was measured at the catchment outlets. Evapotranspiration (ET) rates were calculated for the four catchments as the difference between precipitation and discharge (actual ET measurements are currently being distributed across catchments). The annual water balance was then calculated for three waters years (2008-2010, **Figure 34**).

Similar precipitation amounts were estimated for the four catchments around Redondo Peak. Water Year 2008-2009 had the highest precipitation (and highest ET rates), while 2009-2010 had the lowest amount of precipitation. Precipitation depths calculated based on the seasonal lapse rates show that La Jara received the highest amount of the precipitation (P) during the three water years, while Upper Jaramillo received the lowest amount (**Figure 33**). During the three years of analysis, Upper Jaramillo had the highest discharge (Q) and lowest ET, while La Jara had the lowest discharge and highest ET (**Figure 34**). ET rates are related to water availability, aspect and incoming solar radiation. On-going work is focused on improving the estimation of precipitation and ET in each catchment, and analyzing water balances on a shorter time frequency.

Table 1. Catchment characteristics defined on a 10m resolution DEM

Catchment	La Jara	History Grove	Upper Jaramillo	Upper Redondo
Mean elevation (m)	3106	2948	2929	2957
Elevation range (m)	2706-3432	2689-3305	2720-3322	2705-3258
Area (km^2)	3.67	2.42	3.06	0.79
Slope---mean (σ)	15.60 (7.57)	12.69 (6.51)	13.36 (8.17)	16.52 (8.81)
Aspect (%) †				
North	4.7	2.7	28.4	24.6
Northeast	27.2	16.7	18.5	0.4
Northwest	0.5	0.3	31.4	43.0
Southeast	12.5	19.3	2.7	0.0
South	12.3	15.8	0.4	1.2
Southwest	10.3	8.8	1.3	8.8
West	1.5	0.7	8.7	21.8
East	31.0	35.8	8.6	0.2
EEMT (MJ.m^{-2})				
Mean (σ)	41.24	39.80	40.49	39.84
EEMT range	37.15-46.07	36.96-44.37	38.16-48.19	34.29-49.53
Annual incoming solar radiation (W - hour . m^{-2}) ‡				
Mean (σ)	73,978.47 (14,463.08)	74,904.08 (10,035.15)	57,210.08 (12,490.73)	57,097.78 (16,481.59)
Incoming solar radiation range	21,061.53-113,191.76	34,434.95-103,994.40	20,555.79-92,064.41	19,044.56-99,048.96

† % of the catchment

‡ Defined with ArcGIS solar analyst for the year 2010

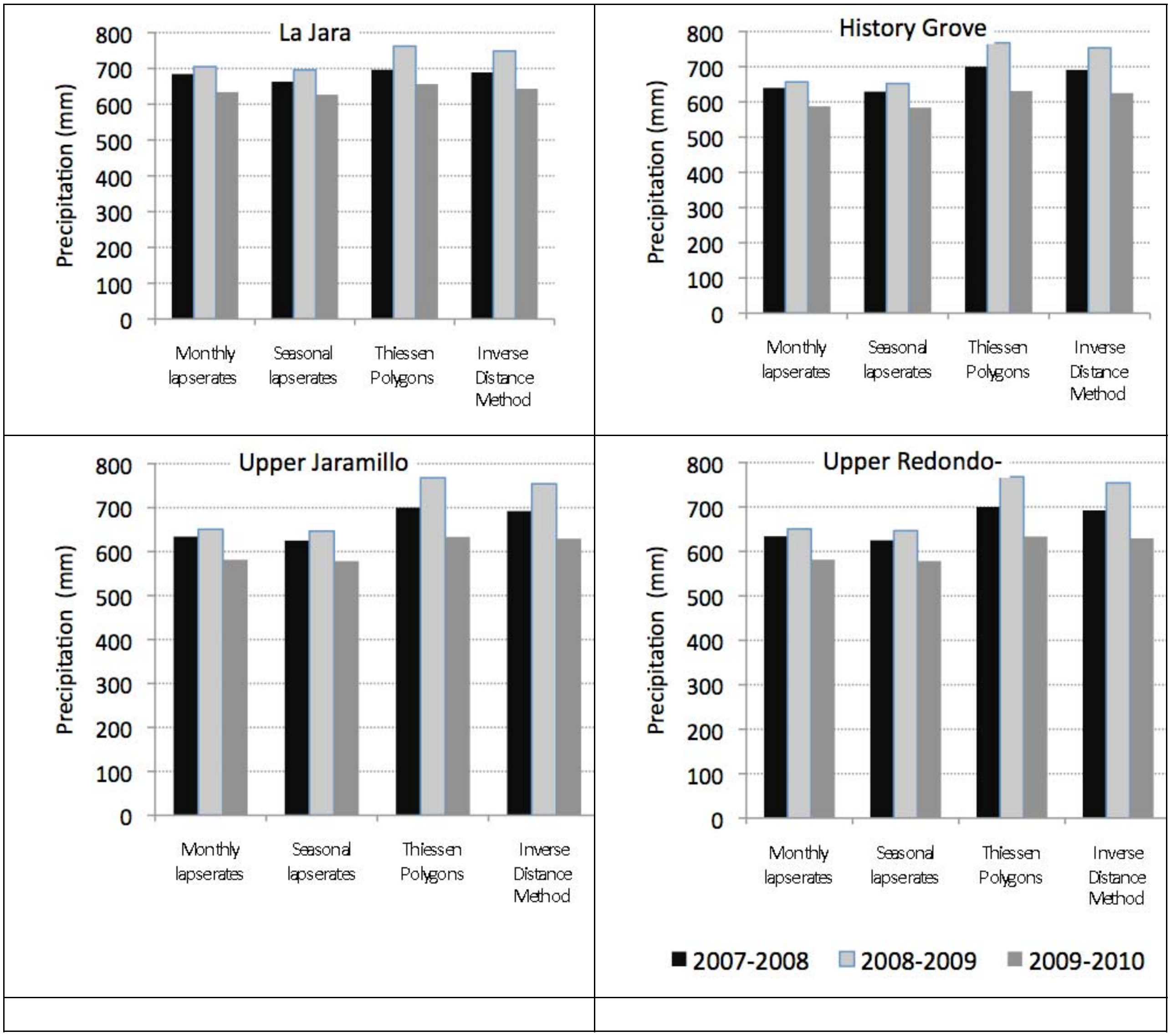


Figure 33. Rainfall amounts per catchment during the water years 2007-2008, 2008-2009 and 2009-2010 applying four methodologies (Zapata et al., unpubl. data)

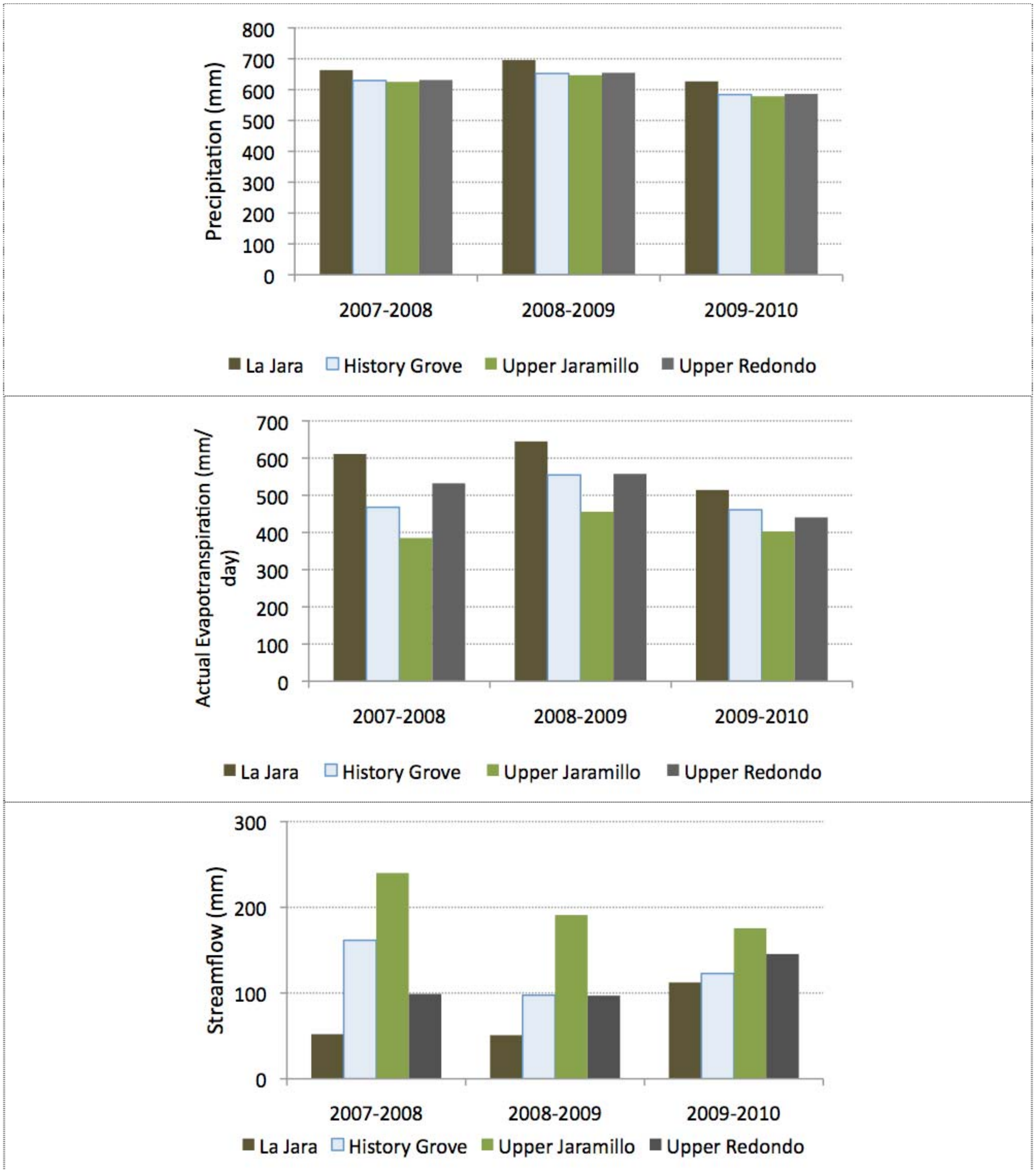


Figure 34. Water balance for La Jara, History Grove, Upper Jaramillo and Upper Redondo during the water years 2007-2008, 2008-2009 and 2009-2010 (Zapata et al., unpubl. data).

Table 2. Runoff and evaporation ratios for four catchments draining Redondo during three water years 2007-2008, 2008-2009, 2009-2010

Q/P	LA JARA	HISTORY GROVE	UPPER JARAMILLO	UPPER REDONDO
2007-2008	0.08	0.26	0.38	0.16
2008-2009	0.07	0.15	0.30	0.15
2009-2010	0.18	0.21	0.30	0.25

ET/P	LA JARA	HISTORY GROVE	UPPER JARAMILLO	UPPER REDONDO
2007-2008	0.92	0.74	0.62	0.84
2008-2009	0.93	0.85	0.70	0.85
2009-2010	0.82	0.79	0.70	0.75

<u>*JRB stream water DOC fluxes:*</u> Quantitative carbon analysis from flume samples around Redondo peak in the JRB indicate the highest DOC and lowest dissolved inorganic carbon (DIC) concentrations at the onset of snowmelt (mid April) (**Figure 35**). Highest DOC concentrations (12 mg L^{-1}) were measured in Jaramillo Creek at the lower flume, and there is a positive correlation between DOC concentrations, and DOC/DIC ratios in both La Jara and Jaramillo drainages with discharge (e.g., **Figure 36**). In addition, a decrease in the $\delta^{13}C$ values of DIC, to values similar to soil organic matter, during peak discharges suggests flushing of soil organic carbon to streams. In contrast, during low flow periods $\delta^{13}C$-DIC values are similar to spring waters, suggesting groundwater inputs of DIC. The high $\delta^{13}C$-DIC values in groundwaters and stream waters, draining the volcanic terrains, may be due to extensive subsurface microbial cycling of carbon, or addition of enriched carbon sources (e.g. disseminated calcite), something that is currently being investigated, using additional solute and isotope tracers, and molecular tools such as fluorescence spectroscopy (**Figure 37**).

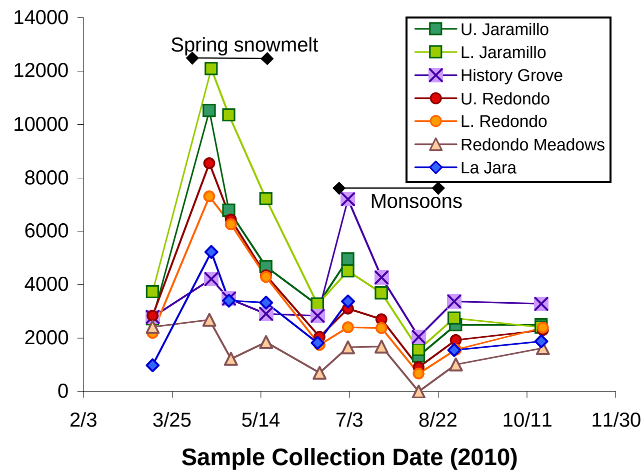
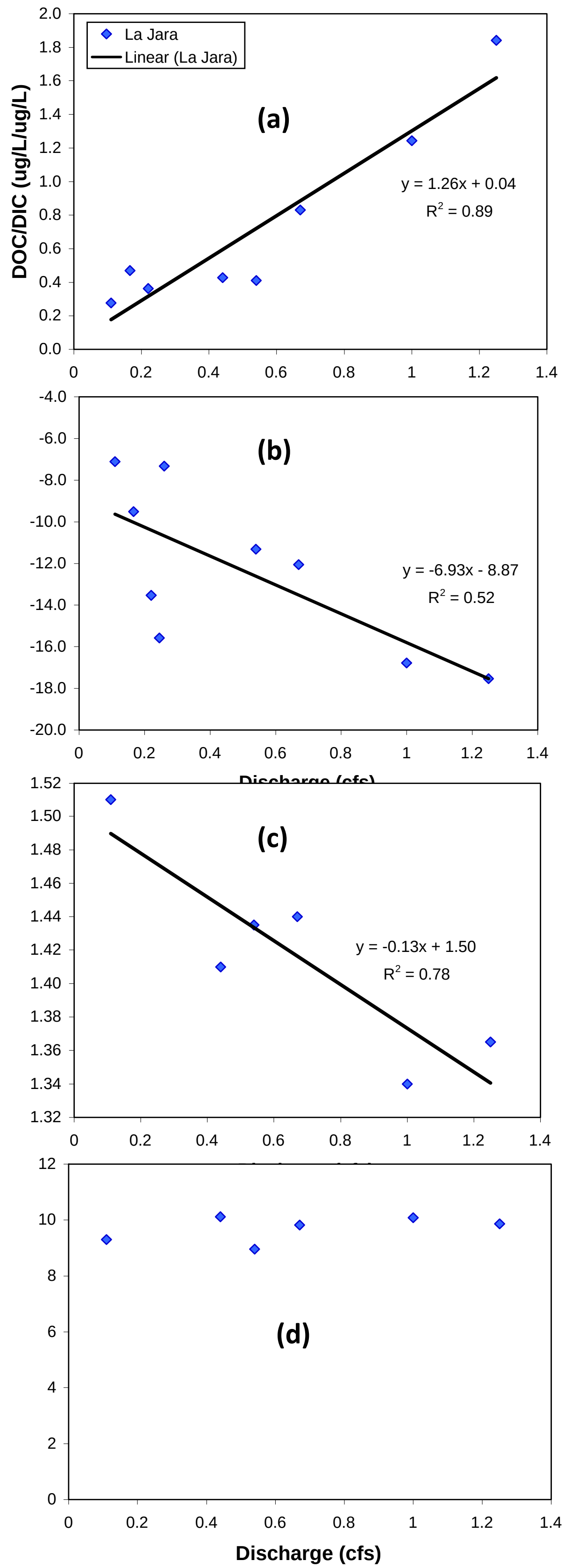


Figure 35. Dissolved organic carbon (DOC) concentrations (μg L^{-1}) in streams draining Redondo peak during spring snowmelt and summer (2010).

Fluorescence spectroscopic analysis provides valuable information on source and molecular properties of DOM. Excitation – emission matrixes (EEM, **Figure 37**) reveal several maxima characteristic of plant (e.g., lignin and associated aromatics) and microbial-derived compounds. Whereas the former derive largely from decomposition of terrestrial biomass (allochtonous DOM), the latter derive also from in-stream algal biomass (authochtonous). The relative contributions of these are indexed using the

Figure 36. (a) Positive correlation between DOC/DIC ratios and stream discharge for La Jara drainage is shown in the left. (b) Negative correlation between carbon isotope value of DIC and stream discharge. (c) Negative correlation between discharge and fluorescence index. Low FI corresponds to terrestrial sourcing whereas higher values tend to indicate greater autochtonous (i.e., algal) contributions (J. Perdrial unpubl. data). Panel (d Si concentrations in La Jara are invariant with discharge. (See **Figure 37** for selected excitation-emission matrices used for calculating FI.) (Perdrial et al., *in prep*.)



fluoresence index (FI). A strong negative correlation between discharge and FI for La Jara drainage (**Figure 36c)** indicates increasing contributions of allochtonous DOM with increasing discharge, with maximum values occurring at early onset of snowmelt.

Total dissolved nitrogen (TDN) data show similar trends with highest values from Lower Jaramillo samples and a steady decrease for the other flumes around Redondo (counterclockwise). However, DN concentration values are offset in time relative to peak DOC values, with highest concentrations at the end of April (4-26-10) rather than Mid-April (4-16-10).

SCM Nutrient dynamics: In the high elevation (Marshall Gulch) catchment in the SCM we have investigated nutrient dynamics in paired hillslopes with different bedrock lithologies (i.e. granite vs. schist) to determine how parent material and landscape position influences organic carbon and nitrogen cycling. Weekly surface water grab samples were collected at three gauged sites in the Marshall Gulch catchment: basin outlet (MGout), schist hillslope outlet (Sout) and granite hillslope outlet (Gout). Water samples were analyzed for dissolved organic carbon and nitrogen species, in addition to other constituents. Soil waters were collected from suction lysimeters installed at the bedrock-soil interface.

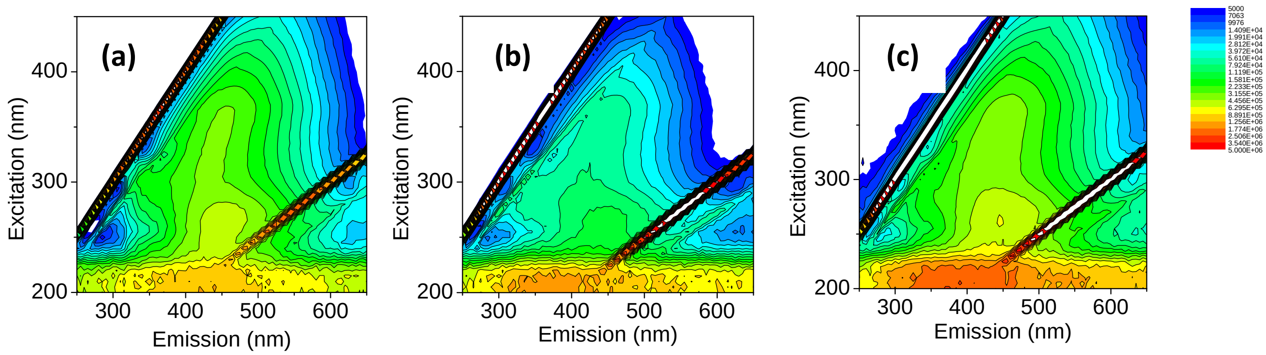


Figure 37. Excitation-emission spectra for (a) upper Redondo, (b) Redondo Meadow, and (c) La Jara Creeks (June 2010 sampling in JRB-CZO. (Perdrial et al., unpubl. data).

Total dissolved nitrogen (TN), nitrate (NO_3-N), nitrite (NO_2-N), and dissolved organic carbon (DOC) concentrations were slightly lower in stream waters draining the schist (**Figure 38**) versus granite (**Figure 39**) hillslopes. We hypothesize that the thicker soils developed on the schist hillslope have higher cation exchange capacities to retain nutrients compared to thinner soils developed on the granite hillslope. Mean and median concentrations of DOC, TN, NO_3-N and NO_2-N decrease downstream between the granite hillslope outlet, the schist hillslope outlet, and the Marshall Gulch outlet. This may suggest in-stream processing of organic carbon and N, dilution or adsorption of DOC. The highest DOC concentrations in Marshall Gulch stream waters were observed in the spring. Additional analysis of NH_4 will help to differentiate organic-N from TN. Similar analyses are also being conducted for the newly instrumented mid-elevation site in the SCM to investigate the influence of EEMT on carbon and nitrogen dynamics.

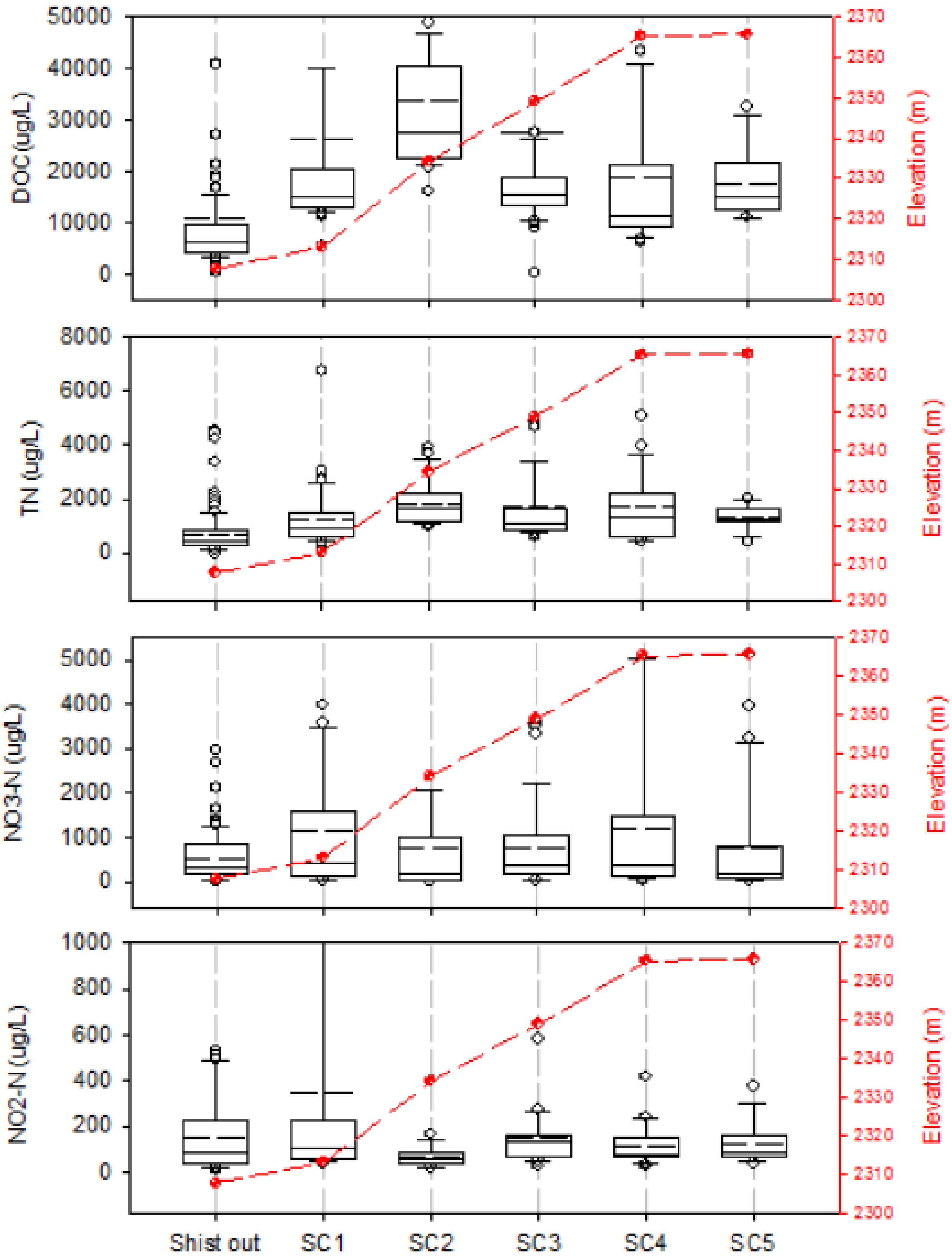


Figure 38. Dissolved organic carbon (DOC), total nitrogen (TN), nitrate (NO_3-N), and nitrite (NO_2-N) concentrations in soil waters along the schist hillslope (Zapata et al., unpubl. data).

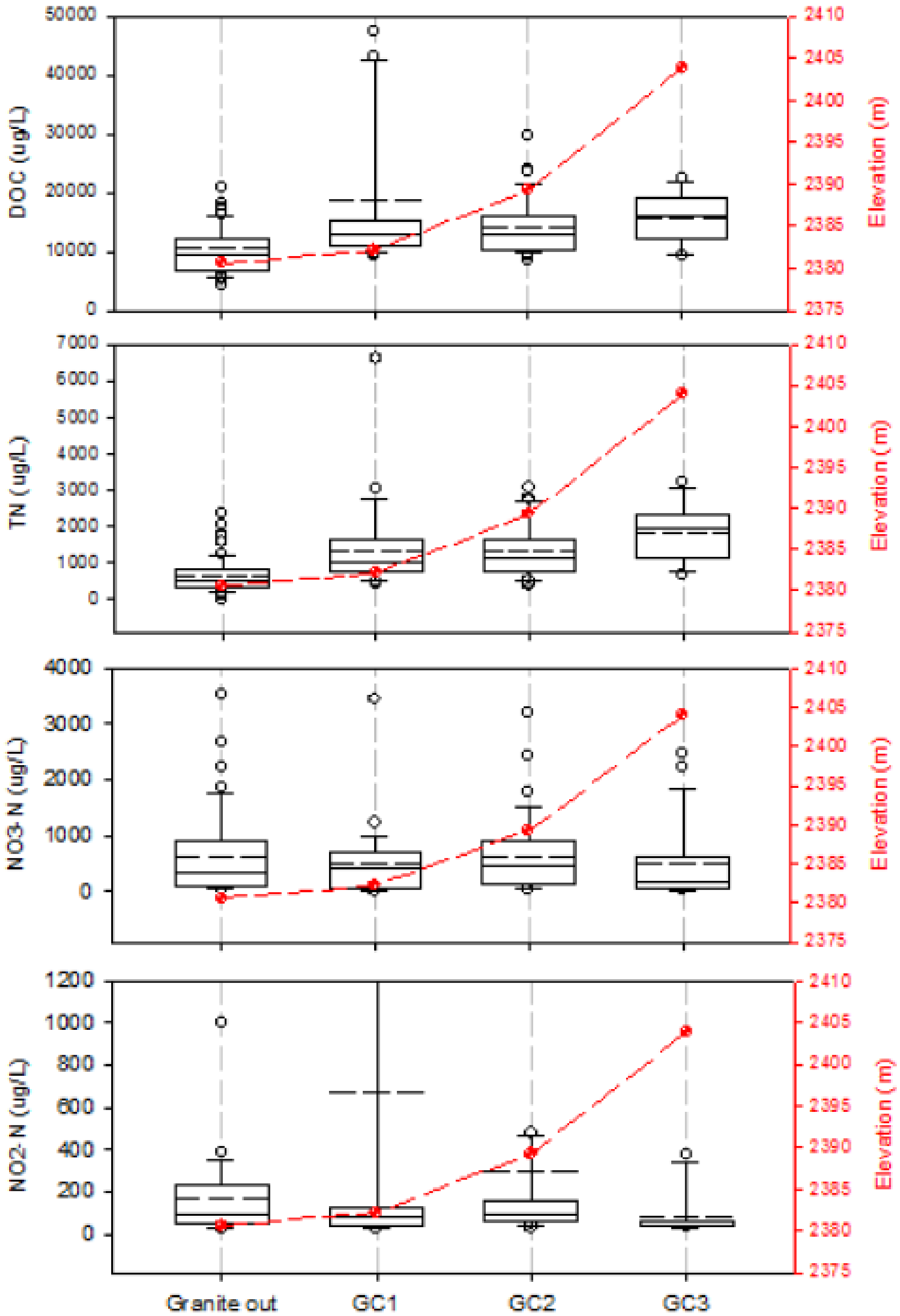


Figure 39. Dissolved organic carbon (DOC), total nitrogen (TN), nitrate (NO_3-N), and nitrite (NO_2-N) concentrations in soil waters along the granite hillslope (Zapata et al., unpubl. data).

JRB Solute sources and chemical denudation: A multi-tracer approach is being utilized to determine solute and nutrient sources to stream waters draining Redondo Peak in the JRB. We hypothesize that during relatively dry periods, the majority of solutes in stream waters are derived from groundwater and atmospheric/dust inputs, while during wet periods (i.e., summer monsoons and spring snowmelt), flushing of shallow soils provides additional solutes to streams. Peak discharge in La Jara Creek occurs during spring snowmelt, yet little change in major cation concentrations of stream waters were observed in 2010 (**Figure 40**), suggesting a constant input of groundwater to streams throughout the year, consistent with previous studies (Liu et al., 2008; Kostrezwski, 2010). Higher frequency (daily) sampling of La Jara Creek in 2011 shows more variability in stream cations during snowmelt. Stream water cation budgets are dominated by Si, Ca, and Na, consistent with weathering of plagioclase. Similar results have been observed for other headwater catchments (History Grove, Upper Jaramillo, Upper Redondo) draining Redondo Peak. Larger, low-lying catchments, such as the East Fork of the Jemez River and Lower Jaramillo Creek show greater inputs of snowmelt to stream waters based on solute chemistry.

Initial strontium (Sr) isotope results (**Table 3**) for La Jara catchment indicate that streamwaters are slightly more radiogenic than groundwater, and less radiogenic than dust and soils. This supports the hypothesis that streamwater base cations are primarily sourced from mineral weathering (unradiogenic volcanic bedrock), with additional inputs from a more radiogenic endmember (potentially dust). On-going measurements of Ge/Si ratios and Sr isotopes of endmember water sources (e.g. soil waters, precipitation, springs) and stream waters will help further constrain solute sources and flowpaths. Chemical denudation rates are being calculated for the seven catchments draining Redondo Peak, and will be compared with physical denudation rates (being measured by the LSE group). In addition, chemical denudation rates for each catchment will be compared with transit times and hydrologic partitioning results (e.g. amount of groundwater storage) to determine controls on chemical weathering.

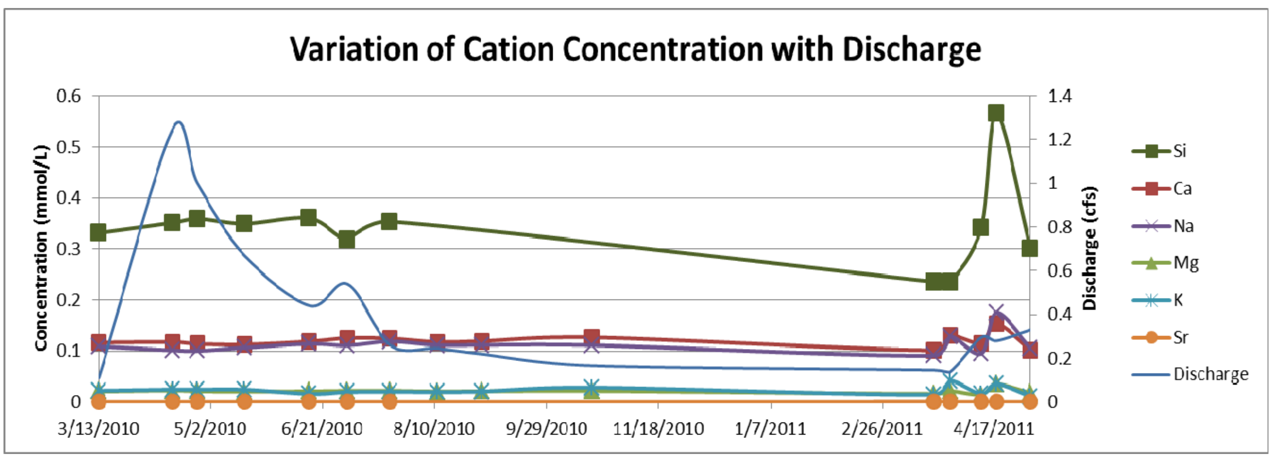


Figure 40. Cation concentrations in La Jara Creek plotted with stream discharge for 2010 (grab samples) and 2011 (autosampler (ISCO) samples) (McIntosh et al., unpubl. data).

Table 3. Preliminary strontium isotope results from La Jara Creek catchment (Porter et al., unpubl. data).

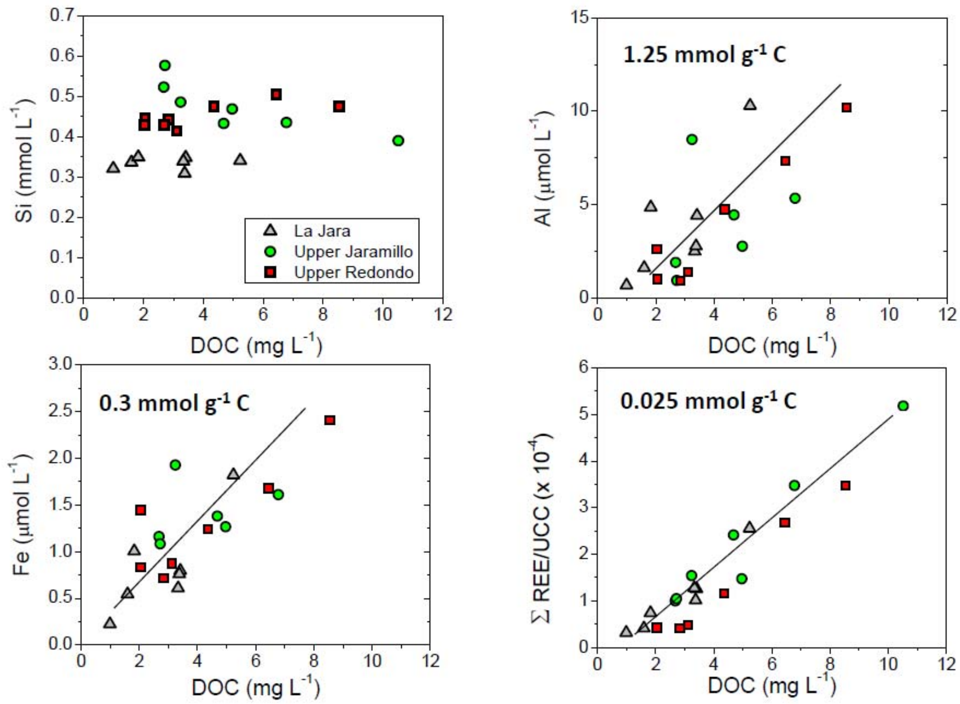
Sample	Sample Date	Sample Type	Ca (mmol/L)	Sr (mmol/L)	87Sr/86Sr	±
S201	3/13/2011	Flume Grab Sample	0.1358	0.0003	0.70753	0.00001
S213	3/13/2011	Seep Grab Sample (Groundwater)	0.1324	0.0003	0.7075	
S221	3/21/2011	West Fork Tributary Grab Sample	0.1664	0.0004		
S308	4/4/2011	Flume Grab Sample	0.1101	0.0003	0.70753	0.00001
P41	3/21/2011	Pit 6 Snow	-	0.00001	0.7082	0.0005
P42	3/21/2011	Pit 4 Snow	-	0.00003	0.70844	0.00002
P25	3/13/2011	Dust Layer in Snow	-	0.00004	0.71036	0.00001
Pit 4		Soil	9.8327	1.2737	0.71415	
Pit 6		Soil	8.5007	1.1584	0.72228	
Bedrock		Tuff	4.9251	0.0502	0.7108	
Bedrock		Dome	7.7691	0.3971	0.706425	

Upscaling solute sources and chemical denudation in JRB: Preliminary results show the dominance of snowmelt discharge (from elevated Cl/Na ratios, for example) into the East Fork of the Jemez River and Jaramillo Creek, which drain large open/wetland areas, in April-May. In contrast, headwater mountain catchments, such as La Jara and History Grove, show little input of snowmelt to stream discharge even during peak melt; the majority of discharge is from old groundwater, as evidenced by constant [Si] (e.g., **Figure 40**) and $\delta^{18}O$ values, and previous mixing model results using SO_4 and Cl. High [DOC] and low $\delta^{13}C$-DIC values suggests some component of soil carbon inputs.

Cation ratios (e.g. Ca/Sr) in stream waters are similar to results from other volcanic terrains, and there is no relationship between Ca+Mg *vs*. HCO_3, suggesting that cations are dominantly sourced from silicate weathering with little evidence for carbonate dissolution. We will be measuring snowmelt and precipitation (wet/dry) chemistry and isotopes this Spring-Summer to better constrain non-bedrock sources of solutes, so that we can calculate chemical denudation rates for the severn catchments surrounding Redondo Peak to test hypotheses about water and carbon availability (based on EEMT), and relations between water transit times and mineral weathering. These results will enable comparison with SSB and LSE results, as well as other CZO sites and previous catchment studies.

DOM and chemical denudation: Correlations between lithogenic element loss and DOC concentrations (**Figure 41**), along with the fact that DOC correlates with stream discharge (**Figure 36a**), suggest potentially strong biotic controls over chemical denudation of certain (DOM-complexing) lithogenic elements in forested upland JRB catchments (La Jara, History Grove, Upper Jaramillo). Although weak correlation is observed for Si (whose molar efflux is high relative to Al, Fe and trace polyvalent metals such as the rare earth elements), stronger correlation for the cationic metals is observed. Regression slopes provide a measure that compares favorably with the estimated charge density of dissolved organic matter (**Figure 41**).

Figure 41. Relation of Si, Al, Fe and rare earth element concentrations to DOC in three headwater catchments of the East Fork of the Jemez River. DOM concentrations increase with flume discharge suggesting a role for DOM in metal complexation chemical denudation (From Chorover et al., 2011).



Whereas headwater catchments in the JRB show little dilution of cationic weathering products with increasing discharge (**Figure 40**), a different "decoupling" of lithogenic elements is observed in the Marshall Gulch (SCM) site, where two distinct chemical denudation trends are observed in concentration-discharge relations. In this mixed conifer ecosystem, non-hydrolyzing cations (Ca, Mg, Na and K), as well as bicarbonate and silica, do show decreasing concentration with increasing discharge, consistent with dilution of these groundwater-derived solutes with event water (**Figure 42**).

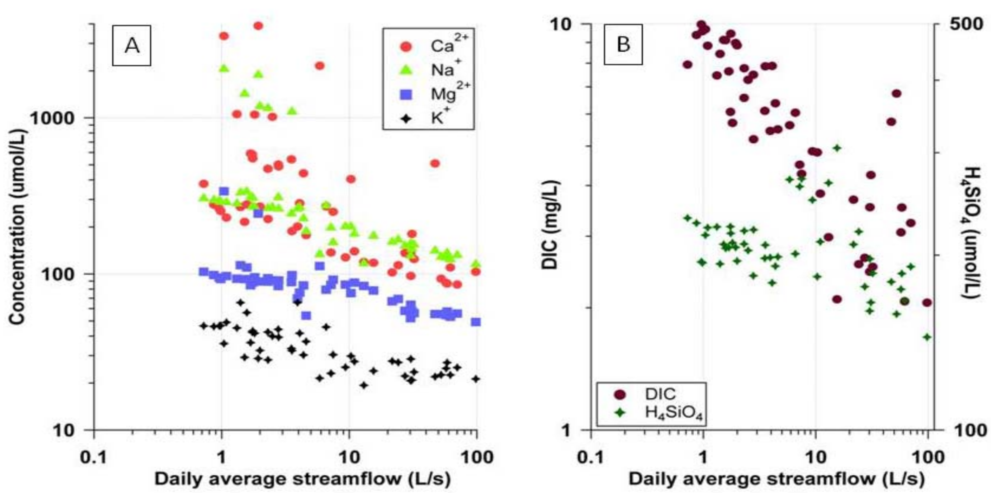


Figure 42. Concentration-discharge relations at Marshall Gulch outlet for (A) non-hydrolyzing cations and (B) dissolved inorganic carbon [dominantly HCO_3^-] and silica. (Jardine et al., unpubl. data.)

In contrast to the dilution effect observed for non-hydrolyzing cations, lithogenic polyvalent hydrolyzing cations (Al, Fe, and lanthanides) exhibit increasing concentration with increased discharge, coincident with increased DOC concentration (**Figure 43**). This behavior is consistent with the formation of polyvalent metal-DOC complexes in the near surface soils, and their mobilization during snowmelt and monsoon rain events. This set of observations highlights the importance of critical zone biota (via DOM production) that affects large changes in the stoichiometry of landscape chemical denudation with hydrologic dynamics and associated shifts in dominant catchment flow paths.

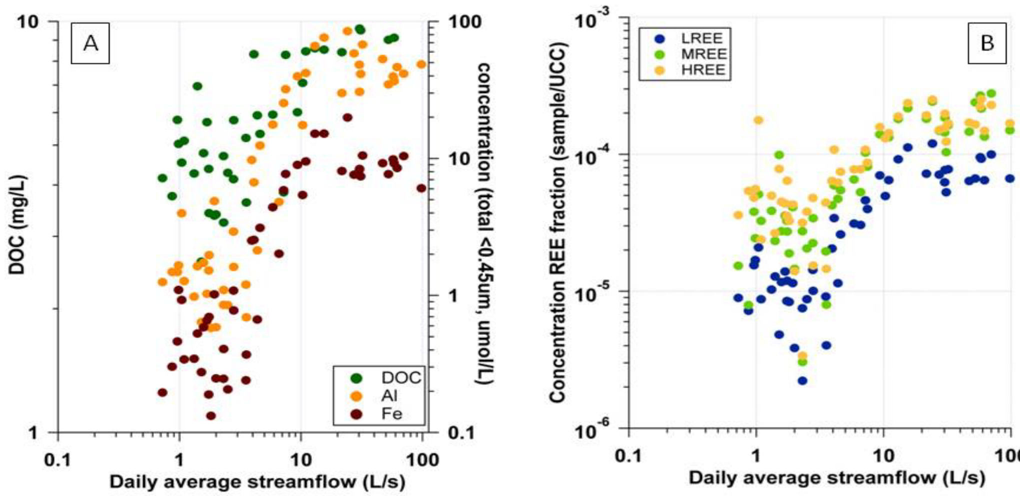


Figure 43. Concentration-discharge relations at Marshall Gulch outlet for (A) hydrolyzing cations and DOC and (B) low, medium and high mass rare earth elements (REE)s. (Jardine et al., unpubl. data)

2.4 Landscape Evolution Theme

Calibration and testing of upland hillslope evolution models in a dated landscape: Banco Bonito: The great complexity of the volcanic deposits in the JRB region pose a challenge to geomorphic and pedologic studies. For this reason, PI Pelletier, working with a team of students in Fall, 2010, chose to focus on landscape evolution in Banco Bonito, the youngest volcanic deposit in the region. Pelletier and his students tested upland hillslope evolution models and constrained the rates of regolith production, colluvial transport, and eolian deposition over geologic time scales in the dated Banco Bonito volcanic landscape in northern New Mexico using field measurements of regolith thickness, geochemical analyses of soil, bedrock, and regional dust samples, numerical modeling of regolith production and transport, and quantitative analyses of airborne Light Detection and Ranging (LiDAR) Digital Elevation Models (DEMs). Within this volcanic landscape, many topographically-closed basins exist as a result of compressional folding and explosion pitting during eruption (**Figure 44**). The landscape has evolved from an initial state of no soil cover at 40 ± 5 ka to its modern state, which has regolith ranging from 0 to 3+ m, with local thickness values controlled primarily by topographic position. Our models constrain the rate of potential weathering or bare-bedrock recession in the study area to be in the range of 0.02 to 0.12 m kyr^{-1} and the rate of colluvial transport per unit slope gradient to be in the range of 0.2 to 2.7 m^2 kyr^{-1}, with higher values in areas with more above-ground biomass. We concluded that a depth-dependent colluvial transport model better predicts the observed spatial distribution of regolith thickness compared to a model that has no depth dependence (Pelletier et al., *in press*). This study adds to the database of estimates for rates of regolith production and transport in the western United States and shows how dated landscapes can be used to improve our understanding of the coevolution of landscapes and regolith.

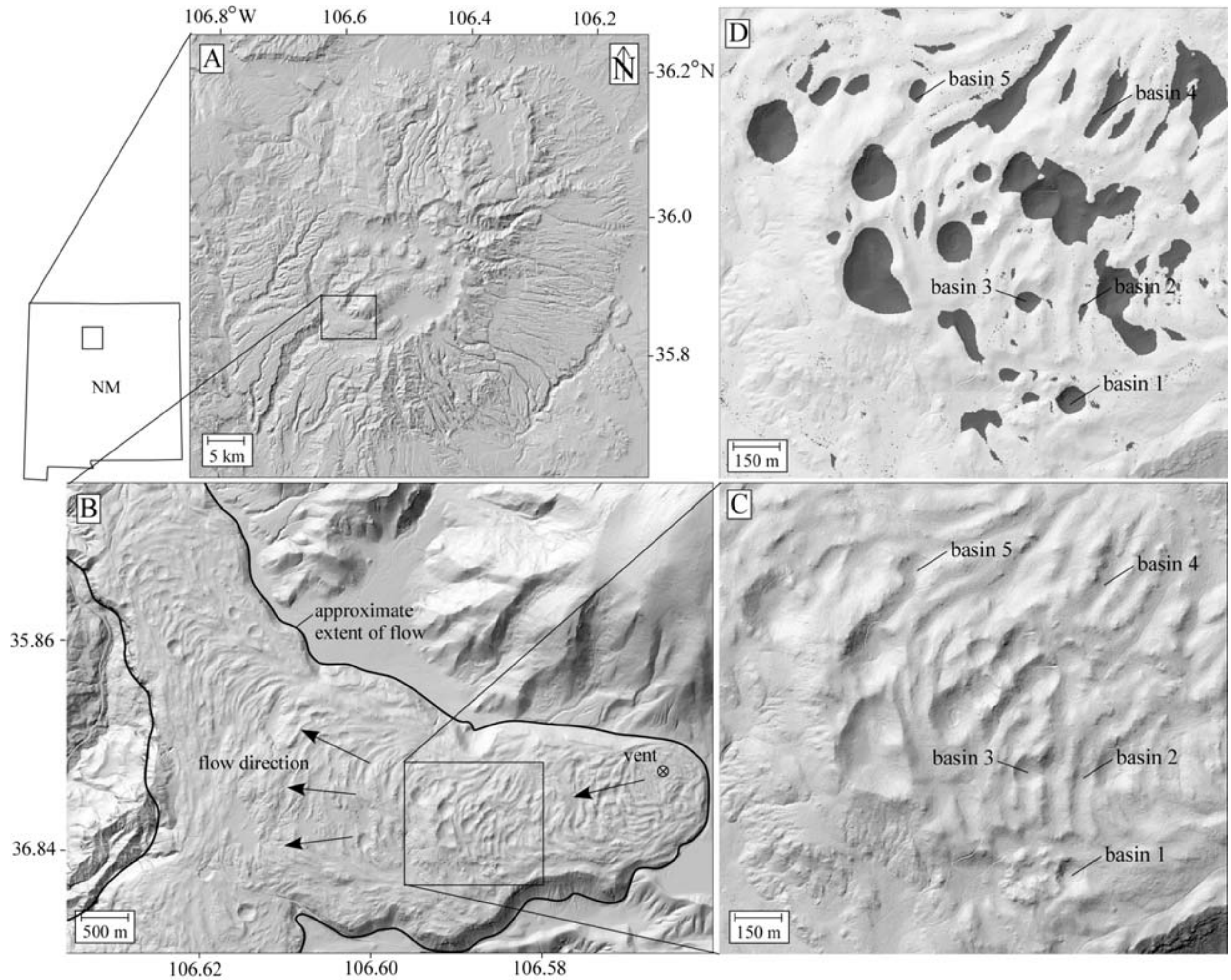


Figure 44. Shaded-relief maps of the Banco Bonito study site and surrounding region. (A) Valles Caldera region, northern New Mexico, (B) Banco Bonito volcanic flow and adjacent Redondo Mountain (NE corner of map), (C) subset of the Banco Bonito flow where field work was conducted with locations where the five basins where detailed soil presence/absence and thickness data were obtained. (D) Same area as (C), but including a transparent overlay illustrating topographically-closed basins. (Pelletier et al., *in press.*)

Numerical modeling of landscape, vegetation and soil co-evolution in the SCM over geologic time scales: Strong correlations exist among landscape processes in the SCM such that warm, dry, low elevation portions of these ranges are characterized by low biomass, thin soils, low water-storage potential, steep slopes, and a high valley density. Cooler, wetter, higher-elevation portions of these ranges have systematically higher biomass, thicker soils, higher water-storage potential, gentler slopes, and lower valley densities. Moreover, all of these variables vary with climate/elevation in different ways, i.e. some are more nonlinear than others. Slope gradient and aspect also exert an important control on these variables, with steep, south-facing hillslopes characterized by landscapes associated with drier-than-average conditions at a given elevation and north-facing slopes associated with wetter-than-average conditions. The right panel in **Figure 45** illustrates variations in relief, above ground biomass, soil thickness, and the average distance to the first-order valley (inversely related to valley density) calculated using LiDAR data and field measurements in the SCM. As the plots show, soil thickness increases nearly linearly with elevation while above ground biomass and distance to valley increase nonlinearly with elevation. Hillslope relief (computed at 100 m scale) shows less total variation across elevations than the other variables do, increasing by only about a factor of 2 to a maximum value where biomass and distance to valley increase most abruptly. These trends are very similar to those found in the Piñaleno Mountains, so they are robust patterns in the Sky Islands of the southwestern U.S.

The relationships among relief, soil, biomass, and distance to valley reflect the underlying role of climate in controlling the rates of landscape processes, and also reflect co-evolutionary feedback mechanisms among these processes that tend to amplify differences in rates set by climate and rock type. For example, thicker soils with a higher water storage potential that form at higher elevations/north-facing slopes tend to have greater biomass, thereby causing lower runoff ratios and increased rates of colluvial transport that promote still thicker soils, less-steep slopes and lower valley densities. Thicker soils and lower-relief, less-fluvially-dissected slopes, in turn promote greater biomass, infiltration, and evapotranspiration in a positive feedback.

PI Pelletier, working in collaboration with the entire UA CZO team, has developed a numerical model that provides a starting point for modeling the co-evolution of energy, water, carbon, and geology over geologic time scales we will perform in the project. This model was first described at the AGU 2010 Fall Meeting (Pelletier et al., 2010 Abstract EP42A-03). The Pelletier model uses EEMT to relate monthly precipitation, temperature, and ground-surface solar radiation (including variations with slope gradient and aspect) to derive bedrock weathering rates and vegetative biomass. Note that EEMT is an energy-based variable that combines temperature and precipitation into a single variable. Using EEMT as a driver, soil is produced in the model using the soil production function of Heimsath et al. Soil is transported down slope in the model using colluvial and slope wash/fluvial geomorphic processes using best-available information on how these processes vary with climate and biomass. For a given uplift rate, soil thickness, drainage density, and relief are key model outputs. These outputs are highly interrelated: e.g. because soil thickness controls the rate of colluvial transport and greater colluvial transport promotes a decrease in drainage density. The output of the model as applied to the uplift rate and climate of the SCM across the elevation gradient is shown on the left panel of **Figure 45**. The model reproduces the trends in relief, valley density, soil thickness, and vegetative biomass quite well considering that only one parameter (a soil erodibility coefficient) was used to optimize the fit between models and data.

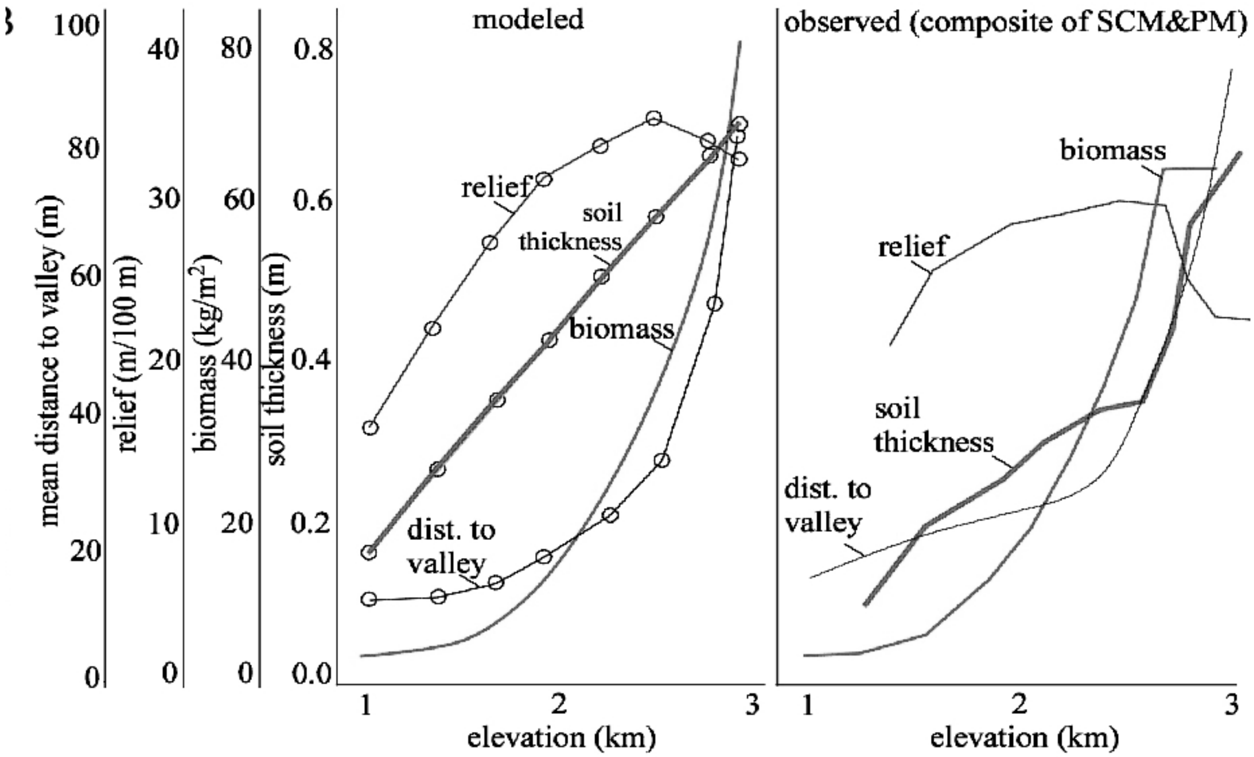


Figure 45. Comparison of numerical model (left panel) and actual (right panel) elevation transects of relief, average soil thickness, above-ground biomass, and average distance to valley. Model combines climatically-controlled bedrock weathering/soil production with models for soil erosion coupled to vegetation growth. Data in right panel is derived from field measurements and analysis of airborne LiDAR data. (Pelletier et al., *in prep*.)

3. Data Management Activities

Our JRB-SCM CZO data management specialist, Dr. Matej Durcik, has been working closely with members of the cross-CZO data management team (PI Mark Williams, CU Boulder) to consolidate hydrologic and hydrochemical time series data in a CUAHSI format that can be posted on line at CZO home servers and then harvested by "CZO central", for uploading to the San Diego Super Computer. All data being generated by the CZO is being geared toward presentation in the requisite format. Geochemical data acquisition (spatial data on distribution of geochemical concentrations, mineralogical data, etc.) are being incorporated into the Penn State led geochemical data base program that will permit eventual inclusion of the data into EarthChem (PI Kirsten Lehnert).

4. Opportunities for Training, Development, and Mentoring Provided by the Project

The multiple graduate and undergraduate students involved in this project have gained invaluable field and laboratory skills, and research experience working as part of a large interdisciplinary team. In addition, funding of a new REU site proposal at Biosphere 2 (B2) has provided excellent opportunities for undergraduate research experiences associated with the JRB-SCM CZO. Several B2 REU students were involved in CZO research during summers of 2010 and 2011, as described in "Personnel" section of this report. Three postdoctoral scientists (Dr. Julia Perdrial, Dr. Adrian Harpold and Dr. Bhaskar Mitra) are also receiving training and mentorship experience as part of this grant.

REU student Cynthia Wright presented initial (summer 2010) results of the Bigelow Tower carbon exchnage work (**Figures 21-23**) at the 2010 Society for Advancement of hispanic/Chicanos & Native Americans in Science (SACNAS) annual meeting, and she won the Best Poster in Ecology Award. As a result of this award, Wright was invited to present the work at the Joint Meeting of the Society of Wetlands Scientists and Wetland Biogeochemistry Symposium (Prague, Czech Republic, July 2011). Barron-Gafford presented the full data set at the Annual Meeting of the Ecological Society of America (Austin, Texas, Aug. 2011) and will lead the publication that is currently in preparation.

5. Outreach Activities Undertaken by the Project

The CZO project is developing a collaboration with the Biosphere 2 (B2), where CZO science and related findings will be displayed in conjunction with the B2-led "Landscape Evolution Observatory" (LEO) that will involve three replicated zero order basin hillslope models. The public display pertaining to LEO is going to focus on both LEO related activities and also complementary research occurring in CZO field sites. This project is funded for the Spring 2011 semester by the UA Water Sustainability Program and supports a graduate student in Ecology and Evolutionary Biology. Public displays at Biosphere 2 provide unique opportunites to reach a very large number of public visitors each year.

A wide array of information, including data, personnel and interpretive media are being uploaded regularly at the Jemez-Santa Catalina CZO website (www.czo.arizona.edu). For example, a draft video generated before and during the CZO All Hands Meeting at Biosphere 2 is now posted at that location.

6. Publications Resulting From Research

Published and Submitted Papers:

Adams, H. D., C. H. Luce, D. D. Breshears, M. Weiler, V. C. Hale, C. D. Allen, A. M. S. Smith, T. E. Huxman. (in review). Ecohydrological consequences of drought- and infestation-triggered tree die-off. *Ecohydrology*.

Broxton, P. D., P. A. Troch, and S. W. Lyon. 2009. On the role of aspect to quantify water transit times in small mountainous catchments. *Wat. Resour. Res.* W08427, doi:10.1029/2008WR007438

Chorover, J. 2011. Impact of soil physicochemical and biological reactions on transport of nutrients and pollutants in the Critical Zone. Chapter F10 in Handbook of Soil Science. Taylor and Francis Group LLC. *In press*.

Chorover, J., P. Troch, P. Brooks, C. Rasmussen, J. Pelletier, J. McIntosh, K. Lohse, M. Schaap, D. Breshears, T. Meixner, S. Papuga, T. Huxman, A. Harpold and J. Perdrial. How water, carbon, and energy drive critical zone evolution: The Jemez–Santa Catalina Critical Zone Observatory. *Vadose Zone J.* **10**, 884-899 (Special Issue on Critical Zone Observatories)

Gustafson, J. R., P. D. Brooks, W. C. Veatch, and N. P. Molotch, (in revision) Snow sublimation estimates using natural tracer concentration and isotopic fractionation in a semi-arid forested catchment *Wat. Resour. Res.*

Newman, B. D. , D. D. Breshears, and M. O. Gard. 2010. Evapotranspiration partitioning in a semiarid woodland: ecohydrological heterogeneity and connectivity in vegetation patches. *Vadose Zone Journal*: in press.

Mahmood, T. H, Vivoni, E. R., 2011. A climate-induced threshold in hydrologic response in a semiarid ponderosa pine hillslope. *Wat. Resour. Res*. (Minor revision).

Mahmood, T. H, Vivoni, E. R., 2011. Breakdown of hydrologic patterns upon model coarsening at hillslope scales and implications for experimental design. *J. Hydrol*. (In review).

Pelletier, J.D., and C. Rasmussen, Geomorphically-based predictive mapping of soil thickness in upland watersheds, *Wat. Resour. Res.*, **45**, W09417, doi:10.1029/2008WR007319, 2009a.
Pelletier, J.D., and C. Rasmussen, Quantifying the climatic and tectonic controls on hillslope steepness and erosion rates, *Lithosphere*, **1**, 73-80, 2009b.
Pelletier, J.D., Engelder, T.M., Comeau, D., Hudson, A., Leclerc, M., Youberg, A., and S. Diniega, Tectonic and structural control of fluvial channel morphology in metamorphic core complexes: The example of the Catalina-Rincon core complex, Arizona, *Geosphere*, **5**, 363-384, 2009.
Pelletier, J.D., L.A. McGuire, J.L. Ash, T.M. Engelder, L.E. Hill, K.W. Leroy, C.A. Orem, W.S. Rosenthal, M.A. Trees, C. Rasmussen, J. Chorover, Calibration and testing of upland hillslope evolution models in a dated landscape: Banco Bonito, New Mexico, USA, *J. Geophys. Res. Earth Surface*, in review.
Rasmussen, C., P.A Troch, J. Chorover, P. Brooks, J. Pelletier, and T. Huxman. 2010. An open system framework for integrating critical zone structure and function. *Biogeochem*.. **102**, 15-29.
Rasmussen, C., S. Brantley, D. Richter, A. Blum, J. Dixon, O.A. Chadwick, and A.F. White. 2011. In Press. Strong climate and tectonic control on chemical weathering in granitic terrain. *Earth Planet. Sci. Let.* **301**, 521-530.
Urgeghe, A. M., D. D. Breshears, S. N. Martens, and P. C. Beeson. 2011. Redistribution of runoff among vegetation patch types: on ecohydrological optimality of herbaceous capture of runon. *Rangeland Ecology and Management* 63: in press.

<u>Theses:</u>

Jardine, A. 2011. Aqueous phase tracers of chemical weathering in a semi-arid critical zone. M.S. Thesis in Hydrology and Water Resources, University of Arizona, Tucson AZ. 94 p.

<u>Papers "In preparation" - to be submitted within the next 12 months:</u>

Heidebuchel, I. et al. (in prep) Estimation of long transit times from relatively short data sets in ephemeral catchments.
Heidebuchel, I. et al. (in prep) Geologic and topographic controls on hillslope mean transit times in a semi-arid mountain catchment.
Jardine, A., P. A. Troch, J. Chorover, and others (in prep) Dissolved rare earth elements in a semi-arid mountain critical zone.
Law, D. J., D. D. Breshears, M. H. Ebinger, C. D. Allen, and C. W. Meyer. (in prep) Soil C and N hydrological functional units within an eroding woodland hillslope: ecohydrological-biogeochemical coupling via runoff-driven redistribution and loss. For planned submission to *Journal of Arid Environments*.
Lohse, K.A., P.D. Brooks, C. Stielstra, J. Chorover, and C. Rasmussen. Variation in soil carbon and nitrogen with EEMT and vegetation in the Jemez River Basin Critical Zone Observatory
McIntosh, J. et al. (in prep) Influence of mean transit times on chemical denudation rates in a rhyolitic semi-arid catchment.
Pelletier, J.D. and CZO team (in prep), Large-scale coevolution of topography, hydrologic pathways, soil development, and vegetation in mountain ranges of the southwestern United States.
Perdrial, J., J. McIntosh, A. Harpold, P. Brooks, P. Troch, J. Ray, X. Zapata-Rios, J. Chorover (in prep). Impact of catchment aspect and transit times on stream water carbon characteristics.

<u>Published Abstracts & Presentations of Results (only those presented since last annual NSF report):</u>
**Invited, **Students*

Brooks, P. D.; A.A. Harpold; A.J. Somor; P.A. Troch; D.J. Gochis; B.E. Ewers; E. Pendall; J.A. Biederman; D. Reed; H.R. Barnard; F. Whitehouse; T. Aston; B. Borkhuu (2010) Quantifying the effects of mountain pine beetle infestation on water and biogeochemical cycles at multiple spatial and temporal scales. Abstract U33B-04 (was B31E-0348). Annual Meetings of the American Geophysical Union, December 2010.

**Broxton, P.D.; P.A. Troch; P.D. Brooks (2010) Can Landscape Heterogeneity Buffer or Exacerbate Changes in Mountain Hydrology under Different Climatic Conditions? (Poster) Abstract H33C-1143. Annual Meetings of the American Geophysical Union, December 2010.

**Bunting, D. P.; E.P. Glenn; S.A. Kurc; R.L. Scott; P.L. Nagler (2010) Estimating large-scale evapotranspiration in arid and semi-arid systems: A multi-site study linking MODIS and Ameriflux data. (Poster) Abstract H31B-1000. Annual Meetings of the American Geophysical Union, December 2010.

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7. Contributions to within Discipline

As described in detail above, ongoing research in multiple coordinated projects is resulting in substantive, peer-reviewed contributions within the fields of ecology, geochemistry, hydrology, and geomorphology. These disciplinary contributions are strengthened by the inter-disciplinary linkages that are being made to allied disciplines via cross-cutting CZO science themes.

8. Contributions to Resources for Research and Education

In so far as the principal intent of the CZOs is to establish natural laboratories for use by the broader earth sciences community, we have made significant progress in this respect through installations of sampling equipment and sensors in the SCM at low, intermediate and high elevation sites, and an intensive instrumentation array in the JRB high elevation (mixed conifer) site. Fire-impacted high elevation, and unburned intermediate elevation sites in the JRB will see initial instrument installations in fall 2011.

The JRB-SCM CZO is coordinating with the new Biosphere 2 REU/RET site to provide an exciting venue for their earth system sciences summer research program. Several of the CZO investigators hosted REU/RET students in their lab groups during summers of 2010 and 2011 focusing on CZO research.

PI Jon Pelletier taught a graduate course on geomorphology of the Banco Bonito flows in the JRB in Fall of 2010. Field results deriving from this course resulted in a peer reviewed publication in *J. Geophys. Res.* PIs (Paul Brooks and Jennifer McIntosh) developed and taught a graduate seminar course (HWR 696B) on hydrobiogeochemistry of seasonally snow-covered catchments, in Spring 2011, drawing heavily from recent CZO-related results. Seven students, 2 postdocs, and 1 technician supported by the CZO project participated during the spring semester, and traveled to the JRB CZO over Spring Break to learn snow and surface water sampling techniques.

9. Contributions to Society

Chorover, J. 2010. “Living in, discovering the critical zone”. Invited article for special “Science supplement” issue of the Arizona Daily Star (Tucson daily newspaper), November 14, 2010.