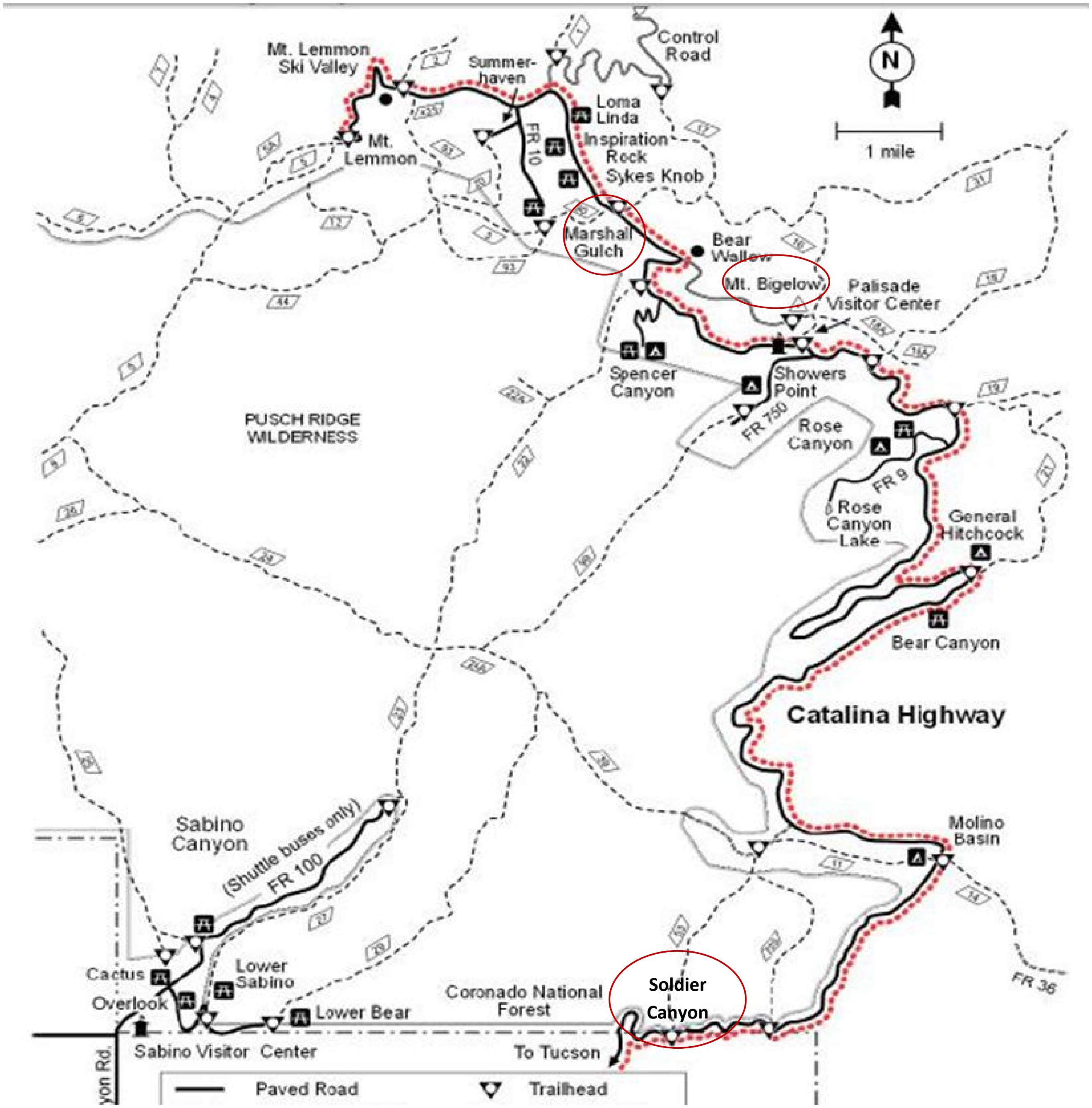
CZO All Hands Meeting

# Mt Lemmon - Santa Catalina Mountains Field Trip

May 10, 2011, 7:30 am - 6:30 pm
Stops at: Soldier Canyon, Mount Bigalow Flux Tower, Marshall Gulch ZOB
Pick-up your lunch bag at breakfast!!

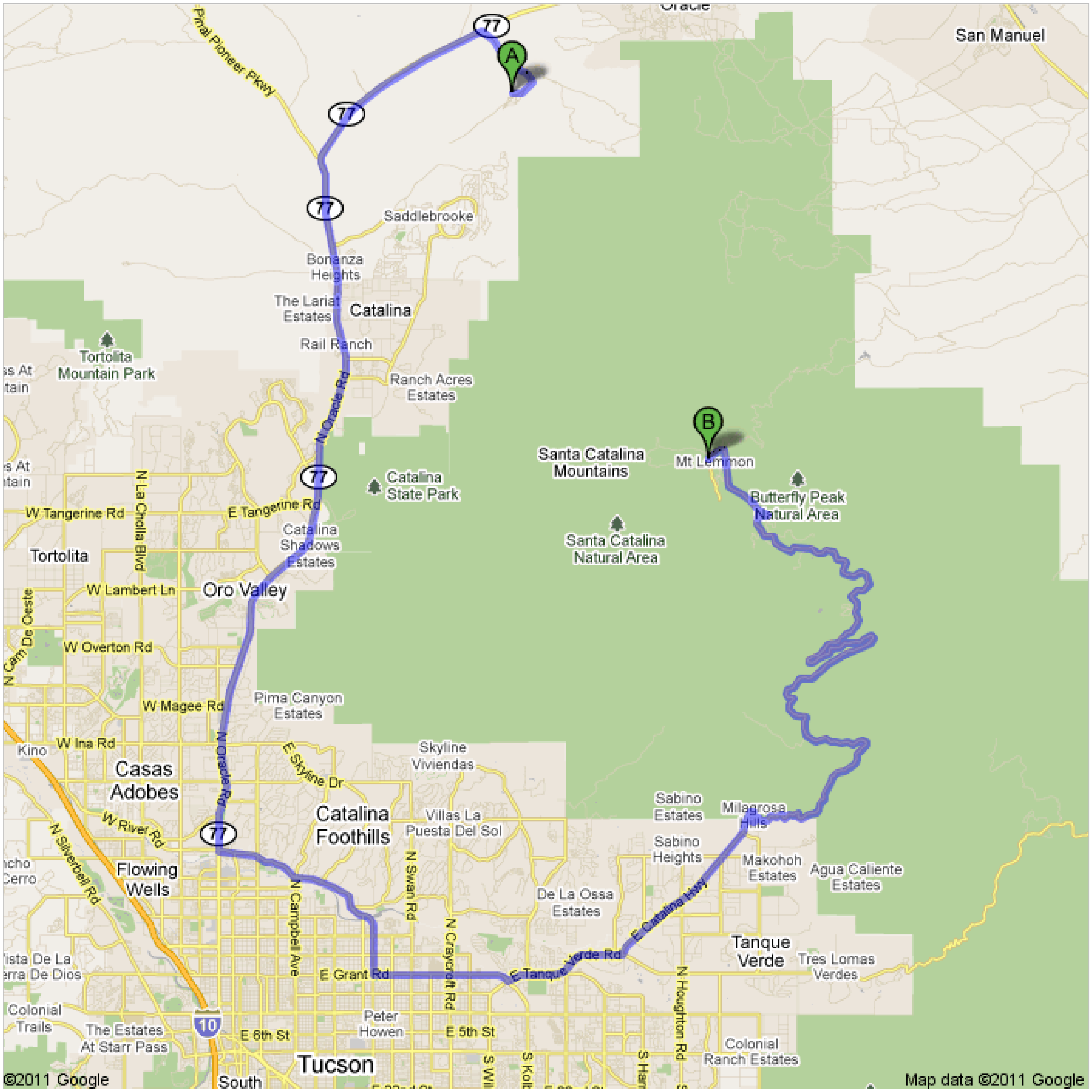



This work is supported by the National Science Foundation's Critical Zone Observatory Program project entitled Transformative Behavior of Water, Energy and Carbon in the Critical Zone: An Observatory to Quantify Linkages among Ecohydrology, Biogeochemistry, and Landscape Evolution”, grant EAR-0724958. Additional support has also been provided by the Philecology Assocation of Fort Worth Texas, the University of Arizona Water Sustainability Program, SAHRA, and USDA Agricultural Research Service.

Google maps

**Directions to United States Government: Mount Lemmon Post Office**
12984 N Sabino Canyon Rd, AZ 85619-9997 - (520) 576-1427
**69.3 mi** – about **2 hours 2 mins**

**Save trees. Go green!**
Download Google Maps on your phone at **google.com/gmm**



National Critical Zone Observatories Program
All Hands Meeting Field Trip - Tuesday, May 10, 2011
Biosphere 2 - Mt. Lemmon

**Field Trip Schedule**

**Tour of Santa Catalina Mountains CZO**

6:45 Quick Breakfast

7:30 Buses depart from Biosphere 2

8:30 Rest stop at Tanque Verde & Catalina Highway (30 min)
9:00 depart

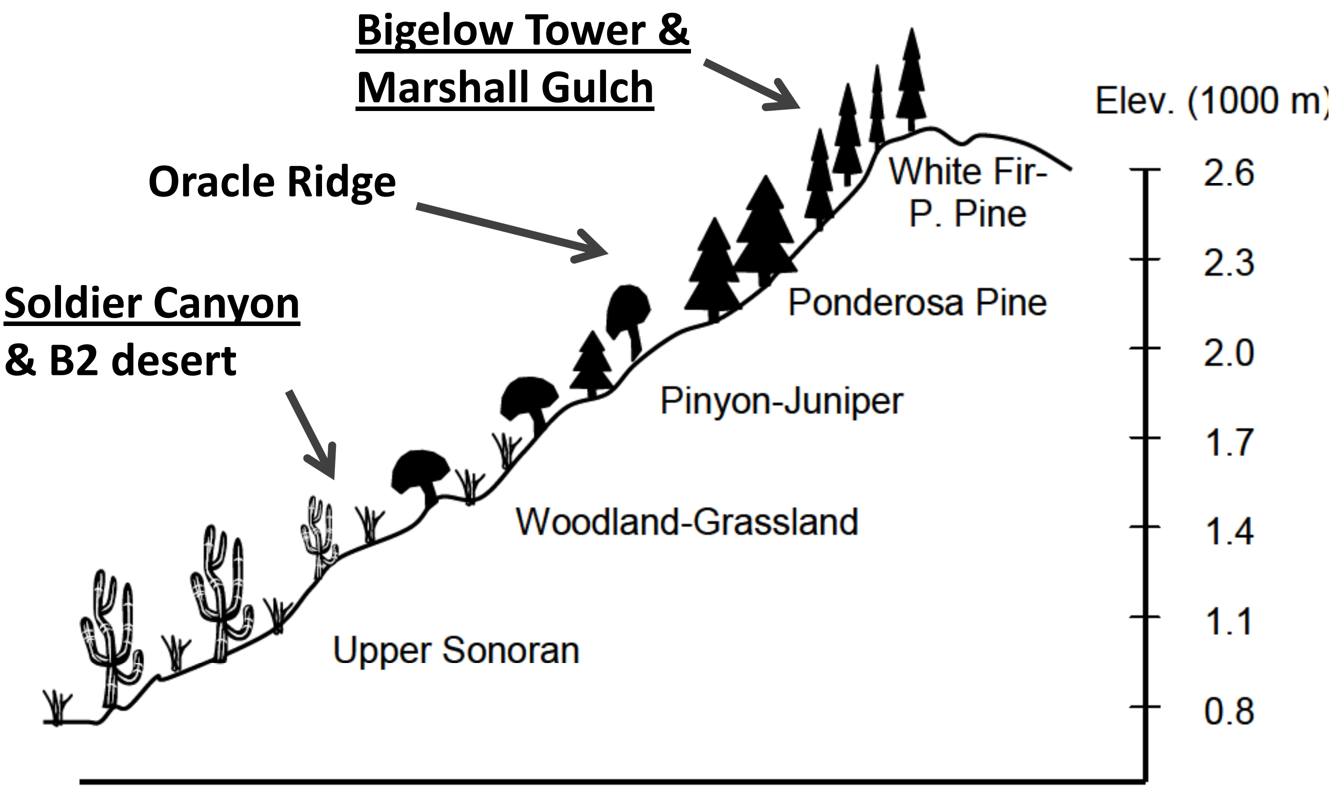
9:20 Geomorphic & Ecologic overview - Soldier Canyon pull-off (60 +25 min)
10:45 depart

-- Lunch on the bus or after first stop

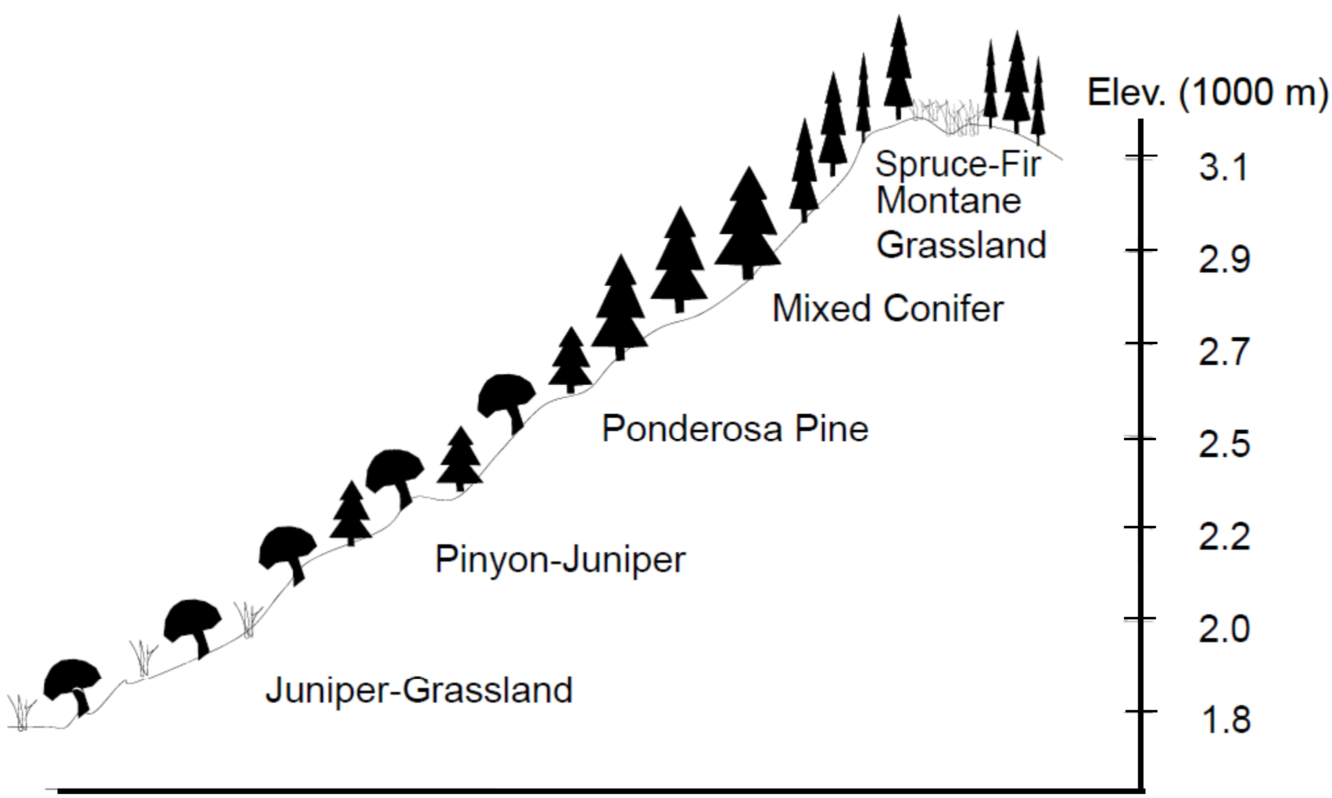
| Bus A | Bus B |
|---|---|
| 11:30 Mt. Bigelow eddy covariance tower (120 min on site) 1:30 depart | 11:45 Marshall Gulch catchment experiments (120 min on site) 1:45 depart |
| Bus - wait at Summerhaven for other bus | |
| 2:00 Marshall Gulch catchment experiments (120 min on site) 4:00 depart | 2:10 Mt. Bigelow eddy covariance tower (120 min on site) 4:10 depart |

6:30 Arrive at Biosphere 2

7:00 Dinner




Santa Catalina Mountains (AZ)




Jemez River Basin (NM)

**Santa Catalina Mountains CZO:**

**Soldier Canyon - Tucson Basin**

**Field Trip Overlook**


## Background:

Mountain block recharge (MBR) in snow-covered mountains in the semi-arid SW of the US is one of the dominant processes that provide basin aquifer water resources to municipalities and industries. It is important to understand how this resource is likely to change in a warming climate with associated vegetation shifts.

This study combines hydrologic, chemical and isotopic tracers to determine how incoming snowmelt and rainfall is partitioned between evapotranspiration, shallow subsurface runoff and deep percolation to basin aquifers, and what are the associated transit times along these different flowpaths.

Quantification of water balances in complex mountain systems, such as the Jemez and Santa Catalina Mountains, will lead to improved conceptual and mathematical models of MBR. Such improved models will be extremely useful in order to predict the direction of change to the water balance under different climate scenarios.

## 1. Santa Catalina Mountains Study, AZ

### Santa Catalina Mountain (SCM) Catchments:

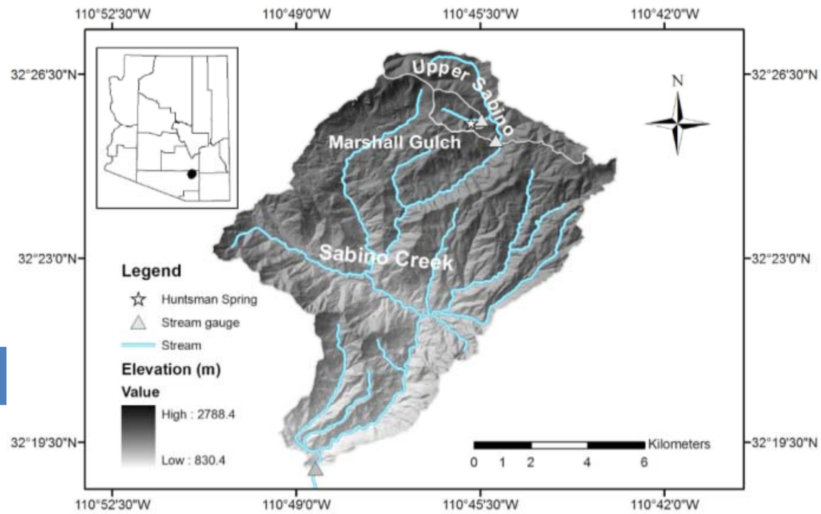
•Marshall Gulch (1.5km$^2$ drainage area) and Upper Sabino (8.8km$^2$) catchments are the headwaters for Sabino Creek (91km$^2$).
•Elevation ranges from 830m (base) to 2780m (Mt. Lemmon).
•Average annual precipitation is ~300mm (base), and increases to 690-940mm (top).
•Approx. 50% precipitation from summer monsoons (high intensity, short duration storms), and 50% precipitation from winter rains (low intensity, long duration frontal storms, snow at high elev). These wet periods are separated by prolonged dry periods.

## Overarching Science Questions:

✓*What are the various water sources, flowpaths and transit times to stream flow in mountain catchments, and how do they vary in space and time? How are these water sources linked to basin aquifer recharge?*

## 1. Santa Catalina Mountains Study, AZ - cont'd

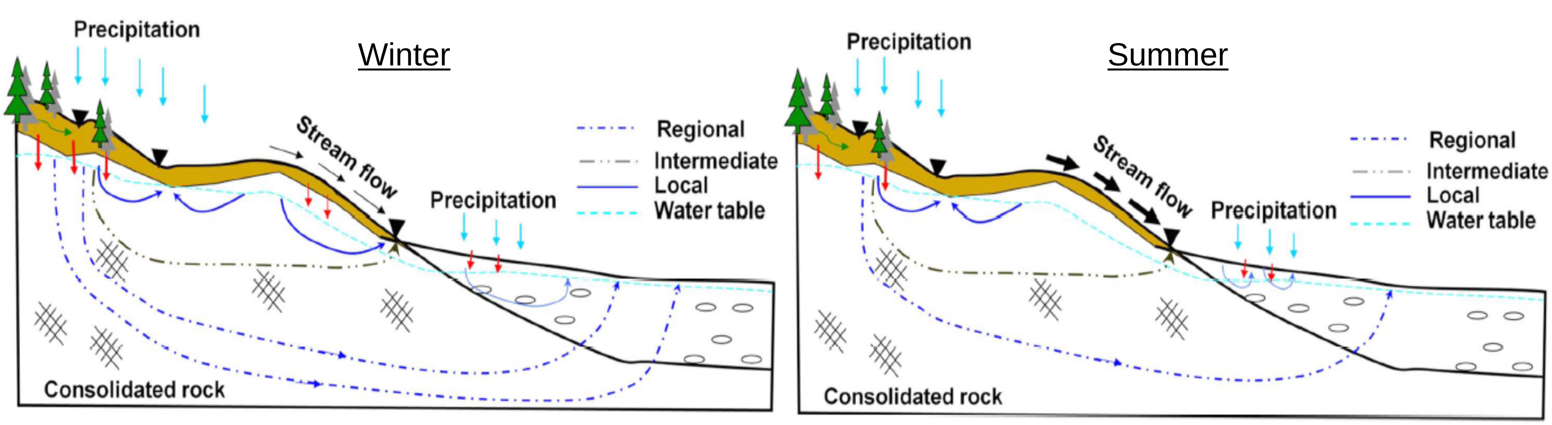
**Sabino Creek Catchment**
**Santa Catalina Mountains CZO**



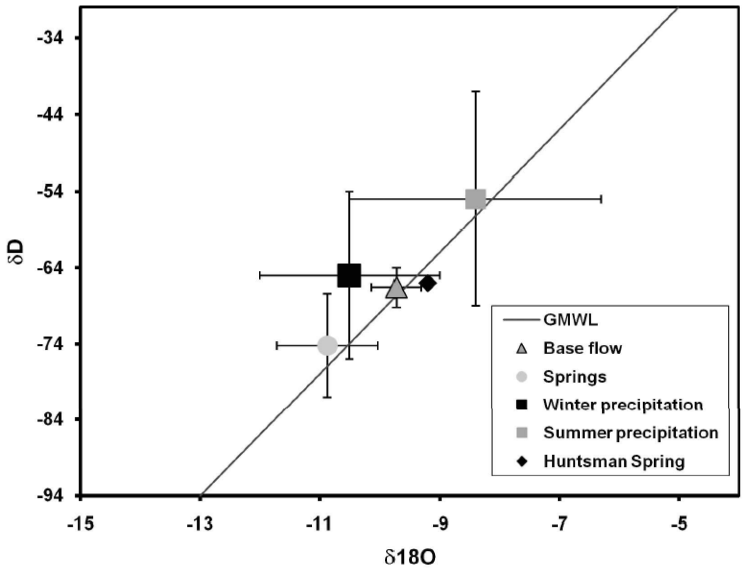

### Conceptual Model of MBR:

•High elevation catchments (Marshall Gulch and Upper Sabino Creek), with thicker soils, higher precipitation, and lower temperatures are the major contributor to MBR.
•During wet seasons soil water infiltration at high elevations contributes to deep aquifer and fractured bedrock storage. This storage sustains flow in Marshall Gulch, Upper Sabino and Sabino Creek during dry periods.
•At lower elevations (Sabino Creek), steep terrain with thin soils on side slopes promotes rapid surface runoff, especially during the monsoon season. Surface runoff may infiltrate into permeable stream channel sediments and alluvial aquifers contributing to Mountain Front Recharge.

**Conceptual Model of MBR in SCM-CZO**



## Isotopic Composition of Endmember Source Waters Contributing to Stream Flow




**Isotopic evidence supports conceptual model of MBR:**

- Most spring water samples in the SCM are younger than 50 years, suggesting short transit times through a relatively permeable bedrock aquifer, and have isotopic signatures of winter precipitation recharge with no evidence of evaporation.
- Base flow in Marshall Gulch and Upper Sabino Creek is dominated by winter precipitation stored in fractured bedrock.
- Lower elevation, Sabino Creek, base flow indicates a mixture of summer precipitation (rainfall runoff and bank storage) and high elevation winter precipitation (deep circu.).
- Mountain front groundwater is dominated by winter precipitation (deep circulation), in addition to shallow recharge through mountain streams.
- Tucson basin groundwater is dominated by winter precipitation recharge (high elevation MBR + low elevation recharge through local washes).

**Storage-Discharge Relations to estimate MBR rates:**

- MBR rates quantified by estimating storage changes caused by precipitation seasonality in the deep aquifers in fractured bedrock.
- Seasonal changes in catchment storage dynamics investigated by recession flow analysis - calculating differences in base flow prior to and after the precipitation season.
- Storage-discharge relations calculated at multiple scales.
- Average post-precipitation season stream flows are larger in winter versus summer for Upper Sabino and Sabino Creek (2007-2008).
- Marshall Gulch average post-precipitation season stream flow slightly higher in summer because of strong 2007 monsoons.
- 50-72% of MBR in Sabino catchment originates from upper elevations. Rest of recharge occurs in lower portions of watershed likely due to direct infiltration into alluvial riparian aquifer and bank storage processes.

## Quantification of Mountain Block Recharge (MBR)

| Catchment | Winter MBR (mm) | | Monsoon MBR (mm) | | Annual MBR (mm) | |
|---|---|---|---|---|---|---|
| | 2007 | 2008 | 2007 | 2008 | 2007 | 2008 |
| Marshall Gulch | 7.2 | 10.3 | 7.7 | 4.5 | 14.9 | 14.8 |
| Upper Sabino | 1.5 | 5.6 | 0.2 | 2.4 | 1.7 | 8.0 |
| Sabino Creek | 0.6 | 4.6 | 0.2 | 0.8 | 0.8 | 5.4 |

**Contact**. For collaboration or more information contact:
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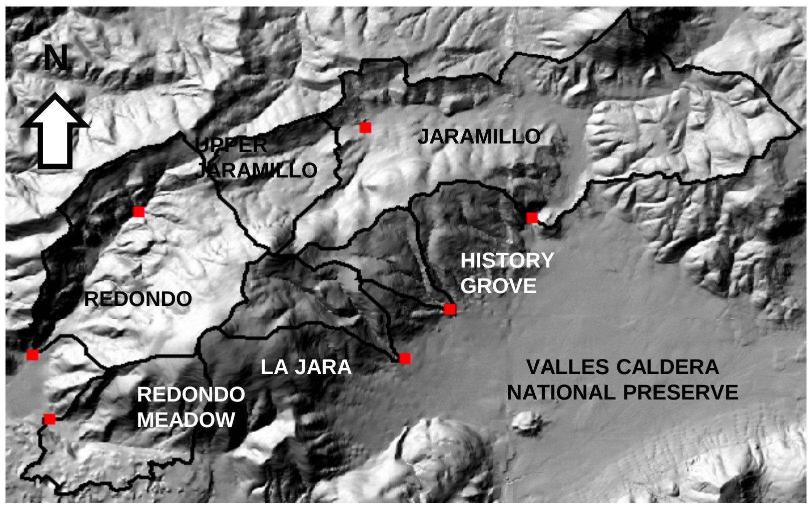
*JRB-SCM CZO website: http://www.czo.arizona.edu/*

## 2. Redondo Peak Catchments, Jemez Mountains Study, NM

**Upper Jemez River Basin (JRB) in the Valles Caldera National Preserve (VCNP).**

- The VCNP encompasses approx a 22 km wide nearly circular
caldera in the middle of the Jemez Mountains. Redondo Peak is located in the center of the caldera with an elevation of 3432 m.
- Several streams drain Redondo Peak: La Jara (3.7 $km^2$ ) History Grove (2.4 $km^2$) Jaramillo (26.6 $km^2$) Upper Jaramillo (3.1 $km^2$) Redondo (13.4 $km^2$) Upper Redondo (0.8 $km^2$), and Redondo Meadow (1.1 $km^2$).
- Elevation ranges from 2300m (base) to 3432m (Redondo Peak).
- Average annual precipitation is less than 800mm per year.
- Approx. 65% of annual precipitation falls as snow between October and April. 35% falls as rainfall especially during the monsoon between July and August.

### Catchments draining Redondo Peak in the Valles Caldera National Preserve (VCNP), NM.

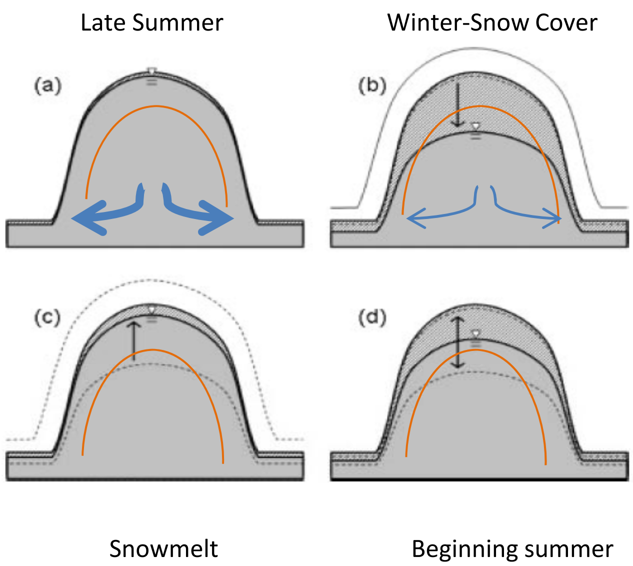



*Flume locations shown in red squares.*

## Conceptual model of MBR in the Jemez River Basin

•The sub-surface layers in the upper elevations of Redondo Peak are highly permeable; it can be assumed that the presence and absence of channel streamflow is closely coupled with the position of the water table.
•During the late summer the water table is close to the surface as a consequence of monsoon precipitation.
•During the winter as snow accumulates there is limited to no water input to the water table and the water table drops.
•During the snowmelt season water infiltrates and the water table rises.
•During the summer evapotranspiration and plant uptake tend to draw down the water table in Redondo Peak ( Lyon et al., 2008).

### Conceptual Model of MBR and sources of stream discharge in Redondo Peak, Jemez River Basin, NM




## Research Approach and Methods:

To constrain the source, timing and flowpaths of water to stream flow and basin aquifers (via MBR), we are applying a multi-tracer and multi-scale (both in space and time) approach:
• A zero order basin in La Jara Catchment has been instrumented with a meterological tower, snow and soil lysimeters, and piezometers for hydrometric and chemistry analysis.
•Streamflow is measured at 7 flumes installed in the 6 catchments around Redondo Peak.
•Water samples are collected from precipitation, soil, springs and surface water for chemical and isotopic analysis in all the catchments.

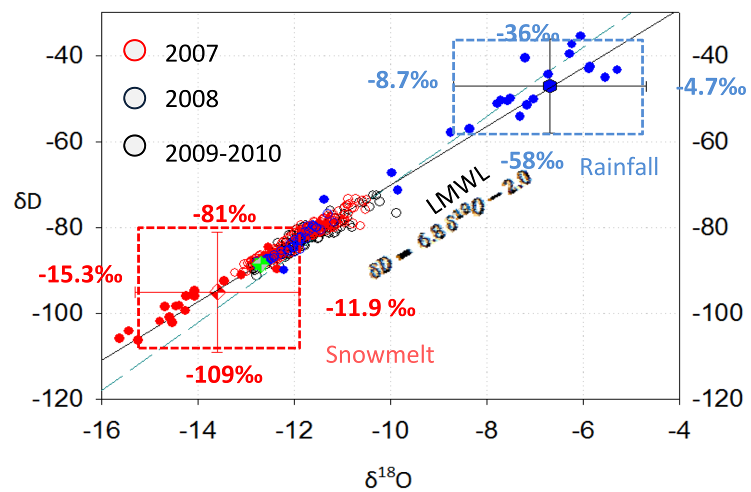
## References:


Ajami, H., Troch, P.A., Maddock, T., Meixner, T., Eastoe, C. (2011) Qauntifying mountain block recharge by means of catchment-scale storage-discharge relationships. Water Resources Research, 47, W04504.
Lyon, S.W., Troch, P.A., Broxton, P.D., Molotch, N.P., Brooks, P.D. (2008) Monitoring the timing of snow melt and the initiation of streamflow using a distributed network of temrperature/light sensors. Ecohydrology, 1, 215-224.

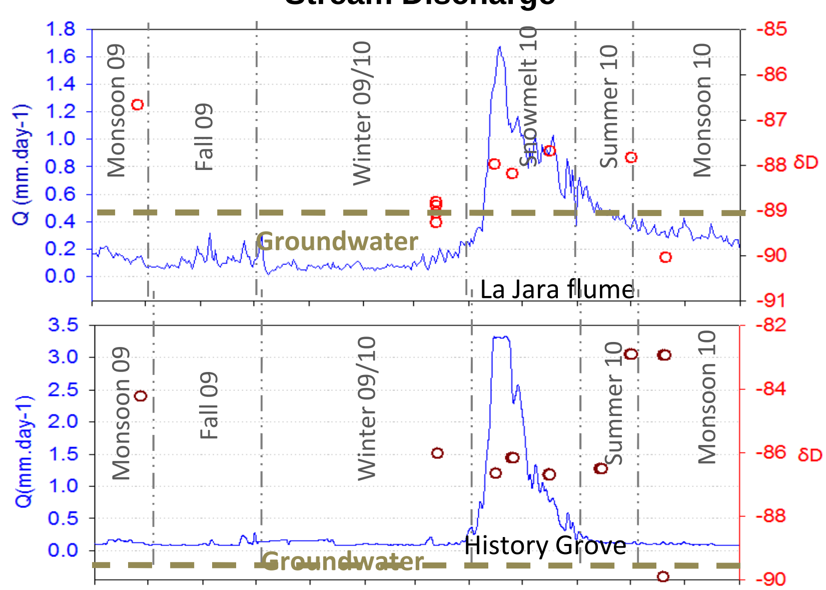

## Preliminary Results on MBR in Jemez River Basin:

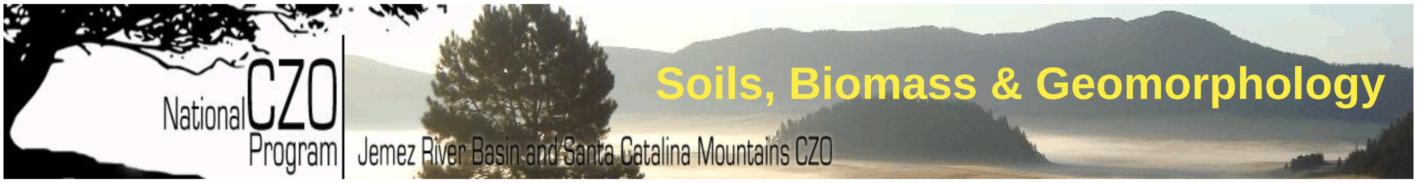
•Streams around Redondo Peak have stable isotope values within the range of local snowmelt, rainfall, and groundwater, plotting along the local meteoric water line (LMWL).
•Isotopic composition of endmember waters are combined with other chemical tracers (e.g. Cl, $SO_4$, DOC) to quantify various source water contributions and flowpaths to stream flow.
•Little variation in the stable isotope composition of stream water throughout the year, within the range of groundwater values, suggests groundwater inputs dominant stream discharge.
•Catchments, such as La Jara and History Grove have similar physical characteristics (e.g. areas, elevations, slopes and aspects), yet have different hydrologic responses and source water contributions (see discharge and isotope plots below). We hypothesize these differences between catchments are related to differences in effective energy and mass transfer (EEMT).

### Isotopic Composition of Stream Waters Compared to Snowmelt, Groundwater and Precipitation Inputs




### Seasonal Variability in Isotopic Composition of Stream Discharge





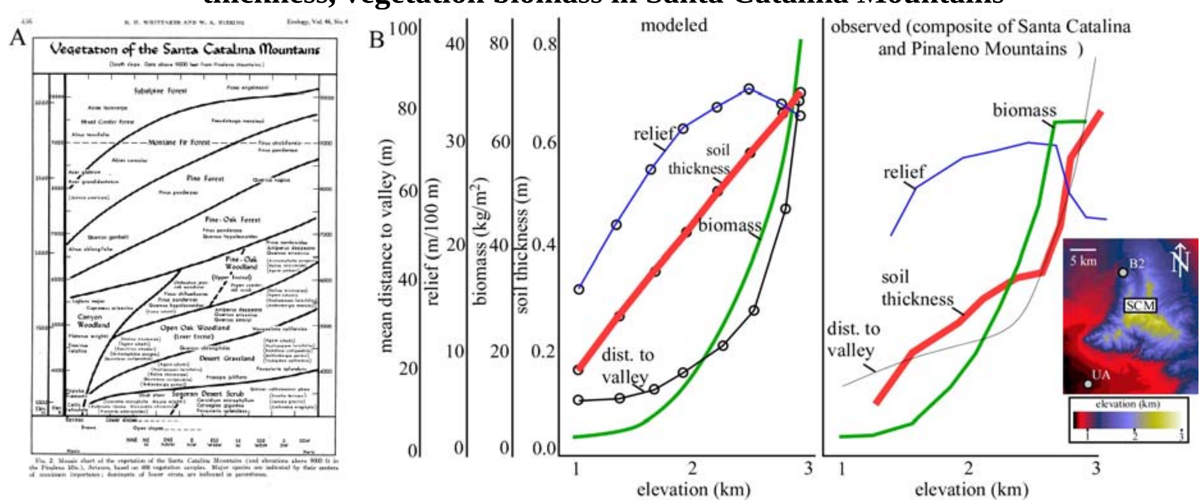

**Variations in soils, biomass, and geomorphology across the SCM elevation/EEMT gradient**

Key points:

- Distinctive correlations exist among soils, vegetation, and landforms in SCM.
- These correlations partly reflect the central role of climate in all CZ processes but also the feedbacks among runoff/infiltration, soils, vegetation, and landform development.
- Numerical models that explicitly couple soil development, ecology, and geomorphology and that use EEMT as the "driver" of CZ processes reproduce the observed patterns.

The Santa Catalina Mountains (SCM) span climates from the Sonoran Desert (at 800 m a.s.l.) to mixed conifer forests (at over 2500 m a.s.l.) (Fig. 1A), all in an area comprised principally of granite/gneiss and subject to a uniform tectonic history dominated by late Oligocene-early Miocene tectonic uplift. Strong correlations exist among CZ processes 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 Fig. 1B 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 available airborne LiDAR data and field measurements. As the plots show, soil thickness increases nearly linearly with elevation while above-ground biomass and average 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.

**Fig. 1: Study sites and comparison of modeled vs. observed measures of topography, soil thickness, vegetation biomass in Santa Catalina Mountains**

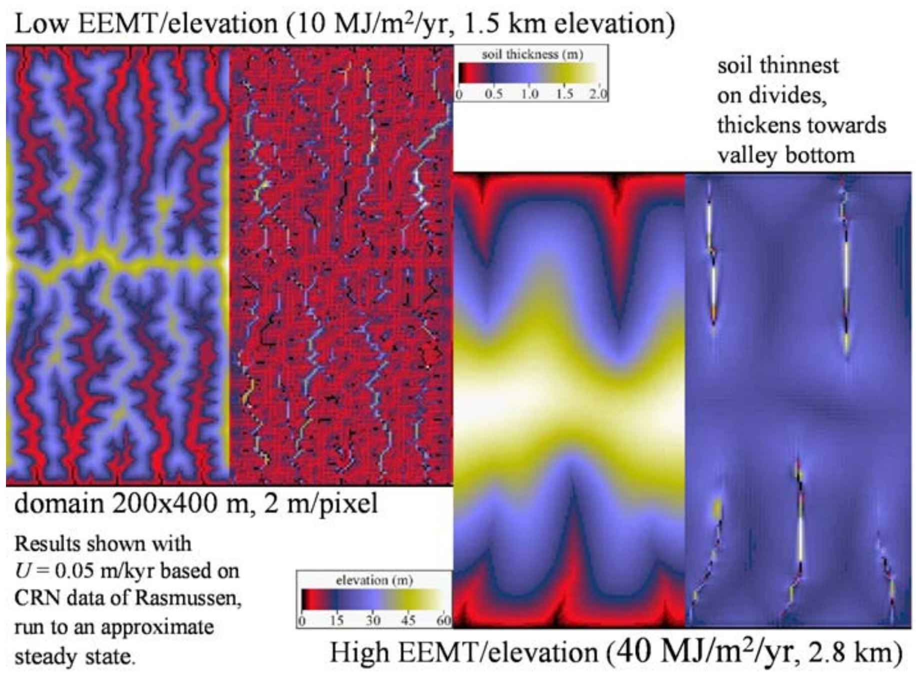



(A) SCM is a classic locality for the study of climatic control of biomes (e.g. Whittaker and Niering, 1965). (B) Comparison of numerical model (left panel) and actual (right panel) elevation transects of relief, average soil thickness, above-ground biomass, and average distance to valley across the SCM gradient. 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.

The relationships among relief, soil thickness, 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.

The UA CZO team has developed a numerical model that reproduces the observed variations (Fig. 1B) 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. Using EEMT as a driver, soil is produced in the model using the soil production function of Heimsath. Soil is transported down-slope in the model using colluvial and slope wash/fluvial geomorphic process models that incorporate the best-available information on how these processes vary with climate and biomass. For a given rock uplift rate, soil thickness, drainage density, and relief are key model outputs. These outputs are highly interrelated: e.g. 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 measured rock uplift rate and climate of the SCM across the elevation gradient is shown on the left panel of Fig. 1B. 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. Fig. 2 and the accompanying caption illustrate and describe the topography and soil thickness output of the model (expressed as color maps) for a low elevation/EEMT case and a high elevation/EEMT case.

**Fig. 2: Example output of the numerical model for low and high elevation/EEMT values**




Shown above are color maps of elevation and soil thickness output by the numerical model. The model is run to an approximate topographic steady state condition with an uplift rate constrained by CRN data. At low elevation/EEMT, valley density is high and soil thicknesses/depths-to-bedrock are low. Conversely, at high elevation/EEMT valley density is low and soils are thick. Within each model, soils are thinner on ridgetops and thicken towards valley bottoms, similar to the pattern observed in SCM.

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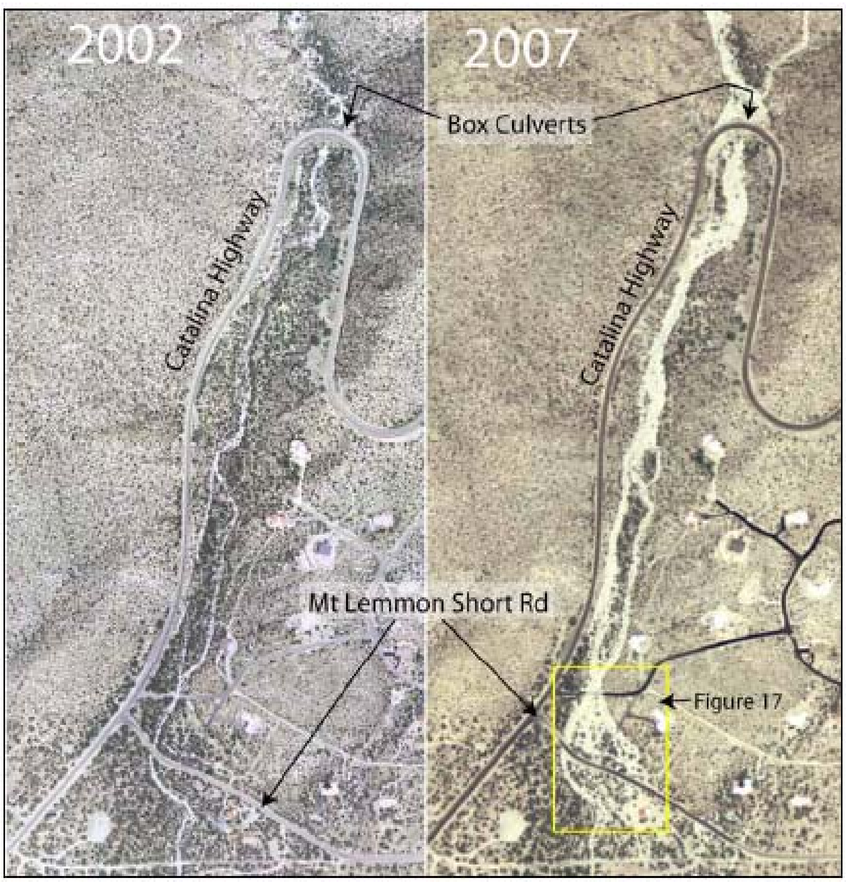
This work is supported by the National Science Foundation's Critical Zone Observatory Program project entitled Transformative Behavior of Water, Energy and Carbon in the Critical Zone: An Observatory to Quantify Linkages among Ecohydrology, Biogeochemistry, and Landscape Evolution", grant EAR-0724958.


# DEBRIS FLOWS OF THE SANTA CATALINA MOUNTAINS, AZ

CZO-All Hands Meeting May 10,2010

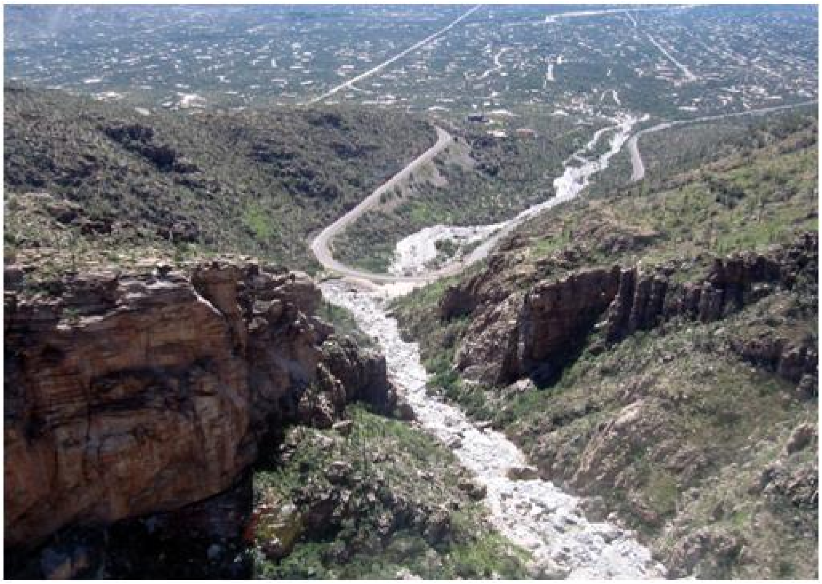
On July 31, 2006 the last pulse of a five-day monsoonal precipitation event caused massive flooding and slope failure on the south-facing canyons of the Santa Catalina Mountains. Debris flows occurred in nine of the south-facing canyons, of which five had debris flows reach the mouth of the canyon or beyond. Prior to this event, debris flows were recognized as a hazard but were only documented in the upper reaches of the canyons. This event sparked a renewed interest in debris flows as a geologic hazard and caused the Arizona Geological Society (AZGS) to complete mapping projects in many of the canyons, resulting in new information on past debris flow deposits.




**Before and after aerial photos of Soldier Canyon (AZGS)**

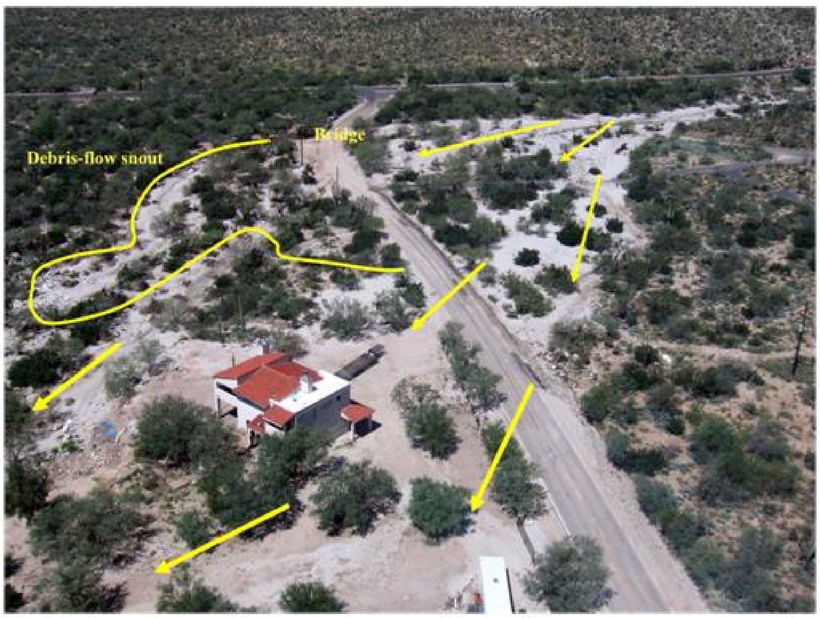
One of the canyons highly affected by the 2006 event was Soldier Canyon. At least two pulses of debris flows cascaded under and over the Catalina Highway. The debris flow deposits recently mapped in Soldier Canyon by the AZGS included units dating back to ~28 ka. The best estimate of a recurrence interval for debris flows in these canyons is on the order of 2,000 years.

**DEBRIS FLOW -** A quick moving mass of >60% sediment/debris and <40% water. Debris flow deposits include massive, poorly sorted terraces and levees. Debris flows can be caused by high precipitation, earthquakes, volcanic eruptions, and fires.



**View downstream of Soldier Canyon after 2006 event**

Debris flows caused by the 2006 event started as multiple slope failures in the upper canyons caused by saturation of thin soil and colluvium by extended rainfall. Saturated soils have high pore pressures and less shear strength, therefore allowing for mobilization of soil. The debris flows that occur off the south slopes of the Santa Catalina Mountains are different from those studied in other locations in that they are very coarse grained and lack the fine-grained material that makes up a fluid matrix found in "common" debris flows. This lack of a fine fraction presents a new challenge in explaining debris flow movement and rheology.




**View upstream on Soldier Creek fan after 2006 event**

Youberg, A., Cline, M.L., Cook, J.P., Pearthree, P.A., and Webb, R.H. 2008, Geologic mapping of debris flow deposits in the Santa Catalina Mountains, Pima County, Arizona: Arizona Geological Survey OFR-08-06.

Webb, R.H., Magirl, C.S., Griffiths, P.G., and Boyer, D.E., 2008, Debris flows and floods in Southeastern Arizona from extreme precipitation in July 2006-Magnitude, frequency, and sediment delivery: United States Geological Survey OFR 2008-1274.

**Santa Catalina Mountains CZO:**

**Mount Bigelow Flux Tower Site**


# Vertical fluxes of carbon and water

**Monitoring ecosystem-scale vertical carbon and water fluxes in the Critical Zone using eddy covariance.** The objectives of the site center on extending our understanding of the sensitivities and feedbacks associated with carbon and water flux in the critical zone to our current and future climate. Western North American Forests represent a potential, yet uncertain, sink for atmospheric carbon. Much of our lack of knowledge is due to lack of $CO_2$ monitoring stations within these sometimes-rugged regions.

The **Ecohydrology and Hydrologic Partitioning (EHP)** theme targets capturing linkages between vegetation, hydrology, and critical zone evolution. Therefore, objectives at these sites center on (*i*) understanding the sensitivities and feedbacks associated with vertical water, carbon and energy fluxes in the critical zone and (*ii*) placing those fluxes within the context of lateral fluxes addressed by the SWD theme and subsurface storage and transformations addressed by the SSB theme.

**Questions currently being addressed by the EHP Team include:**

* *What roles do seasonally variable forms of precipitation (snow vs. rain) playing in differentially driving both the vertical fluxes and also the ecology of this system?*
* *How sensitive are fluxes of Net ecosystem exchange of carbon (NEE) and evapotranspirational water loss in these semiarid montane systems to variations in temperature and drought stress?*
* *How does water enter, function within, and ultimately leave these ecosystems? How do these parameters vary in response to different forms of precipitation and sizes of precipitation pulses?*

**Tower Instrumentation:**

- ❑ LI-COR 7500 $CO_2/H_2O$ analyzer
- ❑ CSAT 3-D Sonic Anemometer
- ❑ CNR1 Kipp&Zonen Net Radiometer
- ❑ Power: 6 D-Cell Batteries
- ❑ NR-Lite Net radiometer below-canopy
- ❑ HMP45C Vaisala Temperature/ RH probe above, within, and below-canopy
- ❑ Vaisala 2-D Cup anemometer within and below the canopy
- ❑ $CO_2$ profile measurements throughout the canopy and sub-canopy

**Below-canopy and Snow sensors:**

- ❑ Dynamax sap flux sensors within multiple species
- ❑ Soil collars for spot measurements of $CO_2$ and $H_2O$ efflux
- ❑ Judd Ultrasonic snow depth sensors under various degrees of canopy cover
- ❑ Phenocams with striped height pole
- ❑ Soil moisture and temperature profiles associated with snow depth sensors
- ❑ Passive precipitation water samplers

**Sub-surface sensors**:

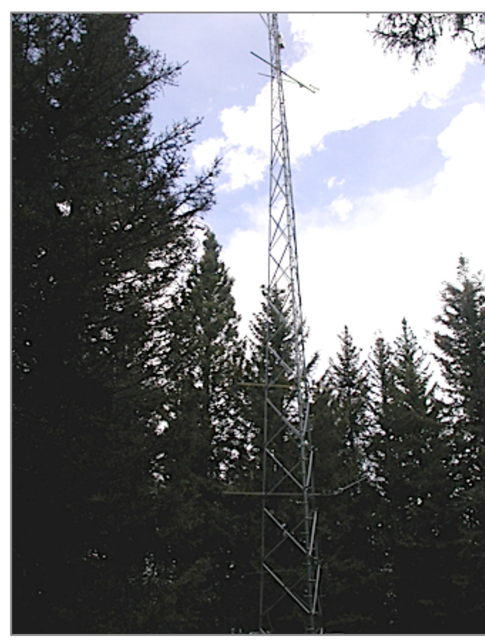
- ❑ HFT3 REBS Soil Heat Flux Plates
- ❑ TCAV Averaging Soil Thermocouples
- ❑ Three profiles of CS616 Soil Water Content Reflectometers at 5 depths

## Santa Catalina Mountains:

Co-located with Mount Bigelow Tower
*tower managed by G. Barron-Gafford*
Elevation ~ 2,500 m
Mixed Conifer Woodland

## Jemez River Basin:

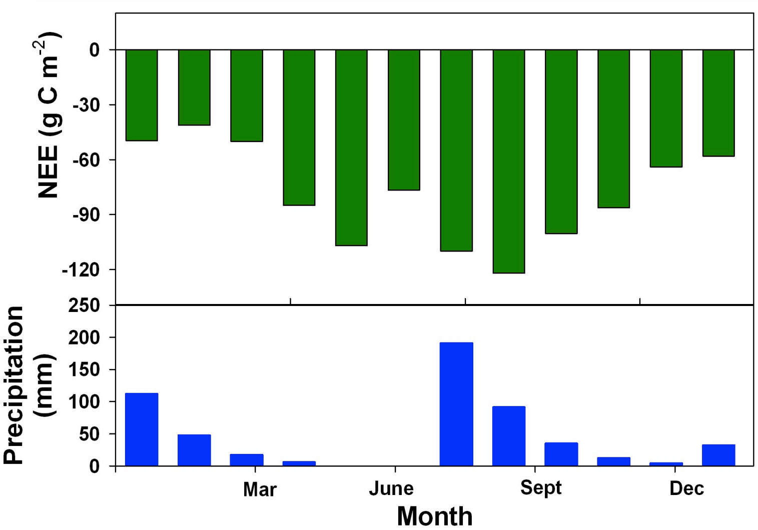
Co-located with Mixed Conifer Tower
*tower managed by M. Litvak*
Elevation ~ 3,000 m
Mixed Conifer Woodland

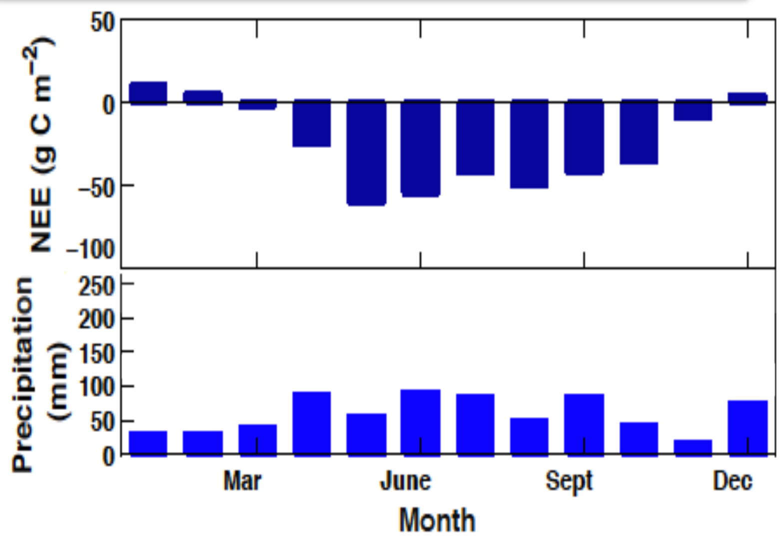


**Climate**. The climate of these sites can be characterized as semi-arid and montane. Air temperature rarely exceeds 30$^{o}$C in the summer at either site. However, winter lows rarely fall below -5$^{o}$C at the SCM tower, but often reach -10$^{o}$C at the JRB site. The region can be extremely dry, with daytime relative humidity below 30% for most of the year, except during the summer North American Monsoon, which delivers significant rainfall to the region.

- Of the approximately 650-700mm of precipitation that reaches the sites annually, ~65% of the annual precipitation falls primarily as snow between October and April, and ~30% falls as rain during the monsoon months between July-September at the JRB site. However, precipitation falls much more bi-modally at the SCM site, with a distinctive monsoon season.
- The JRB site tends to be cooler than the SCM site, though in the two years in which snow depth has been monitored concurrently, the sites have received comparable amounts of total winter snow and summer rain.

**Vegetation and soils**. Though the proportion of individual species differs somewhat, both sites represents a secondary-growth, subalpine, mixed conifer forest composed of Douglas Fir (SCM & JRB), Southwestern white pine (SCM & JRB), White fir (SCM & JRB), Ponderosa pine (SCM), Blue spruce (JRB), and occasional Aspens (JRB). The soils at the SCM site have a moderately coarse texture and become gravelly and cobbly with many stones around 0.75m. Soils that the JRB site are characterized as a loamy sand extend to a greater depth before reaching bedrock.




**Results ~ Ecosystem-scale $CO_2$ fluxes at the SCM site**.

- Preliminary estimates of Net ecosystem exchange of $CO_2$ (NEE) illustrate that the forest is a strong sink for $CO_2$ from the atmosphere (negative NEE) throughout the dry, post-snow-melt period, but $CO_2$ uptake is twice as great during the warm and wet monsoon.
- Measures of NEE estimate net ecosystem-scale carbon flux, but do not yield estimates of fluxes among the vegetation and soils. As such, we have begun bi-weekly measures of these component fluxes within the critical zone.
- NEE may be overestimated due to $CO_2$ efflux that leaves the system through cold air advective flow down-slope.

**Results ~ Ecosystem-scale $CO_2$ fluxes at the JRB site.**

- NEE within the site is positive (indicating a loss of $CO_2$ to the atmosphere) throughout the winter months, but the ecosystem is a strong sink for carbon throughout the temperature-mediated growing season.
- Having been being fully-operational for more than four years, the influence of interannual variability in snow and/or summer precipitation and atmospheric temperature on carbon and water fluxes within the critical zone can now be more robustly quantified.

**Contact us**. To discuss collaborations or learn more about eddy covariance measurements within our CZO, please contact:

Greg Barron-Gafford (SCM site)
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Marcy Litvak (JRB site)
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University of New Mexico
Albuquerque, NM 87131
505.277.5580, mlitvak@unm.edu

*Note: Both of these CZO towers also operate within a network of other regional towers tracking fluxes in semiarid ecosystems*


**Monitoring the Critical Zone using Time-Lapse Digital Photography**. Within the critical zone, important interconnected physical, chemical, and biological processes influence the mass and energy exchange that governs everything from biomass production to water storage. However, many of these processes operate on different temporal and spatial scales, and little is known about how these processes interact. We have begun to quantitatively link these processes by analyzing time-lapse digital images. These images also have the potential to link processes across different disciplines, such as snow hydrology and ecology.

**Approach.** At the Mount Bigelow eddy covariance tower in the Santa Catalina Mountains, and at the Mixed Conifer eddy covariance tower in the Jemez River Basin, we mounted a single overstory "tower-cam" just above the Li-Cor 7500 $CO_2$/$H_2O$ IRGA and three understory "pheno-cams" at heights of 1 m within the footprint of the towers. All four cameras record images hourly.

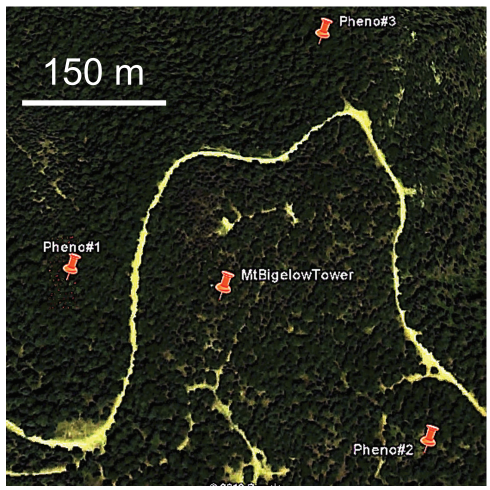
**Understory Cameras:**
- ❑ Moultrie M60 Game Cameras
- ❑ Focal length: 20 to 45 ft
- ❑ Resolution: 6 MP
- ❑ Power: 6 D-Cell Batteries
- ❑ Orientation: North
- ❑ Positioned 1 m above the ground
- ❑ Mounted to trees with bolts
- ❑ Images downloaded ~monthly

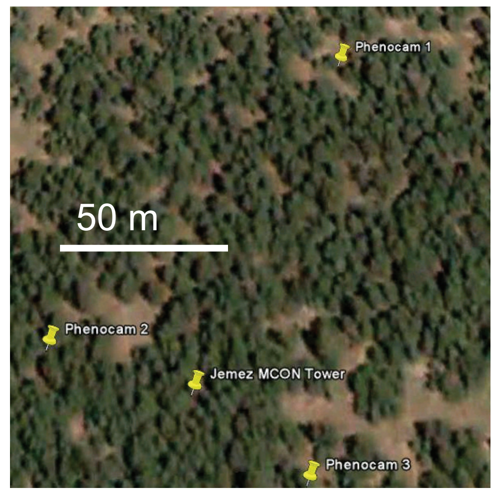
**Snow/Vegetation Stakes:**
- ❑ Added in hindsight
- ❑ Placed in frame of under story cams
- ❑ Positioned straight up using levels
- ❑ Red and white stripes alternate 5cm

**Overstory Cameras**:
- ❑ StarDot NetCam XL
  → *modified to save images to data card*
- ❑ Focal length: 0.2m to ∞
- ❑ Resolution: 3 MP
- ❑ Power: Solar Panel/Marine Battery
- ❑ Orientation: into main wind
- ❑ Mounted just above LiCor-7500
- ❑ Images downloaded ~ monthly

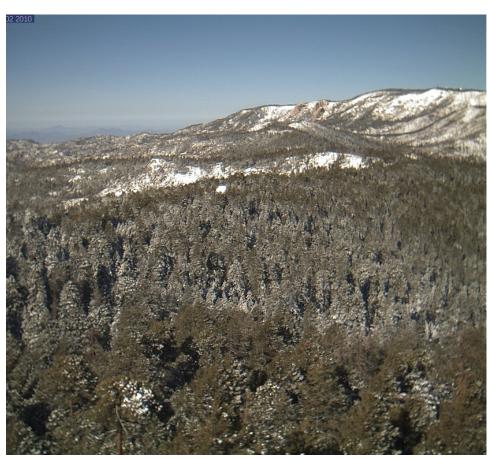
## Santa Catalina Mountains:
Co-located with Mount Bigelow Tower
*tower managed by G. Barron-Gafford*
Elevation ~ 2,500 m
Mixed Conifer Woodland

## Jemez River Basin:
Co-located with Mixed Conifer Tower
*tower managed by M. Litvak*
Elevation ~ 3,000 m
Mixed Conifer Woodland

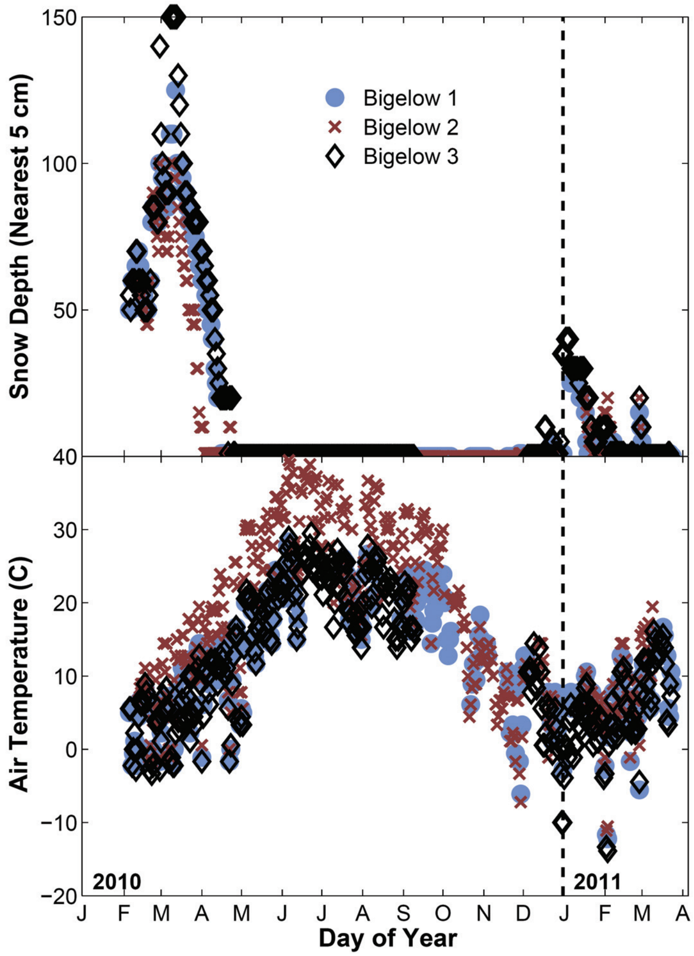


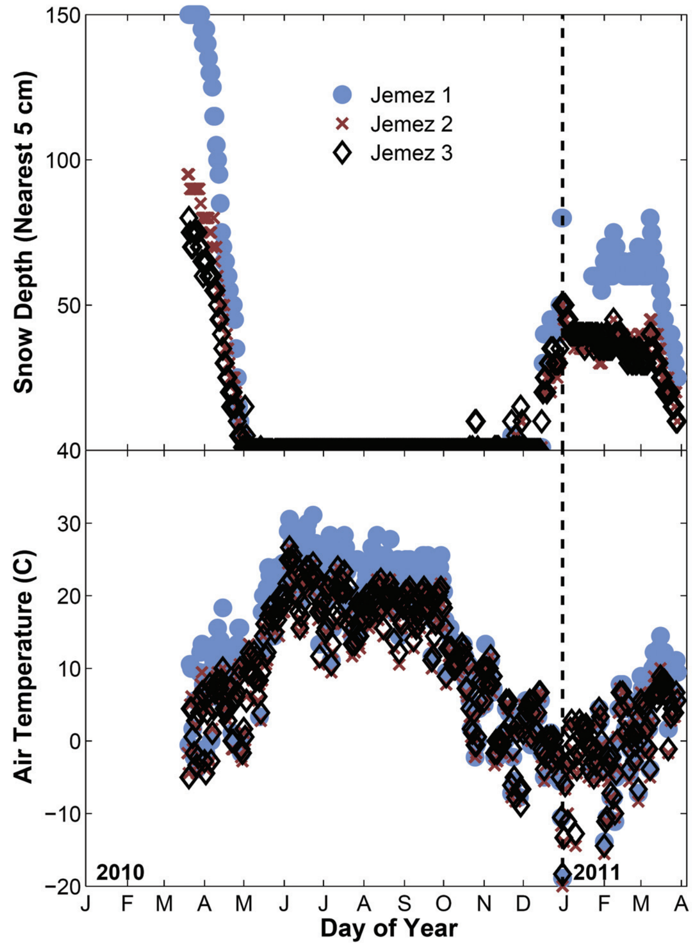





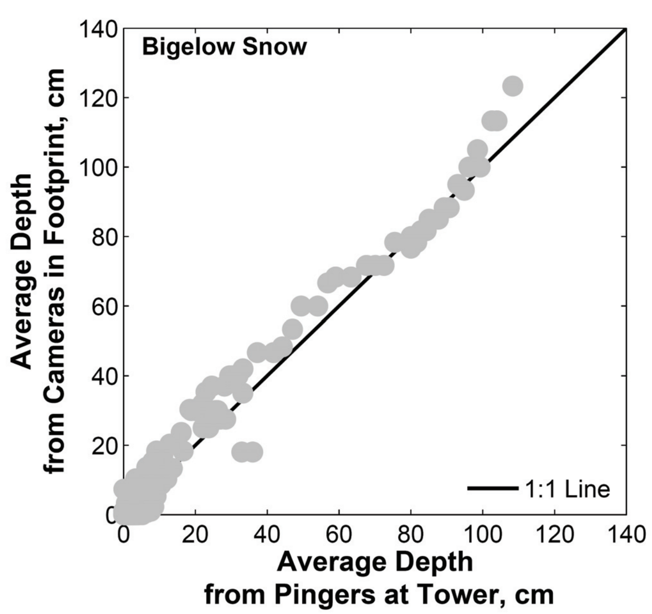



**Understory Digital Image Derived Snow Cover**. The interannual variability of snow cover is captured with the understory digital images at both the Santa Catalina Mountains Bigelow tower and the Jemez Mixed Conifer tower sites. Also, site to site differences can be evaluated. At Bigelow, the warmest camera has the least amount of snow, while at Jemez the warmest camera has the most amount of snow. Going back to the actual images helps us to understand what is driving these snow conditions.




**An Inexpensive Alternative for Snow Depth.** The cost of an installed understory game camera is about $300, including batteries, memory card, and mounting supplies; the cost of a traditional snow sensor is about $700 which does not include the price of the datalogger, deep cycle marine battery and solar panel. Given the close agreement between the depth obtained by both methods, the understory camera appears to be a viable and inexpensive alternative.




**Using the Images to Quantify Greenness and Albedo.** Understory images are being analyzed for greenness to evaluate the contribution of the understory to $CO_2$ uptake. Overstory images are being analyzed for whiteness to evaluate the contribution of snow to the albedo of the area.




**Contact**. For collaboration or to learn more about these time-lapse digital cameras, please contact:
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University of Arizona
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Archived images and movies may be obtained from the JRB-SCM CZO website: www.czo.arizona.edu


**Toward an Improved Understanding of the Role of Transpiration in Critical Zone Dynamics**. An improved understanding of how tree transpiration varies across the critical zone (CZ) will help to elucidate how the vertical water flux modulates the soil moisture balance which in turn influences the subsurface biogeochemical and landscape evolution process across the CZ. Within subalpine mixed conifer ecosystems in the Jemez River Basin (JRB) and Santa Catalina Mountains (SCM) multiple sets of sap flux sensors are proposed or have been established. We will be synthesizing these data to address critical zone questions.

**Installation.** *photos by M. Cavanaugh*

Bark is cleared from installation site. Two 30-mm holes are drilled vertically about 40 mm apart and probes are inserted.

Foam quarter-eggs are taped on either side of the probe needles to protect the sensor wiring and to add thermal insulation.

Reflective bubble wrap is wrapped around the tree/sensor, to prevent the sun from causing large local gradients on the stem.

## Santa Catalina Mountains:


**Mount Bigelow Tower**
- ❑ Installed in June 2010
- ❑ 8 Trees, North and South Sides

→ *3 Mexican White Pine (PIAY)*
→ *3 Arizona Pine (PIAR5)*
→ *1 Douglas Fir (PSME)*
→ *1 Dead Tree*


**Marshall Gulch Schist Drainage**
- ❑ Installed in April 2011
- ❑ 9 Trees, North Sides

→ *4 White Fir (ABCO)*
→ *4 Bigtooth Maple (ACGR)*
→ *1 Dead Tree*

## Jemez River Basin:


**Jemez Mixed Conifer Tower**
- ❑ Installed in 2005
- ❑ 8 Trees, North and South Sides

→ *8 Engelmann Spruce (PIEN)*

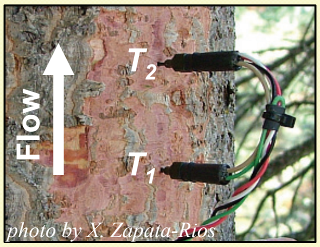

**Mixed Conifer Zero Order Basin**
- ❑ Installed in February 2011
- ❑ 8 Trees, North Sides

→ *4 White Fir (ABCO)*
→ *4 Engelmann Spruce (PIEN)*

**Granier-Style Thermal Dissipation Probe (TDP) Sap Flow Sensors:**
The empirical Granier TDP method is based on liquid velocity heat dissipation theory. Two needles are inserted radially into the sapwood, one needle placed above the other. The upper needle contains a line heat source and a thermocouple junction which is referenced to another junction in the lower needle. The difference in temperature ($d$T) between the two needles is dependent on sap velocity: heat is dissipated more quickly when sap velocity increases and so d$T$ decreases as a result of the cooling of the heat source.

*This synthesis project is being led by JRB-SCM CZO post-doc Bhaskar Mitra.*

**Calculating Sap Flux Density.**




Probe needles measure the d$T$ between the heated needle $T_2$ and the sapwood ambient temperature $T_1$ below. Sap flux density ($F_s$) is calculated with the following empirical equation:

$$F_s = 0.0119K^{1.231} \times 3600 \quad [\mathrm{cm^3\ cm^{-2}\ hr^{-1}}]$$

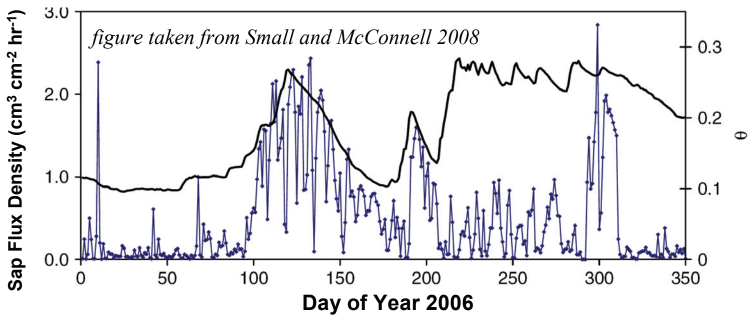
$$K = (\mathrm{d}TM - \mathrm{d}T)/\mathrm{d}T$$

$$\mathrm{d}TM = \mathrm{d}T \text{ when no sap is flowing } (\sim 11\text{pm to 3am})$$

**Sap Flow in Mixed Conifer Ecosystems.** Start dates of sap flow records range from 2005 to 2011. Species are also variable. We plan to investigate at the environmental controls (soil moisture, aspect) on species and stand level transpiration at each of these sites.

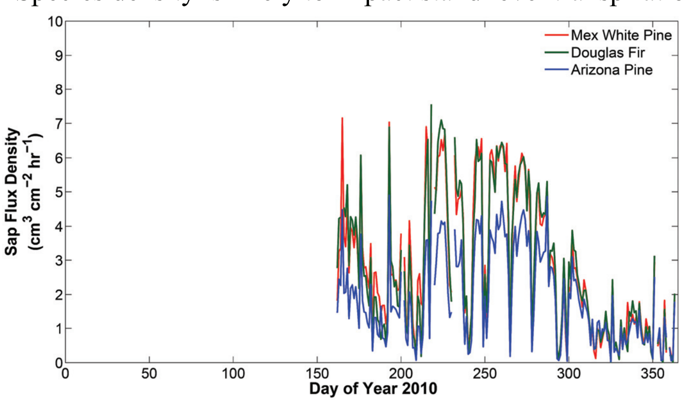
***Jemez Mixed Conifer Tower (Spruce):***

• Soil moisture is a strong control on spruce transpiration.



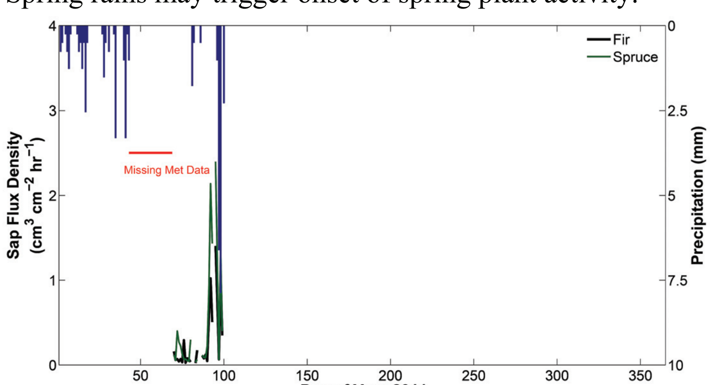

***Mount Bigelow Mixed Conifer (Pine and Fir):***

• Species density is likely to impact stand level transpiration.




***Jemez Mixed Conifer Zero Order Basin (Spruce & Fir):***

• Spring rains may trigger onset of spring plant activity.




**Calculating Stand-Level Transpiration ($T_{stand}$).**

Typically the a version of the following equation is used:

$$J_{\text{tree}} = F_{s\text{-tree}} \times A_{s-\text{tree}} \quad [\mathrm{cm^3\ hr^{-1}}]$$

$$J_{\text{species}} = \left(\sum_{i=1}^{m} J_{\text{tree}_i}\right)/\,\mathrm{m} \quad [\mathrm{cm^3\ hr^{-1}}]$$

$$T_{\text{stand}} = \left(\sum_{i=1}^{n} J_{\text{species}_i}\right)/\,A_G \quad [\mathrm{cm^3\ hr^{-1}\ m^{-2}}]$$

$F_{s\text{-tree}}$ = sap flux density of tree

$A_{s\text{-tree}}$ = sapwood area of tree

m = number of trees of each species

n = number of species

$A_G$ = ground area

Because not all trees in the stand are measured, often allometric relationships for sapwood areas are used, e.g.:

$$A_{s-species} = a \times DBH^b$$

$a$ and $b$ = empirical coefficients

$DBH$ = diameter at breast height

To determine $T_{stand}$ at each of the sites, we plan to combine field campaigns and LiDAR to determine our allometric relationships for upscaling.

**Sap flow papers resulting from these sites:**


❑ Small, E.E., McConnell, J.R., 2008. Comparison of soil moisture and meteorological controls on pine and spruce transpiration. *Ecohydrology* 1:205-214.


**Contact**. For collaboration or to learn more about sap flow sensors in the JRB or SCM, please contact:


❑ ***Mixed Conifer Zero Order Basin***
❑ ***Marshall Gulch Drainages***
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❑ ***Jemez Mixed Conifer Tower***
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Hydrologic Sciences
Desert Research Institute
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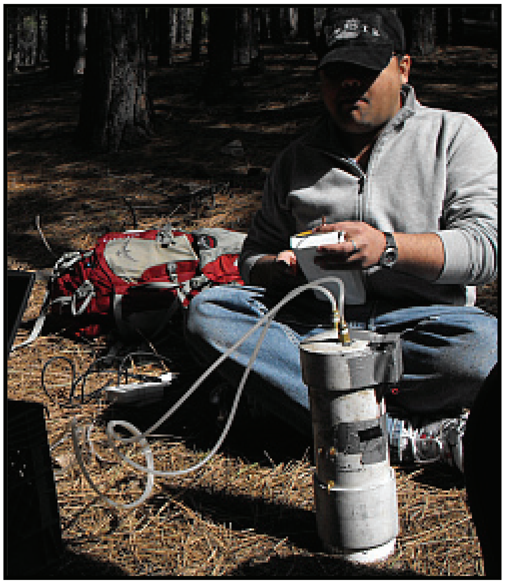
**Influence of Snow Cover Duration on Soil Respiration and Evaporation Efflux in Mixed-Conifer Ecosystems**. Subalpine mixed conifer ecosystems are sensitive to a warming climate and are dependent on snow fall, which is expected to decrease in coming years. We are measuring soil respiration and evaporation within these ecosystems to evaluate how changing snow accumulation and duration of snow cover might affect $CO_2$ and $H_2O$ fluxes out of the soil.



**Approach.** At the mixed conifer ecosystems within both the Santa Catalina Mountains and the Jemez River Basin, we have three understory cameras located within the footprint of an eddy covariance tower. Using the images, we placed 6 soil collars; 3 in short snow duration and 3 in long snow duration. Since July 2010, soil respiration and evaporation data have been collected regularly (~ biweekly) from collars in the Santa Catalina Mountains, and will be collected starting in Summer 2011 in the Jemez River Basin.

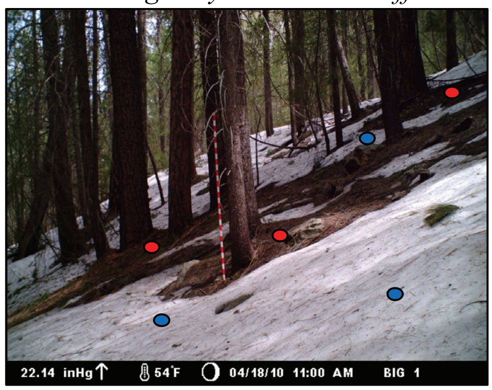
**Instruments:**
- ❑ Licor 840 CO2/H2O Gas Analyzer
- ❑ Delta-T WET Sensor, WET-2
- ❑ Oakton Temp 100 Dual-Input

**Bi-Weekly Measurements:**
- ❑ Soil Respiration
- ❑ Soil Evaporation
- ❑ Soil Temperature top 10 cm
- ❑ Soil Moisture top 10 cm
- ❑ Chamber Air Temperature
- ❑ Depth from top of collar to soil

**Average Snow Duration at Collars:**
- ❑ Long Snow Duration: 56 Days
- ❑ Short Snow Duration: 44 Days

## Santa Catalina Mountains:

Co-located with Mount Bigelow Tower
*tower managed by G. Barron-Gafford*






## Jemez River Basin:

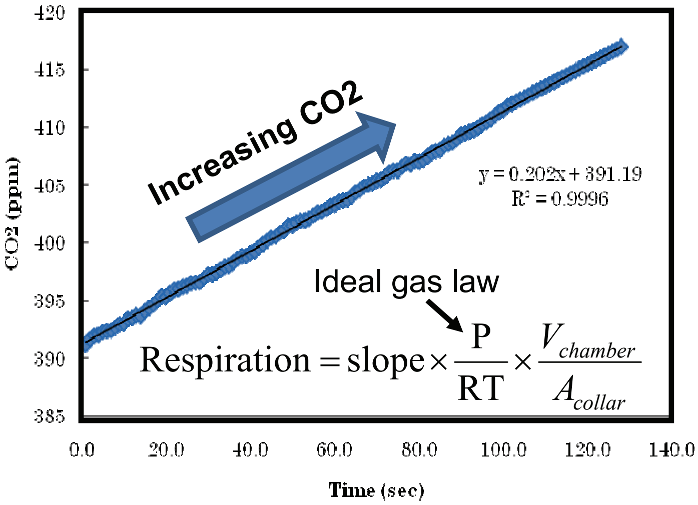
Co-located with Mixed Conifer Tower
*tower managed by M. Litvak*



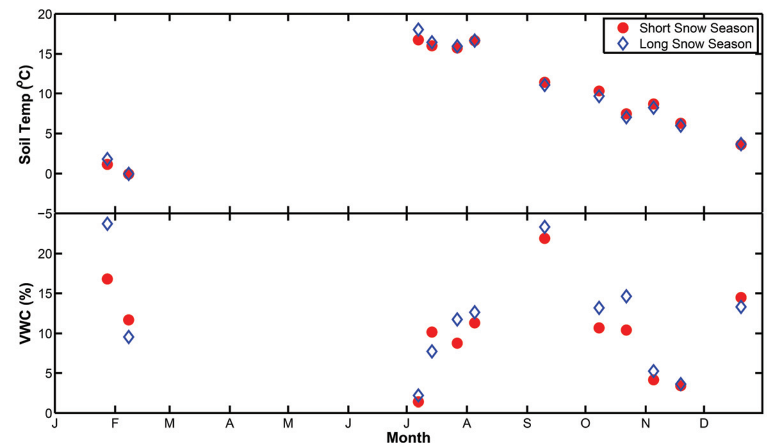

**Using Digital Images to Determine Soil Collar Sites with Long Snow Duration and Short Snow Duration.** We used Images from the understory cameras when snow patchiness could be identified to determine areas in the frame of the image which had long and short snow cover durations. Soil collars were then installed in these locations as "long snow duration" (blue dots in the images above) and "short snow duration" (red dots in the images above) sites. Image time series enable us to confirm that these collars are located appropriately, and that the duration of snow cover at the sites is as expected.

*This project is part of JRB-SCM CZO student Krystine Nelson's Masters work.*

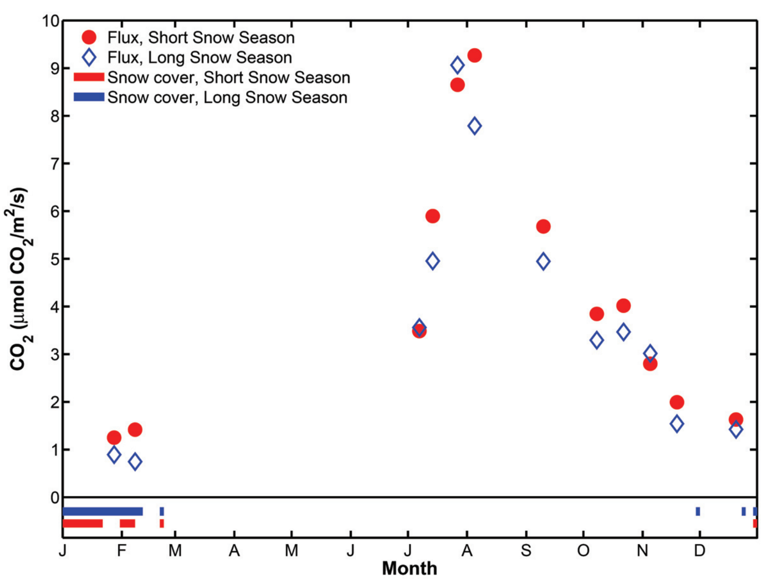
**Calculating Soil Respiration and Evaporation.** The Gas Analyzer measures the concentration of $CO_2$ and $H_2O$ in the chamber over a 2-minute period. This change in concentration over time is used to calculate the fluxes.

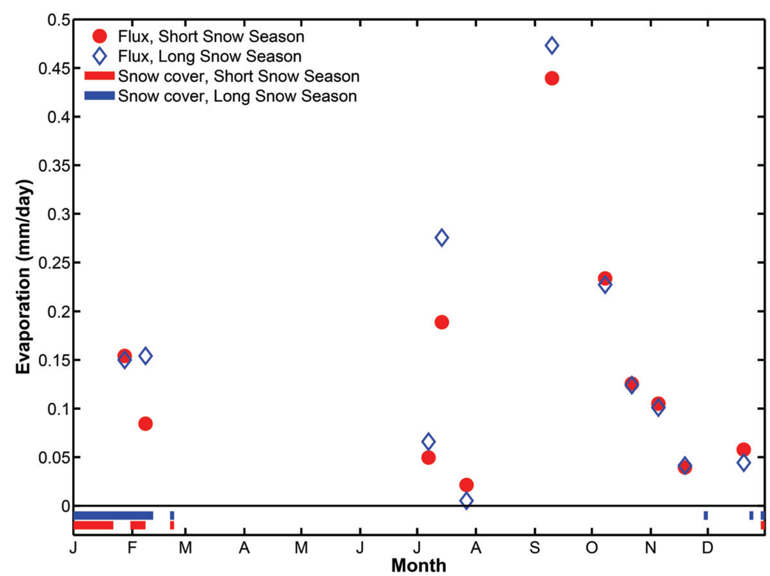



**Soil Temperature and Soil Moisture.** Soil temperatures are very similar between long and short snow duration sites; long snow duration is slightly warmer until late in the summer (September) when long snow duration sites become slightly cooler. Soil moisture is quite variable except in the summer and fall when long snow duration sites are consistently wetter than short snow duration sites.




**Soil Respiration and Evaporation**. Soil respiration peaks in mid-July to mid-August, whereas the peak in soil evaporation occurs later in the summer, in late September. Soil respiration is generally higher at the soil collar sites with short snow duration; additionally respiration fluxes drop more slowly after the peak in these short snow duration sites. Long snow duration sites have higher evaporation fluxes than short snow duration sites during the summer months, otherwise the sites experience similar fluxes.




**Influence of Soil Moisture and Temperature on Soil Respiration and Evaporation.** Surprisingly, soil moisture has no strong relationship with soil respiration when all measurements throughout the year are considered. However, soil temperature appears to be a strong control on soil respiration throughout the year. The opposite is true for evaporation. Soil moisture is strong control on evaporation, while temperature is a very weak control.

| | Soil Moisture | | Soil Temperature | |
|---|---|---|---|---|
| | Long $R^2$ | Short $R^2$ | Long $R^2$ | Short $R^2$ |
| **Respiration** | 0.03 | 0.01 | **0.34** | **0.37** |
| **Evaporation** | **0.26** | **0.38** | 0.01 | 0.01 |

**Contact**. For collaboration or to learn more about soil respiration and evaporation measurements at these JRB and SCM sites, contact:


Shirley (Kurc) Papuga
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or
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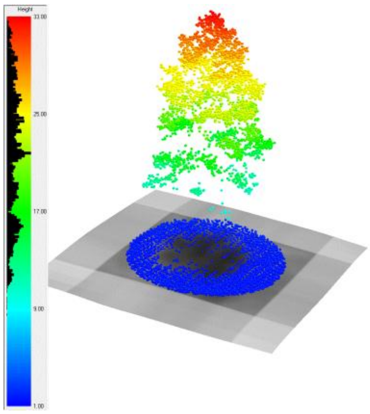
# Precision forestry from LiDAR

**LiDAR Coverage of the Critical Zone in the Jemez and Santa Catalina**. Aerial LiDAR coverage exists for sections of the Santa Catalina mountains and for all of the Valles Caldera National Preserve. Aerial LiDAR has excellent vertical and horizontal accuracy. Densely collected LiDAR data can be used to measure individual tree heights and canopy metrics across landscape scales.



**Approach.** Tree-level field plots have been collected across an environmental gradient. Quantitative observations create an inventory by forest type, observations include: species, health condition, total height, diameter at breast height, and canopy base height. A total of 48 forest plots were collected in the VCNP, and to-date 24 plots have been collected in the Santa Catalina.

**LiDAR Data Potential:**

- ❑ Individual to Landscape Scale inventory
- ❑ Accurate to within $\pm$10 cm
- ❑ Resolution as fine as 25 $cm^3$
- ❑ Individual Tree metrics
- ❑ Landscape scale metrics

**Individual tree metrics:**

- ❑ Tree height, e.g. tree mass
- ❑ Condition (Dead or Alive)
- ❑ Canopy Cover
- ❑ Canopy Bulk Density
- ❑ Canopy Base Height

**Landscape scale metrics:**

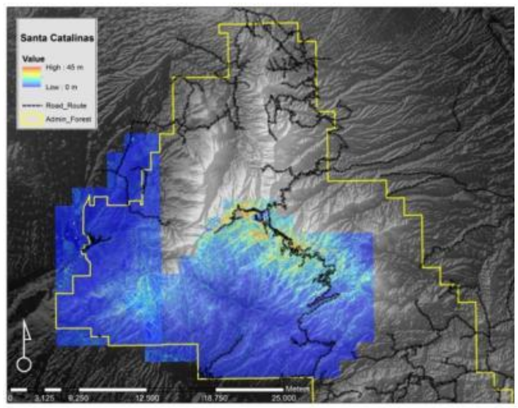
- ❑ Snow Depth
- ❑ Sub-meter Digital Elevation Model
- ❑ Leaf Area Index
- ❑ Biomass

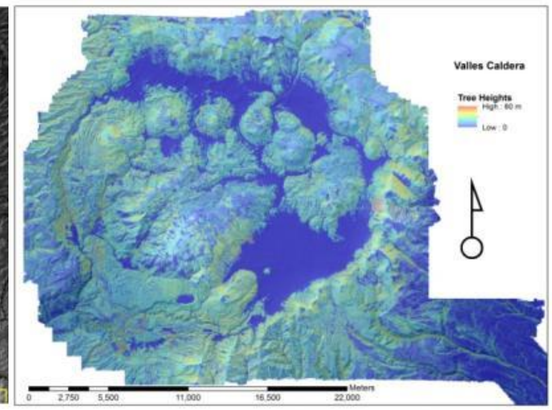
## Santa Catalina Mountains:

LiDAR coverage area: ~90,000 Ha
Point Density: ~ 3.44 points/m^2
RMSE: 37.0 cm vertical, 1.0 m horizontal

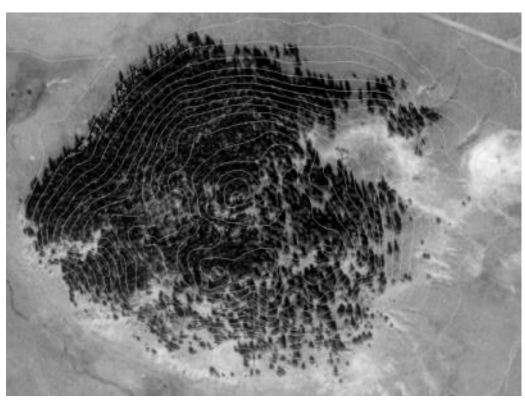
## Jemez River Basin:

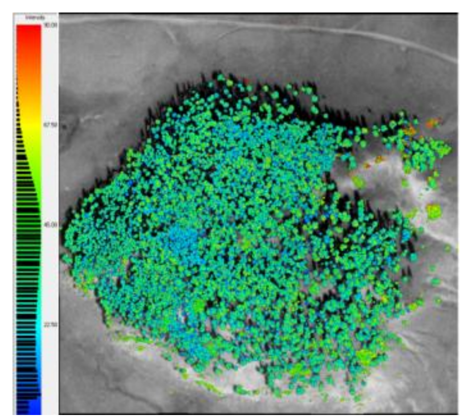
LiDAR coverage area: ~186,000 Ha
Point Density: ~ 8.86 points/m^2
RMSE: 10.0 cm vertical, 1.0 m horizontal

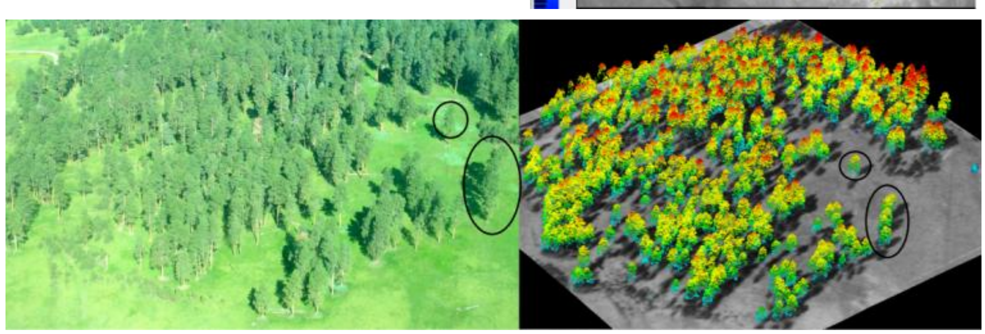


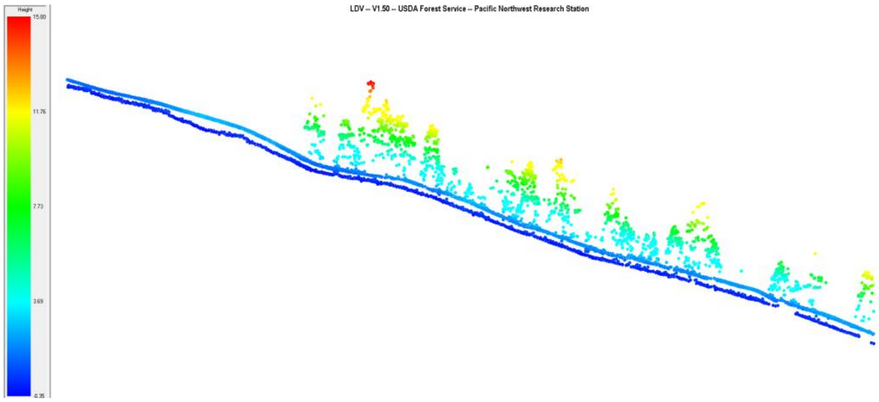

**LiDAR Canopy Heights:** Below are examples of aerial photography and LiDAR tree height surfaces in the Valles Caldera over the La Jara Dome. On bottom is an an oblique image of the History Grove (left) and the LiDAR point cloud (right) with an aerial image draped on the surface.

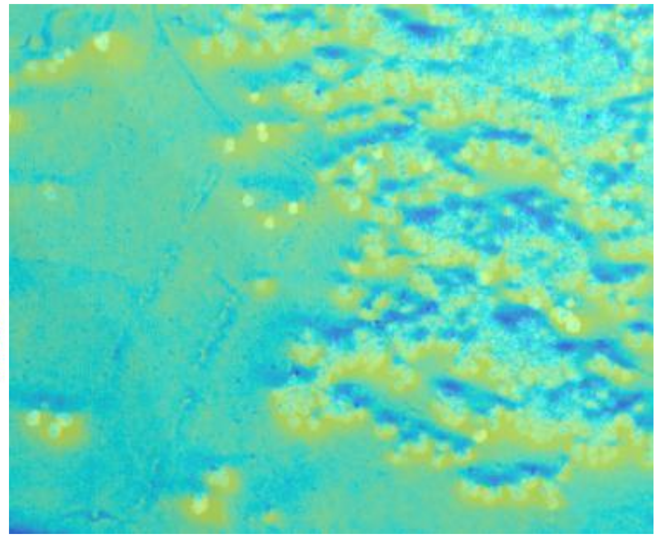


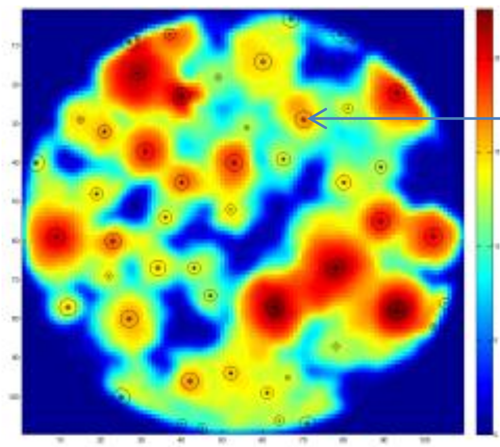


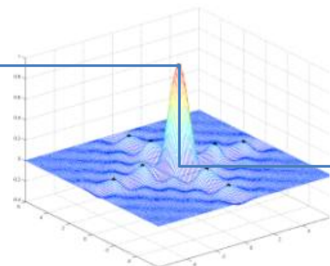


**LiDAR derived Snow depth**. Spatial snow depth surfaces are made by subtracting the VCNP's January 2010 LiDAR flight from the July 2010 flight. Minimum height returns were generated for 'ground' level estimation. A virtual transect (below left) along the north slope of Redondo Peak shows snow depth. Snow depth (right) is calculated as the difference between bare earth surfaces (blue = >100 cm, yellow = <50 cm, red = 0 cm, white = canopy of standing pine trees). Notice the aspect influenced shade-effects of the trees.



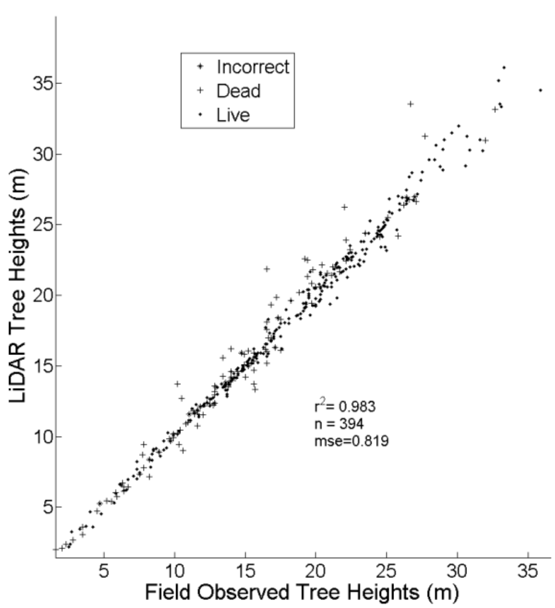





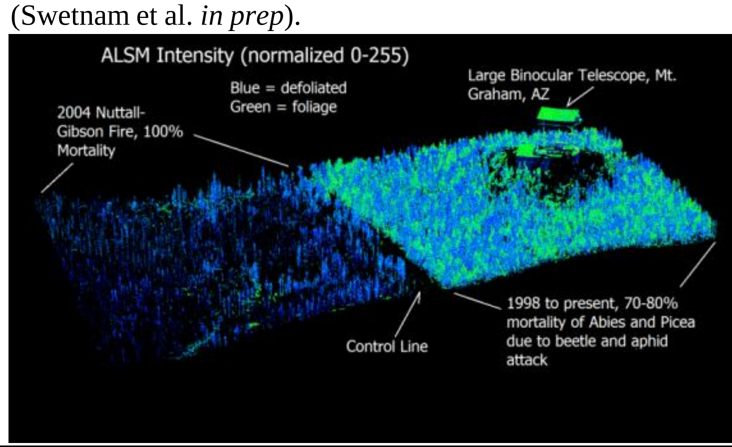


**Individual Tree Identification.** Segmentation of individual trees from either the LiDAR point cloud, or 2D surface models can be done in any order, with a variety of unsupervised techniques. A 'Local Maxima' spatial filter identifies individual stems for correlation to our field based stem-map observations.

**Landscape Scale forest inventory.** Below is a figure from a LiDAR flight in a nearby southern Arizona mountain range (Swetnam et al. *in prep*) showing field-to-LiDAR estimates of tree height; living condition has also been field validated (~95% condition accuracy, 98% height accuracy).




**Determining Mortality from LiDAR Intensity.** LiDAR laser pulses are diffusely or spectrally reflected off of surfaces and returned to the sensor. While intensity is not normalized, it still represents potential inference for determining if a conifer tree or stand is alive or dead (Swetnam et al. *in prep*).

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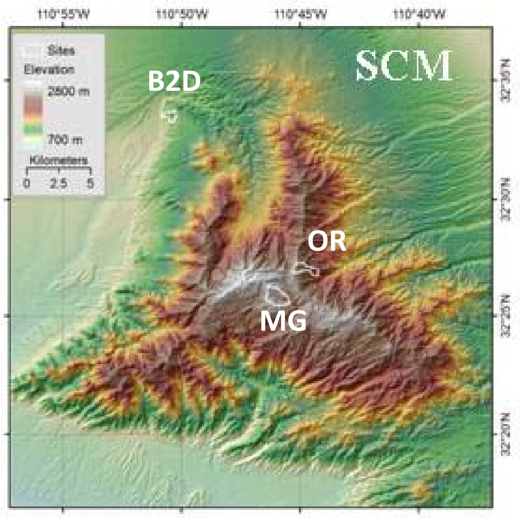
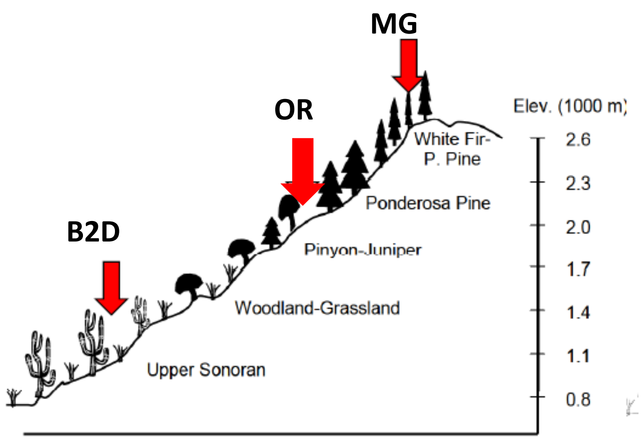
## Santa Catalina Mountains CZO:

## Marshall Gulch Zero-Order Catchment Site

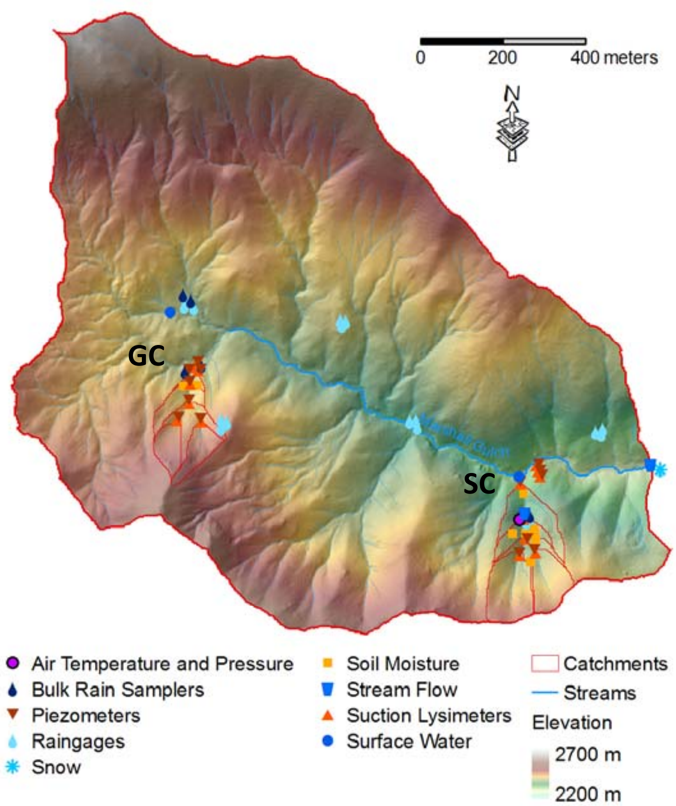

**Santa Catalina Mountains (SCM)** digital elevation map and experimental sites (B2D = Biosphere 2 desert, OR = Oracle Ridge, MG = Marshall Gulch)




**SCM elevation and climate gradients.** The SCM component of the JRB-SCM CZO spans an elevation gradient of 1800 m and five ecosystems: Upper Sonoran Desert, Desert Woodland-Grassland, Pinyon-Juniper, Ponderosa Pine, and Mixed Conifer. Average annual temperatures range from 18$^{o}$C at low to 11$^{o}$C at high elevations while mean annual precipitation ranges from 400 mm to 800 mm across the elevation gradient.

**Geology and soils**. SCM bedrock is dominated by pre-Cambrian and Tertiary aged granites and granodiorite, and Paleozoic aged metamorphic rocks of schist and quartzite. Soils are shallow at low elevation (< 25 to 50 cm) where weathering depth is limited by hot, dry conditions and deeper (ca. 50-100 cm) at high elevation where cool, wet conditions prevail. Schist soils are more deeply weathered, finer in texture, and contain more organic matter than granite soils.

**Marshall Gulch site**. The Marshall Gulch experimental site is the highest elevation and oldest established site in the SCM CZO. The catchment comprises 1.54 km$^2$ and houses two V-shaped ZOBs (schist (SC) and granite (GC)). Both ZOBs are north oriented with relatively steep slopes which have north, northeast and northwest facing aspects. Elevation ranges from 2311 m to 2476 m for SC basin (area is 0.03 km$^2$) and from 2379 m to 2516 m for GC basin (area is 0.05 km$^2$).




**Marshall Gulch instrumentation**. Field equipment in MG has been deployed since June 2007 to measure water, carbon and energy stores and fluxes across the critical zone. Instrumentation throughout the catchment includes clusters of tipping bucket rain gauges, rain water samplers, soil moisture and soil temperature probes, sapflow sensors and a newly installed flume at the schist hillslope. Within the two ZOBs are paired shallow groundwater piezometers and soil water porous cup lysimeters. Streamflows are monitored at the catchment outlet and along with automated outlet sample collection, surface water samples at the outlets of each ZOB are collected weekly for chemical analysis.


**Science Questions** currently being addressed.

- How do geochemical solutes behave as a function of Marshall Gulch stream flow?
- Can stream water saturation indices constrain weathering processes occurring in the catchment?
- Do soil pore water geochemical solute concentrations vary as a function of lithology? Landscape position?

## Stream water geochemical solute behaviors

Weekly collected samples of geochemical solute concentrations exhibit two behaviors as a function of stream flow:

- ***Inversely proportional*** to stream flows (Figure 1)

solutes include major non-hydrolyzing cations, dissolved inorganic carbon (DIC), and silicic acid and are apparently sourced from long transit time base flow stores

- ***Proportional*** to stream flows (Figure 2)

Solutes include dissolved organic carbon (DOC), polyvalent hydrolyzing metals, and trivalent rare earth elements (REEs) and are apparently sourced from short transit time shallow soil stores

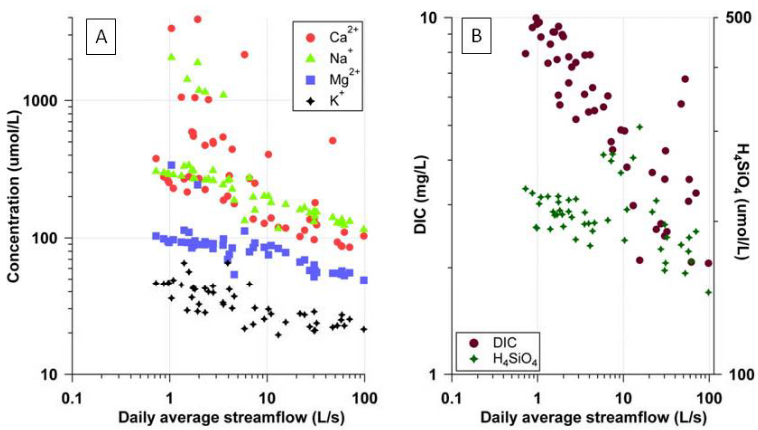



**Figure 2:** Geochemical tracers of base flow A) major non-hydrolyzing cations B) silicic acid ($H_4SiO_4$) and DIC

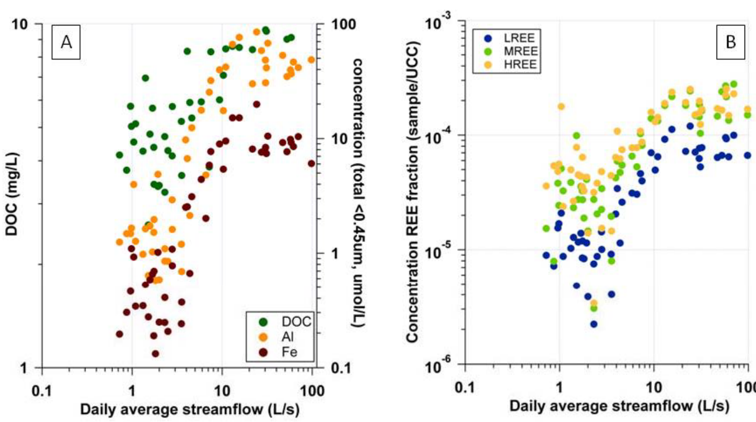



**Figure 3:** Geochemical tracers of shallow soil waters A) DOC and polyvalent metals B) Upper continental crust normalized rare earth element fractions

## Constraining chemical weathering processes

Solid phase X-ray diffraction analysis of mineral assemblages in Marshall Gulch suggest incongruent weathering of albite, anorthite, and K-feldspars to kaolinite. Stream water saturation states with respect to identified primary and secondary minerals calculated via a PHREEQC v2.17 geochemical model support solid phase hypothesis of transformation from albite, anorthite, and K-feldspar to kaolinite (Figure 4).

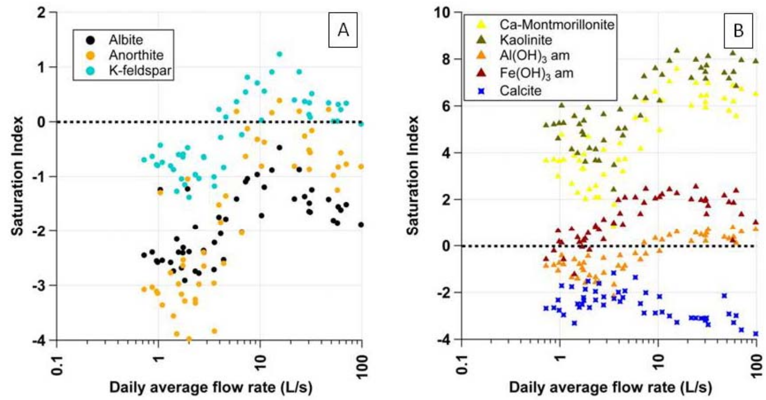



**Figure 4:** Saturation states for A) primary and B) secondary minerals

## Soil pore water geochemical solute behaviors

Lithologic and landscape positional controls are solute specific. The convergent zones of both schist and granite hillslopes appear to be contributing $Na^+$ and $Ca^{2+}$ stream waters during higher flow periods while divergent zones are associated with low flow periods (Figure 5).

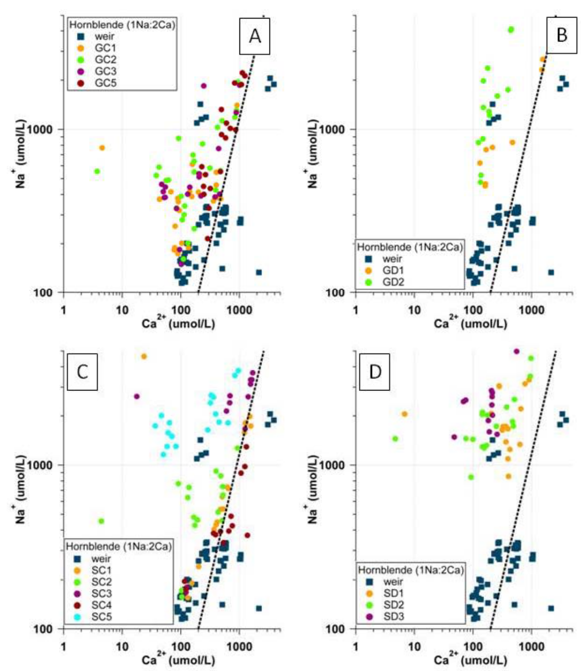



**Figure 5:** Soil pore water $Na^+$:$Ca^{2+}$ ratios. Black dotted line represents ratio for congruent dissolution of hornblende. All panels show stream water ratios (weir) A) granite convergent B) granite divergent C) schist convergent D) schist divergent

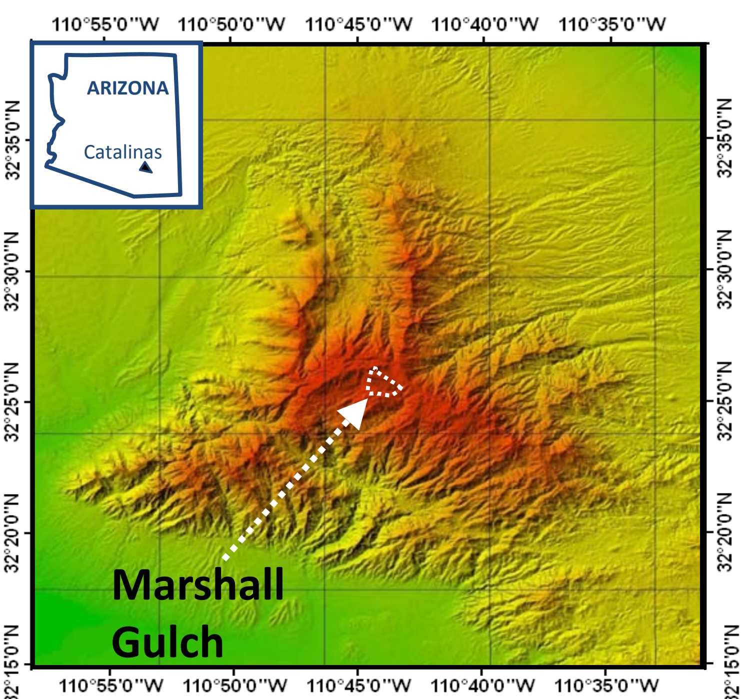

# ISOTOPE HYDROLOGY

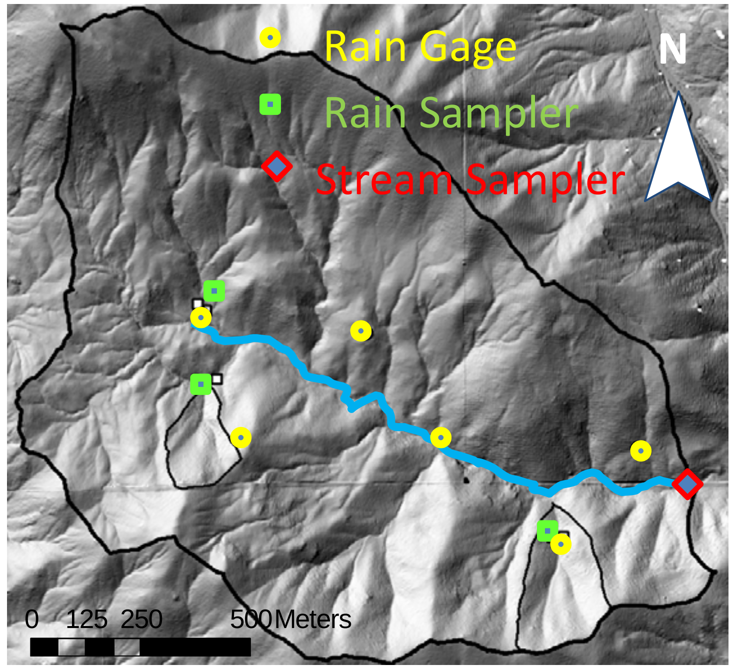
**Background**. The Marshall Gulch catchment is part of the Santa Catalina Mountains Critical Zone Observatory since 2009. Already before that, it was an active research site for isotope hydrology and data collection started in 2006. The current focus of research in Marshall Gulch is on the variability of water, carbon and weathering fluxes: how are they influenced by climate, topography and lithology and which part do they play in the development of the critical zone structure and function. Marshall Gulch is located close to the highest peak of the Santa Catalina Mountains, north-east of metropolitan Tucson, in the Coronado National Forest of southern Arizona.

**Science questions** currently being addressed by the isotope hydrology team are:

- What is the mean transit time of water in the catchment and how does this mean transit time vary over time?
- What is a good descriptor of catchment response that allows for intercomparison of catchments across CZOs?
- What are the main controls of hydrologic response in this semi-arid mountainous catchment?

**SCM Experimental Zero Order Basins**. Marshall Gulch (1.54 km$^2$) is located southeast of Mount Lemon, the largest peak of the mountains (32$^o$25’45”N 110$^o$46’0”W). Two V-shaped ZOBs (Schist (SC) and Granite (GC)) lie within the Marshall Gulch basin. Both ZOBs are north oriented with relatively steep slopes which have north, northeast and northwest facing aspects. Elevation ranges from 2311 m to 2476 m for the Schist basin (area is 0.03 km$^2$) and from 2379 m to 2516 m for the Granite basin (area is 0.05 km$^2$).




**Instrumentation**. In Marshall Gulch field equipment is being deployed in zero-order basins to measure water, carbon and energy stores and fluxes across the critical zone. Instrumentation includes rain gages, rain water samplers, streamflow flumes, snow melt lysimeters, shallow groundwater piezometers, soil moisture and soil temperature probes, soil water tensiometers, and soil water solution samplers.

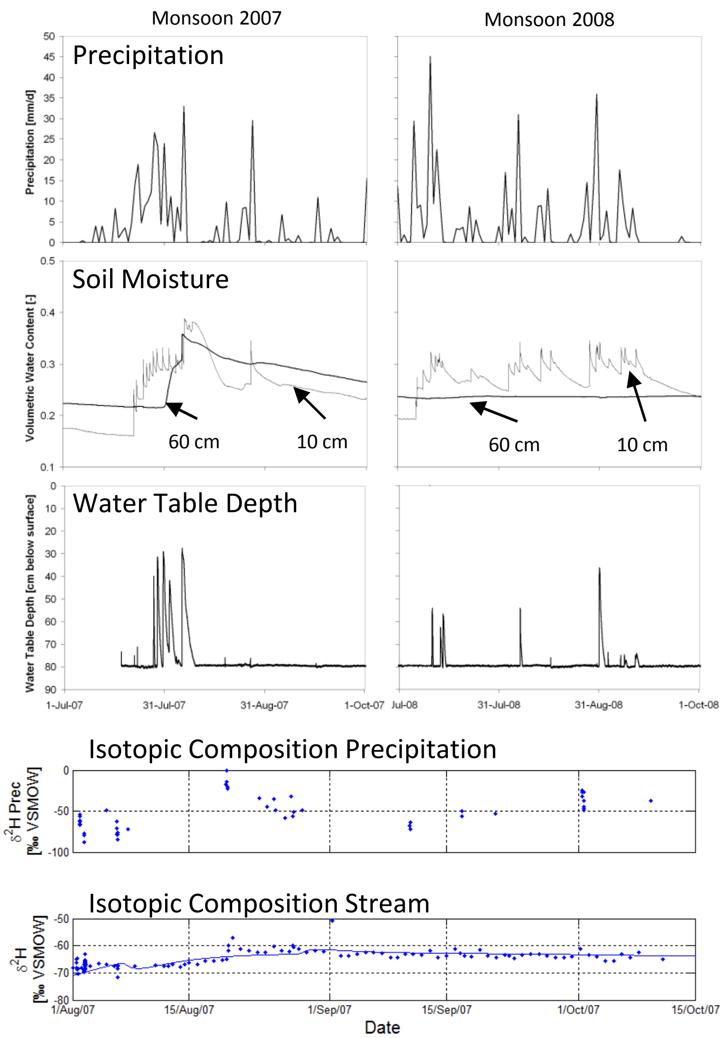
**Data Collection: Chemistry** Water isotope sampling started irregularly in 2006 in both the stream and precipitation. Since 2007 at least weekly samples are being collected for the streamflow, precipitation and soil water. Carbon, major anions and cations and rare earth elements are available since 2009, snow melt isotopes since 2010.

**Data Collection: Hydrology** Stream discharge is measured at the outlet. Precipitation by a network of 18 rain gages. Soil moisture with 55 TDR probes and groundwater levels in the ZOBs with 15 piezometers.

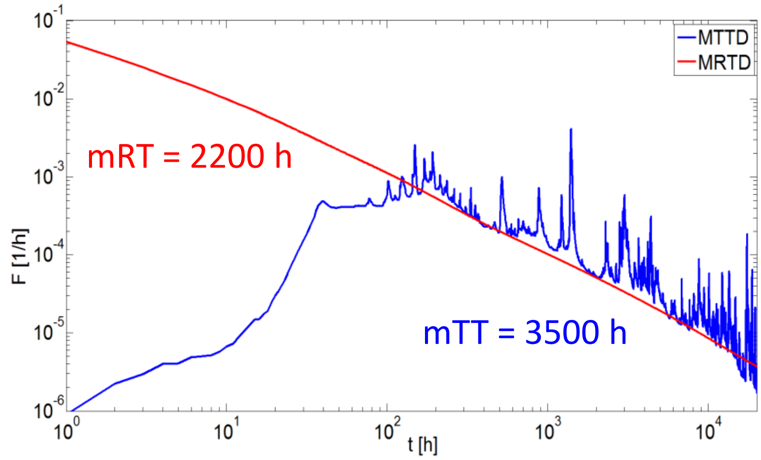
**Geology and soils**. The bedrock in Marshall Gulch is dominated by pre-Cambrian and Tertiary aged granites and granodiorite, in combination with Paleozoic aged metamorphic rocks such as schist and quartzite. The terrain is steep and rugged. Soils are deep (ca. 50-100 cm depending on landscape position). Schist soils are more deeply weathered, finer in texture, and contain more organic matter than granite soils.

**Land use/vegetation**. The vegetation in Marshall Gulch consists mainly of Maple, Ponderosa Pine and mixed Conifer forest.

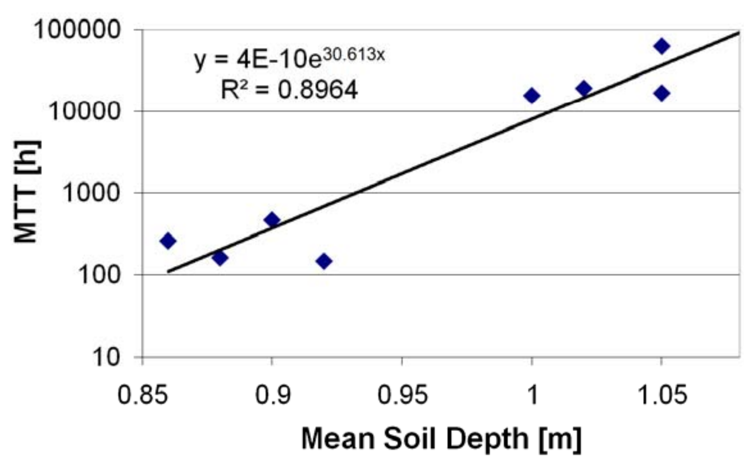
**Climate**. The climate of the Marshall Gulch catchment can be characterized as semi-arid and montane. Mean annual precipitation is 750 mm, delivered mostly during intense summer monsoon (July and August) and as winter snowfall. Average temperature is 9.4 °C and the average lowest and highest temperatures are -3.8 °C and 23.9 °C, respectively. In 2009 (a comparatively dry year with a very weak monsoon season), the total precipitation was 456 mm, minimum temperature -6.7 °C and maximum temperature 27.7 °C.




**Research methods**. We use stable isotopes of water to determine the transit time of water at the ZOB and catchment scale. In our semi-arid catchment with two distinct wet periods (winter and summer) separated by long dry periods, the transit time of water is highly variable with time and depends strongly on water stored prior to precipitation events. Therefore, new methods need to be developed to estimate the variable transit time of water throughout the year. Our approach relaxes the often made assumption of steady-state flow, and estimates both the pressure-wave and the particle wave response function for each precipitation input. The combined use of the pressure-wave and particle-wave response functions allows to construct the so-called Master Response Time Distribution (MRTD) and the Master Transit Time Distribution function of the catchment (MTTD). These functions represents the pdf of all possible respone and transit times.




**Results.** Preliminary results show the wide variety of hydrologic responses that are observable in a semi-arid catchment. Mean transit times range from less than an hour up to several years. Some controls could be identified that directly influence water fluxes, partitioning and transit times. Geology plays a major part since it is one of the main controls of soil development. In the Schist ZOB mean transit times are an order of magnitude larger than in the Granite ZOB, mainly because soil thickness differs. The more weatherable Schist produces thicker soils with larger storage capacities that are finer grained and therefore less conductive. The soils on the Granite are shallower and transfer water faster, therefore their response is much flashier than the response from the Schist. In the Granite ZOB hydraulic connectivity is established quicker than in the Schist ZOB. At the soil bedrock interface a water table builds up more readily and via preferential flowpaths water starts to be transported out of the ZOB. Surprisingly, drainage area or slope of the flow paths do not exert major controls on water transit times.





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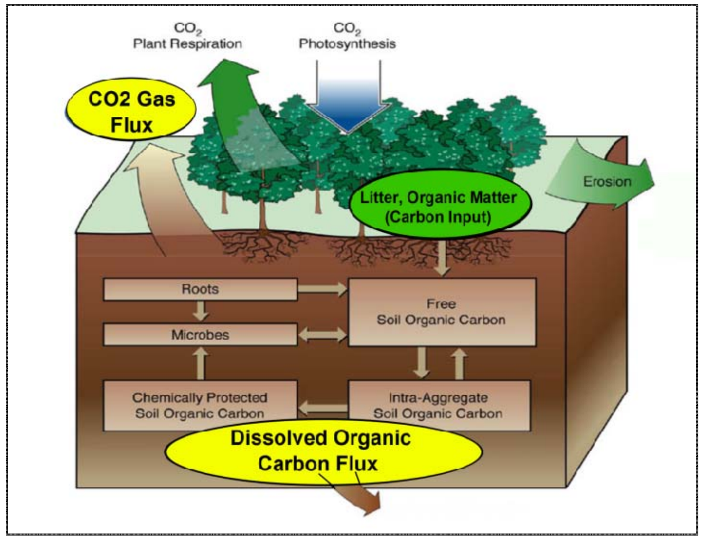
The Santa Catalina Mountains CZO involves co-investigators, collaborators, and students or postdocs from several campuses.


**Relative importance of gaseous and dissolved carbon fluxes from Critical Zone surface soils.**

Soil Organic Matter (SOM) is the largest pool of carbon at Earth's surface. Due to the complexity and diversity of soil systems, fluxes of carbon in and out of this pool are both spatially and temporally variable. This study aims to quantify the relative importance of gaseous vs. dissolved carbon fluxes from shallow surface soils in the critical zone, thereby linking above-ground and below-ground carbon processes. Quantifying these fluxes is essential for constraining Critical Zone carbon balance. DIC and DOC are also important contributors to mineral weathering. We hypothesize that primary drivers of these fluxes are closely related to bedrock weathering and water residence times.

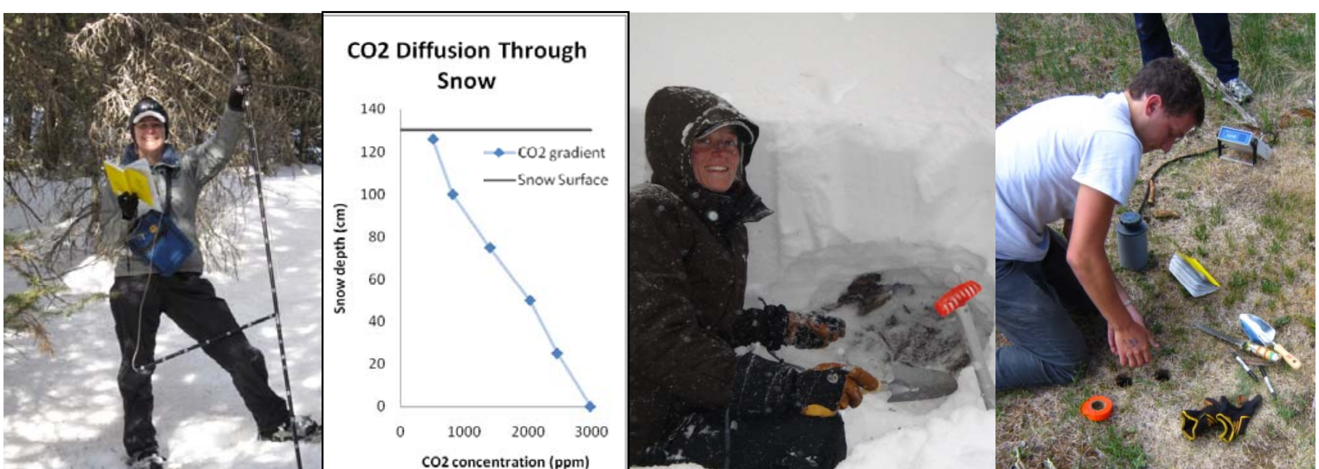



Conceptual model of the principal fluxes of carbon within a shallow surface soil system *(modified from TecEco Pty. Ltd.).*

**Research Questions:**

- How do surface soil carbon fluxes vary across granite vs. schist bedrock types?
- How do these fluxes vary between healthy mixed conifer forest, mixed conifer forest impacted by spruce budworm, and alpine meadow?
- How do these fluxes vary with season?

**Field Methods:** Winter measurement of $CO_2$ efflux through snowpack using a portable PP Systems Infrared Gas Analyzer (IRGA) and probe (A); $CO_2$ concentration gradient through a snowpack (B); Winter soil sampling and installation of mixed bed ion exchange resins to capture leached DOC (C); Summer measurement of $CO_2$ efflux using IRGA and soil chamber attachment, summer soil sampling and resin installation (D).




A B C D

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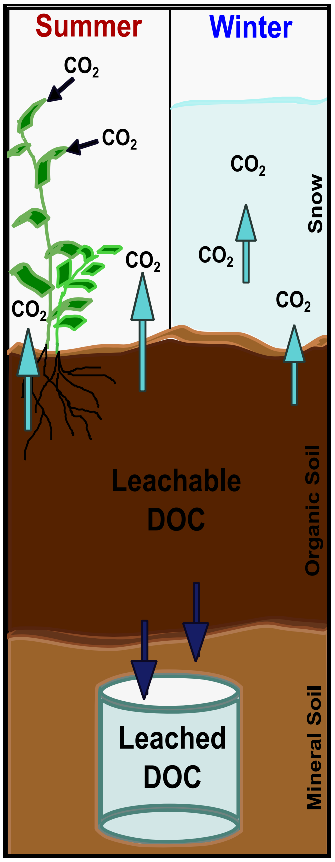
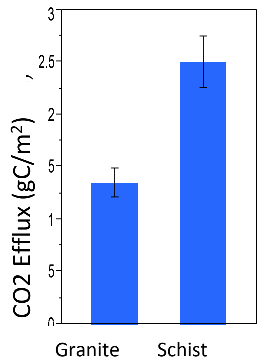
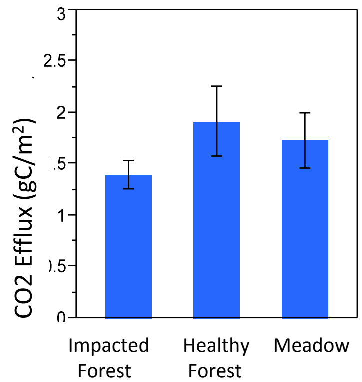
**References:**

Brooks, et al. Water Resour. Res. 35(6), 1895-1902 1999.
Sommerfield, et al. Nature 361, 1993.
Vestin, et al. Geoderma 135, 97–106 2006.

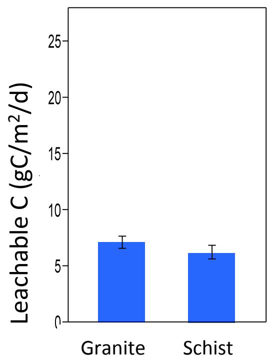
| Shallow Soil System | Marshall Gulch: Bedrock Comparison | Valles Caldera: Vegetation Comparison | Observations |
|---|---|---|---|

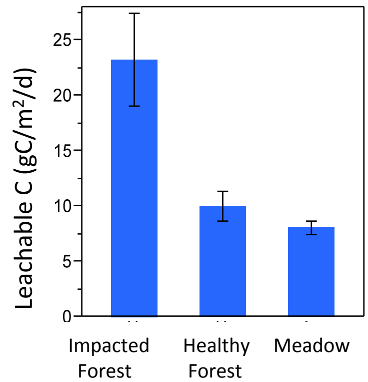



$CO_2$ Efflux:
- •Lower for Granite Bedrock
- •Lower for Impacted Forest.




Leachable DOC:
- •Not significantly different between bedrock types
- •Higher for Impacted Forest.

**Dissolved (Leached) Carbon Flux ?**

Leached DOC: Data not yet available.

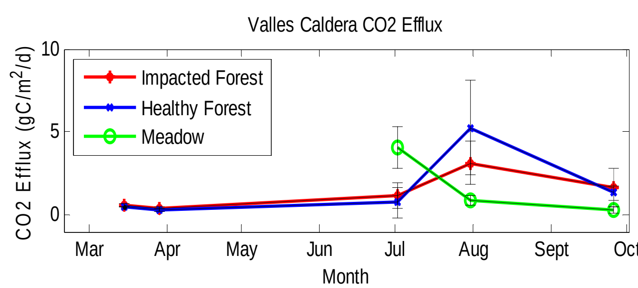
**Preliminary Results:**

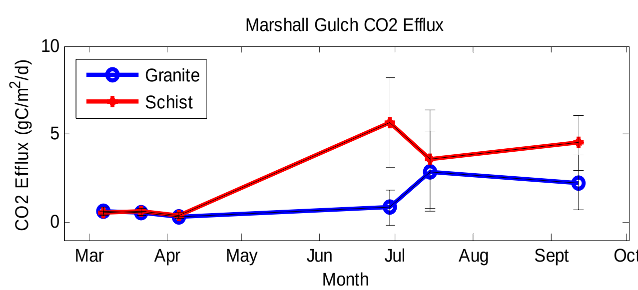
Relative Importance of Gaseous vs. Dissolved Carbon Fluxes:

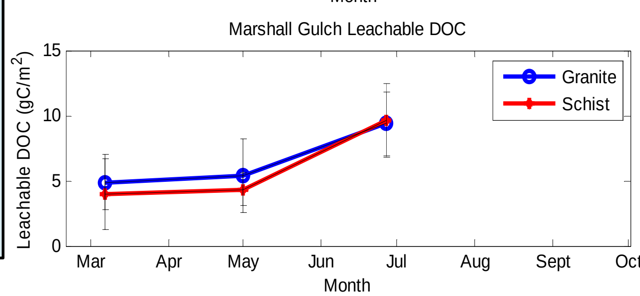
- •Higher Leachable DOC at the Valles than at Marshall Gulch.
- •Impacted vegetation has higher leachable DOC and lower $CO_2$ efflux.
- •Granite soil has lower $CO_2$ efflux than Schist soil.

Seasonal Carbon Flux Variability:

- •$CO_2$ efflux increases in summer (likely due to contribution of autotrophic respiration).
- •Leachable DOC also increases in summer.




**Inferences: Carbon, Water & Weathering Processes**

**Granite Hillslope**

- •Shorter water residence times
- •Less chemical weathering, larger particle size, shallower soils
- •More leachable DOC → less mineralization and/or stabilization of C?

**Schist Hillslope**

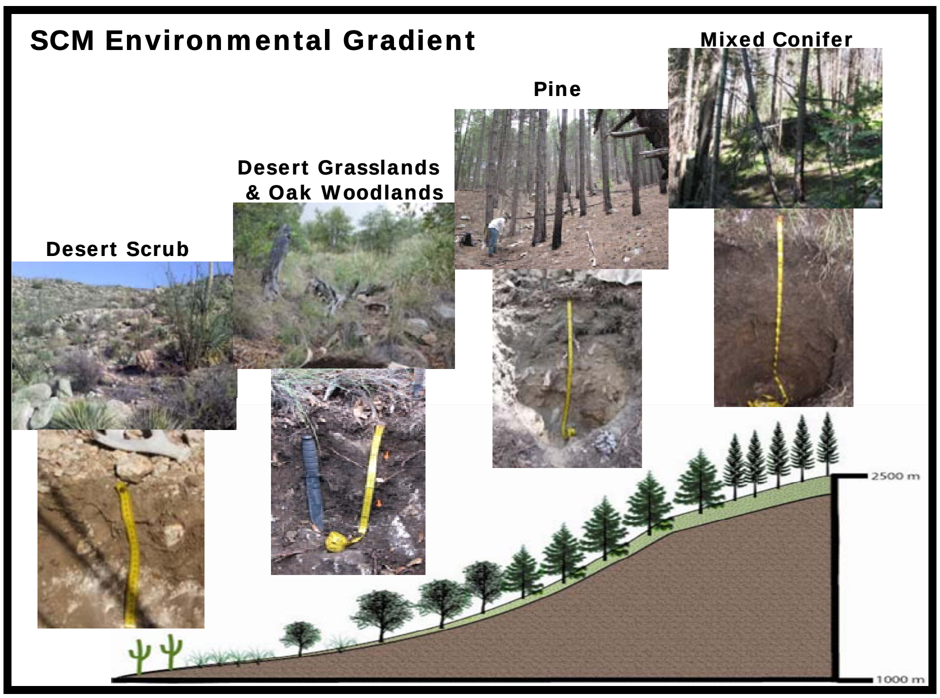
- •Longer water residence times
- •Increased chemical weathering, smaller particle size, deeper soils
- •Higher CO2 flux → more heterotrophic activity

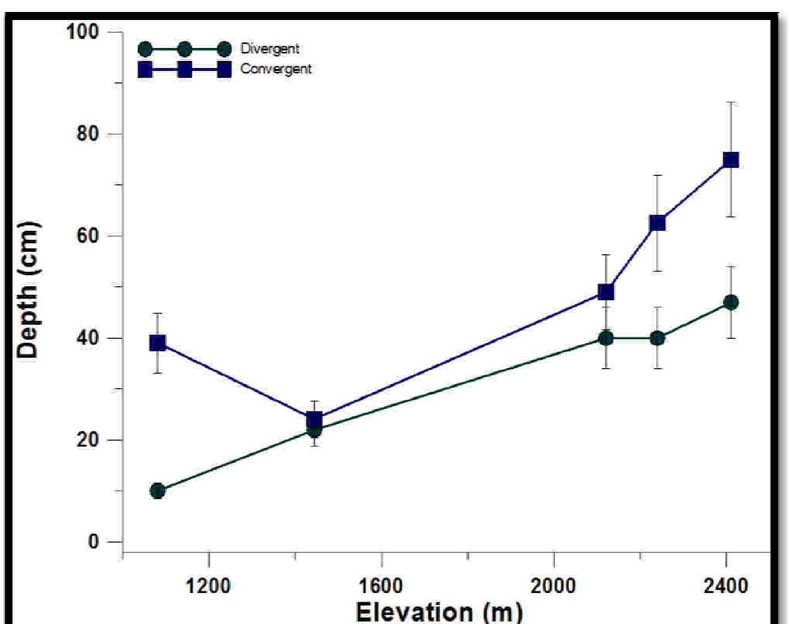

**Overview**

• Precipitation, topography, vegetation distribution and physical erosion rates demonstrate significant control over soil development.

• Soils are being analyzed along the SCM gradient to better understand these interactive controls on chemical denudation and soil mineral transformations in granitic environments.

• Changes in depth to paralithic contact, soil mineralogy, soil carbon distribution, vegetation and canopy cover are observed across the environmental gradient.



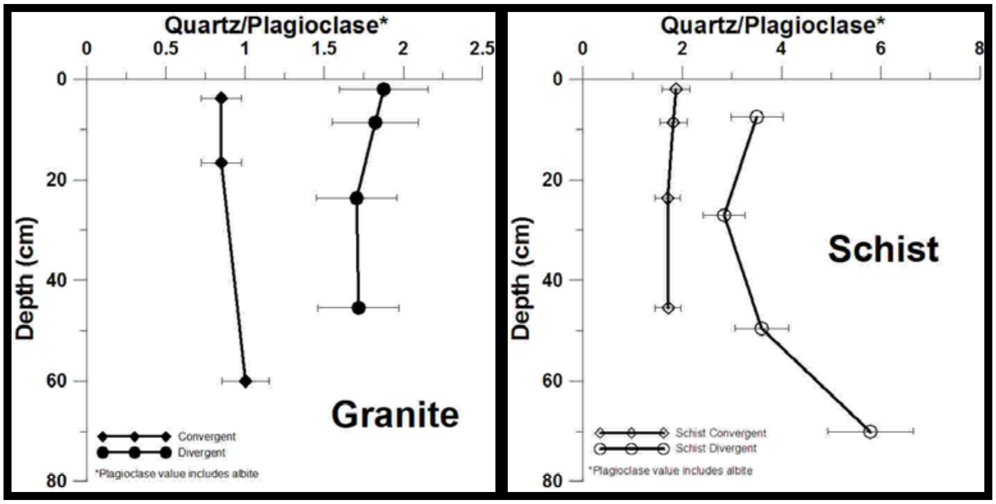




**Depth to Paralithic Contact**.

• Depth to paralithic contact increased with elevation, systematically in divergent positions (28 cm/1000 m) and less consistently at convergent sites.

• Relative differences in depth to paralithic contact between convergent and divergent landscape positions was greatest at the low and high elevation sites

• Product of changes in physical erosion rates across the gradient.




**Soil Chemical Weathering**

• Quartz/Plagioclase (Q/P) ratio → general proxy of chemical weathering in bulk soils. Higher Q/P values → increased degree of chemical weathering.

• At Marshall Gulch (mixed conifer), Q/P ratios were higher in divergent landscape positions compared to convergent ones

• Chemical weathering in convergent landscape positions appears to be inhibited by the collection of solute-rich soil waters originating from adjacent divergent landscape positions.

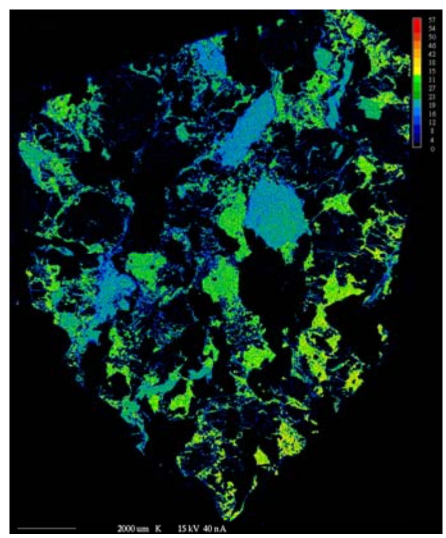
**Primary Mineral Compositions of Granitic Rocks**

• Electron microprobe analyses were used to determine the elemental compositions of primary minerals from representative rock samples along the gradient.

• Si, Mg, Al, Fe were used to characterize mica composition and Ca, Na, K measurements differentiated end members of the feldspar continuum

• Quartz, biotite, orthoclase and calcium/sodium-rich plagioclase feldspars were prominent primary minerals at the low elevation sites and quartz, muscovite, orthoclase and sodium-rich plagioclase feldspars were most dominant at high elevation sites.

• These data reflect differences in rock composition and age of pluton intrusion.



| Mineral | Na (%) | K (%) | Si (%) | Al (%) | Mg (%) | Ca (%) | Fe (%) |
|---|---|---|---|---|---|---|---|
| Low Elevation Mica (Biotite) | 0.10 | 7.24 | 17.63 | 6.95 | 8.47 | 0.03 | 12.60 |
| High Elevation Mica (Muscovite) | 0.19 | 8.34 | 21.12 | 16.29 | 0.53 | 0.00 | 4.24 |
| Low Elevation Plagioclase | 6.29 | 0.36 | 29.70 | 11.89 | 0.00 | 2.88 | 0.13 |
| High Elevation Plagioclase | 7.46 | 0.18 | 30.72 | 11.35 | 0.00 | 1.50 | 0.01 |