Annual Report for Period: 09/2010 - 08/2011
Submitted on: 07/05/2011
Principal Investigator: Bales, Roger C.
Award ID: 0725097
Organization: U of Cal - Merced
Submitted By:
Bales, Roger - Principal Investigator
Title:
CZO: Critical Zone Observatory--Snowline Processes in the Southern Sierra Nevada

Project Participants

Senior Personnel

Name: Bales, Roger
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Tague, Christina
Worked for more than 160 Hours: Yes
Contribution to Project:
Co-PI modeling water and nutrient cycles

Name: Conklin, Martha
Worked for more than 160 Hours: Yes
Contribution to Project:
Co-PI surface-groundwater interaction

Name: Glaser, Steven
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Riebe, Clifford
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Goulden, Mike
Worked for more than 160 Hours: Yes
Contribution to Project:
Flux tower Co-PI, CZO support.

Name: Johnson, Dale
Worked for more than 160 Hours: Yes
Contribution to Project:
Soil nutrients Co-PI. Soil carbon and nutrient analyses, nutrient fluxes, nutrient cycling.

Name: Molotch, Noah
Worked for more than 160 Hours: Yes
Contribution to Project:
Snow surveys and mapping

Name: Houlton, Ben
Worked for more than 160 Hours: Yes
Contribution to Project:
Nitrogen isotopes in streams - planning

Name: Hopmans, Jan
Worked for more than 160 Hours: Yes
Contribution to Project:
Co-PI for soil moisture

Name: Riebe, Clifford
Worked for more than 160 Hours: Yes
Contribution to Project:
Physical weathering rates

Name: Hart, Steven
Worked for more than 160 Hours: Yes
Contribution to Project:
Forest Ecology

Name: Berhe, Asmeret
Worked for more than 160 Hours: Yes
Contribution to Project:
Soil biogeochemistry

Name: Glaser, Steven
Worked for more than 160 Hours: Yes
Contribution to Project:
DUST wireless sensor networks

Post-doc

Name: Hartsough, Peter
Worked for more than 160 Hours: Yes
Contribution to Project:
Experimental design, implementation and ongoing maintenance

Graduate Student

Name: Malazian, Armen
Worked for more than 160 Hours: Yes
Contribution to Project:
Field installation and instrument calibration

Name: Palucis, Marisa
Worked for more than 160 Hours: Yes
Contribution to Project:
In preparation for Ph.D. qualifying exam, used stream and suction lysimeter data from the CZO to test a theoretical model for concentration-discharge relationships in porewaters and streams

Name: Alvarez, Otto
Worked for more than 160 Hours: No
Contribution to Project:
Data management

Name: Kelly, Anne
Worked for more than 160 Hours: Yes
Contribution to Project:
Evapotranspiration and water balance in forest

Name: Musselman, Keith

Worked for more than 160 Hours: Yes
Contribution to Project:
Snow surveys and mapping

Name: Kirchner, Peter
Worked for more than 160 Hours: Yes
Contribution to Project:
Water cycle, soil moisture

Name: Lucas, Ryan
Worked for more than 160 Hours: Yes
Contribution to Project:
Water cycle and meadow research

Name: Kamai, Timir
Worked for more than 160 Hours: No
Contribution to Project:
Datalogger programming and instrument calibration

Name: Swarowsky, Alex
Worked for more than 160 Hours: Yes
Contribution to Project:
Manufacture, calibration and installation of field instruments

Name: Kerkez, Branko
Worked for more than 160 Hours: Yes
Contribution to Project:
Installation, monitoring, and maintenance of DUST wireless network

Name: Fellows, Aaron
Worked for more than 160 Hours: No
Contribution to Project:
eddy-covariance tower field work

Name: Anderson, Ray
Worked for more than 160 Hours: No
Contribution to Project:
Eddie covariance tower field work

Name: Phelps, Gary
Worked for more than 160 Hours: No
Contribution to Project:
Website Manager

Name: Godsey, Sarah
Worked for more than 160 Hours: Yes
Contribution to Project:
geomorphology, the extensions and contraction of the stream network at the CZO in response to snowmelt

Name: Kandelous, Maziar
Worked for more than 160 Hours: Yes
Contribution to Project:
Field installation and lab calibration of soil moisture instruments

Name: Welch, Stephen
Worked for more than 160 Hours: Yes
Contribution to Project:

Helping maintain field network and is developing predictive models using ensemble Kalman filtering techniques to map solar radiation, temperature, and snow depth measurements into swe.

Undergraduate Student

Name: Baumgartner, Thomas
Worked for more than 160 Hours: Yes
Contribution to Project:
Assisted with field installations

Name: Melendez, Denise
Worked for more than 160 Hours: Yes
Contribution to Project:
Assisted with field installations and data analysis

Name: Kelly, Sean
Worked for more than 160 Hours: Yes
Contribution to Project:
Field research and data analysis

Name: Rojas, Adrian
Worked for more than 160 Hours: Yes
Contribution to Project:
Field research and data analysis

Name: Loy, Garrett
Worked for more than 160 Hours: No
Contribution to Project:
Field research and data analysis

Name: Mckuin, Brandy
Worked for more than 160 Hours: No
Contribution to Project:
Field research and data analysis

Name: Pendleton, John-Marc
Worked for more than 160 Hours: No
Contribution to Project:
Field research and data analysis

Name: Xochihua, Ruth
Worked for more than 160 Hours: No
Contribution to Project:
Field research and data analysis

Name: Zumkehr, Andrew
Worked for more than 160 Hours: Yes
Contribution to Project:
Web site management

Name: Curtis, Chris
Worked for more than 160 Hours: Yes
Contribution to Project:
Field technician

Name: Roudeva, Katja
Worked for more than 160 Hours: No

Contribution to Project:
Field installation and lab calibration of soil moisture instruments.

Name: Ngo, Allen
Worked for more than 160 Hours: No
Contribution to Project:
Field installation and lab calibration of soil moisture instruments.

Name: Huynh, Sylvie
Worked for more than 160 Hours: Yes
Contribution to Project:
Field installation and lab calibration of soil moisture instruments.

Name: Hedge, Christine
Worked for more than 160 Hours: Yes
Contribution to Project:
Undergraduate summer intern for summer 2011.

Technician, Programmer

Name: Meadows, Matt
Worked for more than 160 Hours: Yes
Contribution to Project:
Research hydrologist in charge of continuing CZO field program

Name: Winston, Greg
Worked for more than 160 Hours: Yes
Contribution to Project:
Flux tower instrumentation

Name: Liu, Fengjing
Worked for more than 160 Hours: Yes
Contribution to Project:
Geochemical analysis

Name: Tuli, Atac
Worked for more than 160 Hours: No
Contribution to Project:
Field installation of soil moisture instrumentation

Name: Meng, Xiande
Worked for more than 160 Hours: Yes
Contribution to Project:
Data management

Name: Nasta, Paolo
Worked for more than 160 Hours: Yes
Contribution to Project:
Field installation and lab calibration of soil moisture instruments.

Name: Kluitenberg, Gerard
Worked for more than 160 Hours: No
Contribution to Project:
Field installation and lab calibration of soil moisture instruments.

Name: Saintnoy, Albane
Worked for more than 160 Hours: No

Contribution to Project:
Field installation and lab calibration of soil moisture instruments.

Name: Smith, Allyson
Worked for more than 160 Hours: No
Contribution to Project:
Project management, education and outreach coordinator

Name: Smith, Jason
Worked for more than 160 Hours: Yes
Contribution to Project:
Field hydrology technician, data management

Name: Lam, Lawrence
Worked for more than 160 Hours: No
Contribution to Project:
Website development and management.

Other Participant

Research Experience for Undergraduates

Name: Holling, Timothy
Worked for more than 160 Hours: No
Contribution to Project:
Undergraduate research project (Summer 2009)

Years of schooling completed: Junior
Home Institution: Other than Research Site
Home Institution if Other: California State University, Stannislaus
Home Institution Highest Degree Granted(in fields supported by NSF): Master's Degree
Fiscal year(s) REU Participant supported: 2009
REU Funding: No Info

Organizational Partners

Pacific SW Research Station, USFS

The CZO is located at the Kings River Experimental watersheds, a set of research catchments operated by the Pacific Southwest Research Station (PSW), U.S. Forest Service.

Lawrence Livermore National Laboratory

Jean Moran and Brad Esser collected samples for isotope analysis as part of the meadow experiment in summer 2008. Initial analysis has been completed; further sampling and analysis may be conducted in order to obtain adequate data for collaboration on papers.

Other Collaborators or Contacts

The Center for Information Technology Research in the Interest of Society (CITRIS) is an interdisciplinary, and inter-campus collaboration between UC Berkley, Davis, Merced and Santa Cruz. Participants from this collaboration assist with installation, maintenance, and utilization of the Dust Networks wireless sensor platform in the P301 ground-based water balance instrumentation. Additional collaborators include Steve Glaser and the Civil Systems group at UC Berkeley.

Decagon Inc. Contact: Colin Campbell

Scott Tyler, UNR; summer 2008 deployed DTS system for meadow water cycle experiment, has provide input and insight on meadow deployment data processing and interpretation.

Crossbow Technologies; deployed a prototype wireless sensor network system in Wolverton.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
See attached

Findings: (See PDF version submitted by PI at the end of the report)
See attached

Training and Development:
We have developed an instrument clusters for mountain water cycle measurements, which is a great learning experience for all. This sort of integrated measurement network across a catchment has not been done before in the mountains of the Western U.S., at the rain-snow transition. In fact, it has not been done before in a forest away from AC power, and is currently the largest such network we are aware of. Students, postdocs and research scientists are learning strategies that will need to be replicated much more widely in the future.

Outreach Activities:
Some of our main outreach activities involve sharing technology with colleagues in research and operational agencies, giving talks and presentations to public audiences, providing press releases, and conducting newspaper and television interviews. SSCZO colleagues have participated in numerous outreach events, from organizing teacher trainings at national conferences to hosting field trips and classes within the CZO. Below is a summary of a few ongoing and past outreach events important to providing the public with a better understanding of SSCZO research. Additional outreach events are organized into a bibliography at the end of this section.

Recent collaborative media projects

Since February, there have been a number of news reports, articles, TV stories and radio interviews on research conducted at the SSCZO. On February 23, 2011 our technology partner, the UC Center for Information Technology in the Interest of Society (CITRIS), published on its web page a story about the applicability of our CZO instrument cluster to water resources measurement questions (http://citris-uc.org/news/2011/water_sense). As a result of the CITRIS article, the story was picked up by a local Northern California television station (http://www.ktvu.com/video/26992398), and its affiliates in Oregon and Southern California. In addition, nine other print and internet newspaper sites have picked up the story, including the Mariposa Gazette, Patterson Irrigator, PSYSORG.com, YubaNet.com, UC Merced campus news, Modesto Bee, the Merced Sun-Star, Sacramento Bee and the Central Valley Business Times.

During the March 2011 spring snow survey, NPR's KQED California Report Sasha Khokha recorded and produced a 5 minute radio segment on snowpack measurements in the Southern Sierra (http://www.californiareport.org/archive/R201103310850/b. She also wrote an article to compliment the story (http://blogs.kqed.org/climatewatch/2011/03/30/snow-surveys-of-the-future). Mark Grossi from the Fresno Bee also ventured out on the snow survey to report on new advancements in snowpack research (http://www.fresnobee.com/2011/03/20/2318242/sierras-rain-snow-zone-promises.html). Jeff Wheelwright from Smithsonian Magazine attended the survey to research new improvements in snowpack measurements.

After record snowfall in the Sierra Nevada, Roger Bales was invited to speak on NPR's KVPR Quality of Life program about snowpack measurements and how climate change may impact snowfall at the rain-snow transition (aired April 5th) (mms://vpubradio.wmod.llnwd.net/a720/o1/qolshows/20110405.wma).

On April 15, SSCZO participants hosted a TV film crew from Portuguese Public Television and Radio (RTP) at the CZO site. The goal of the film project was to capture how the US was combating different aspects of climate change including research, National Park programs, education and outreach. We were able to partner RTP and Yosemite Institute together to fulfill RTP's mission of filming climate change education.

The UC Berkeley Graduate School of Journalism produced a segment for their production: CNS News - Around California Part 1 on April

29th, at the SSCZO. Steven Glaser and Branko Kerkez of UC Berkeley talked to the film crew about their wireless sensor network technology and new innovations for measuring snowpack (http://vimeo.com/24494053). A third film crew from the University of California traveled to the SSCZO on July 1st to interview students and professors involved in water resources related research.

K-12 and undergraduate education

For the past 3 years, members of the SSCZO have been collaborating with Yosemite Institute (YI) to incorporate SSCZO education and outreach activities in a YI program. YI is a field school based in Yosemite National Park, providing California students with outdoor teambuilding and science experiences. Specifically, we are working to design activities around a mini-instrument system modeled after instrument networks being used in the SSCZO. By constructing this mini instrument cluster on the campus of YI, students participating in a program will become familiar with snow related issues relevant to the Southern Sierras and gain valuable field experiences while collecting scientific measurements. In February 2011, Martha Conklin gave a talk to the YI board of directors regarding climate change and pitching ideas for instrument cluster implementation at the new YI campus. Also in February, Bob Rice, a SSCZO collaborator, gave a talk to YI teachers regarding snow science. Back in October, 2010, Matt Meadows participated in a curriculum development day, presenting new activities to YI instructors. In addition, Martha Conklin spent a day in the field with Scott Borden (YI field programs coordinator) to observe YI's new climate activities and water quality sampling with a 6th grade class. Collaboration with YI is ongoing.

Two college courses have been developed as a result from research activities performed at the SSCZO. In May 2010 and 2011, the UC Davis campus has been using the CZO as an outdoor classroom for an Environmental Monitoring course (ESM108). Students participated in a weekend class trip to the CZO. Taught by SSCZO post-doc Peter Hartsough, students conducted field activities including snow depth and density measurements, stream flow and cross section measurements, soil moisture instrument deployment, and vegetation surveys. Steven Glaser from UC Berkley has been using results from the wireless sensor network in a graduate class called Sensors and Signal Interpretation (CE271).

In May and June 2010 and 2011, SSCZO staff participated in the Southern California Edison Science Days. Elementary and middle school classes traveled to Camp Edison (outside Shaver Lake) and visited stations set up to teach about nature and science. This year's event focused on water. Allyson Smith and Matt Meadows gave a presentation on instrumentation of the hydrologic cycle as performed by SSCZO researchers.

In January 2011, Martha Conklin and Allyson Smith participated in a mother-daughter science camp sponsored by the Merced branch of the American Association of University Women. In its 2nd year, the camp catered to 4-5th grade girls attending local Merced elementary schools. Girls and their mothers learned a new science topic each week, from biology to what makes a good scientist. Under a theme of Engineering, Martha and Allyson gave a short talk on water resources in the Central Valley and had the students get their hands wet using a small scale stream model to teach basic stream properties. During the 2010 science camp, Martha presented the students with a 3-D groundwater model.

Other outreach activities

In cooperation with the US Forest Service Sierra National Forest, the Dinkey Collaborative Forest Landscape Restoration Project is an ongoing effort to collaborate on Forest Service projects as part of the Forest Landscape Restoration Act. Dinkey creek is located next to the CZO, Matt Meadows is a member of the group who represents CZO interests in land management projects.

In May 2011, all CZOs gathered for a meeting in Arizona to give presentations of results and discuss the future of CZO research. This event was attended by 12 SSCZO researchers, collaborators, students and staff, who presented talks and posters.

This fall, SSCZO presented over 15 talks and posters during the American Geophysical Union's (AGU) meeting held December 13-17, 2010 in San Francisco, CA. Data were presented by numerous PIs, graduate students, and research staff. The national CZO program was an exhibitor throughout the duration of the conference, providing information on all CZO sites.

In February 2011, Cliff Riebe participated in the Good Mule Conference, which annually brings local high school and college students together to discuss issues related to activism on the environment and sustainability. Cliff spoke to a group of ~30 students on the 'world water crisis,' first highlighting the importance of water in our daily lives and then discussing the inequity of water availability across the globe. Cliff ended with a presentation of what students can do to mitigate the 'crisis.' Specific reference to water issues in California - and specifically snow pack in the Sierra Nevada - was central to the discussion.

An 8th grade AVID (Advancement Via Individual Determination) class from Bryant Middle School, located in Dos Palos, visited the UC Merced campus in February, 2011. AVID is a class used to prepare and motivate underprivileged grade school students for university life. Matt Meadows and Allyson Smith presented 20 AVID students with an overview of the SSCZO, how it relates to water resources in the Central

Valley, and provided activities on snow depth measurements and mountain stream processes. Reza Ghanbari, a post-doc, assisted during this event.

Also in January, Martha Conklin went to Washington DC for a two day NSF sponsored meeting to review GLOBE (Global Learning and Observations to Benefit the Environment) protocols and bring them up to current standards. Some activities included integrating continuous measurements and exploring how schools could put these measurements in terms of spatial measurements (e.g. satellite and LiDAR). This meeting was triggered by the updating of the GLOBE data base to accommodate continuous measurements. Martha participated in the entire meeting but contributed specifically to the hydrology and solid precipitation measurement components.

In December 2010 Ryan Lucas and other SSCZO researchers organized a one-day Geoscience Information for Teachers (GIFT) workshop during the American Geophysical Union's (AGU) fall meeting. The GIFT session theme was water; the day organized by the SSCZO Education and Outreach presented regional water issues and research conducted by the SSCZO that related to regional water processes. Graduate students from the SSCZO and UC Merced presented their research, its importance relative to climate change and regional water, and a little about their growth from being a high school student to graduate education.

Beginning in June 2009, Ryan Lucas participated in the California Institute for Biodiversity's Sierra Nevada Teacher Institute. Since then, he has become an instructor with the Institute (June 2010), leading activities focused on physical impacts of climate change to the Sierra Nevada and California, system equilibrium and stability, and led a group of 6-12th grade teachers in a water quality experiment. Ryan continues to collaborate with the Institute, leading activities and giving talks to teachers involved with their professional development program. In June 2011, Ryan Lucas participated as an instructor in the Instute's, Advanced Climate Change course for teachers. Ryan gave a presentation on Greenhouse gases other than carbon dioxide. In addition, Ryan led the teachers in an activity revolving around water use in California and potential impacts from global climate change. Ryan also consulted with the teachers as they conducted a group science project over the two weekend course.

SSCZO researchers Roger Bales, Jan Hopmans, Peter Hartsough, Peter Kirchner, and Matt Meadows took part in the California Soil Moisture Monitoring Workshop in May 2010 in Sacramento, CA. Lead by Michael Anderson, California State Climatologist, this workshop brought together a group of experts in soil moisture monitoring to promote collaboration in building a state wide soil moisture monitoring network.

Bibliography of talks, presentations and field trips incorporating topics relevant to the SSCZO

2011

Bales, R. C. The California mountain water cycle: knowns & unknowns, NAE Regional meeting, UC Berkeley, March 31, 2011

Bales, R. C. Snowpack, soil moisture & water balance across the rain-snow transition in a Sierra-Nevada mixed-conifer forest. UC Berkley Seminar. January, 2011.

Bales, R. C. Sierra Nevada snowpack, climate change & water management. University of Utah Seminar. January 2011.

Conklin, M. H. California's water cycle: climate & snowpack. Talk presented at the Yosemite Institute Board Meeting. January 2011.

Conklin, M. H. and Smith, A. S. Environmental engineering and water resources in the Southern Sierras. Presentation and activity for American Association of University Women Girl's Science Camp - Engineering Day. UC Merced. January 2011.

Meadows, M. Southern Sierra Critical Zone Observatory: Integrating measurements for advances in hydrology & geochemistry. Reedley College, Watershed Ecology class guest speaker. February 2011.

Meadows, M., Smith, A. S., and Ghanbari, R. Bryant Middle School AVID (Advancement Via Individual Determination) UC Merced campus visit. February 2011.

R.G. Lucas; M.H. Conklin; S.W. Tyler; F.I. Suarez; J.E. Moran; B.K. Esser, 'Polymictic pool behavior in Sierra Nevada Streams', (2011). UC Merced Research Week. Graduate Student Poster Session

Lucas, R. Climate Change and Water in California. Talk presented to the California Institute for Biodiversity Cal Alive Sierra Nevada Institute Encore Day. February and June 2011.

Rice, R. Mountain Hydrology and the Changing Climate: Measurements and Teaching Techniques. Talk presented at the Yosemite Institute instructor in-service day. February 2011.

Rice, R. Snow and climate in the Sierra Nevada. Talk and field day presented to Mariposa Middle School 8th grade class incorporating manual and automated snow measurement techniques. February 2011.

Riebe, C.S. 'World Water Crisis' presentation to Good Mule Conference, Train Depot, Laramie, Wyoming. February 2011.

Smith, A. S., Meadows, M., and Hedge, C. How SSCZO Researchers Measure Parts of the Hydrologic Cycle in the Southern Sierra Nevada. Southern California Edison's Science Days. Shaver Lake, CA. May and June, 2011.

2010

Bales, R. C. Mountain Water Cycles and Instrumentation. Talk presented to the Sierra Nevada Alliance. April 2010.

Conklin, M. H. Groundwater Resources Presentation. Presentation and activity for American Association of University Women Girl's Science Camp - Engineering Day. UC Merced. January 2010.

Hopmans J.W. The California Critical Zone Oberservatory (CZO). Spring Hydrology Seminar, Institute for Water and Watersheds, Oregon State University. May, 2010.

Hopmans, J.W. Measurements and Modeling of Tree Hydrology Across Rain-to-Snow Transition in the Kings River Experimental Watershed, CA. Civil Engineering Seminar Series. University of California Irvine. March, 2010.

Kirchner, P. B. Interview featured in 'Clue Into Climate, Snow-Pack' internet video featured on KQED education network, science ready to explore. http://www.kqed.org/education/educators/clue-into-climate/water-cycle.jsp

Kirchner, P. B. Presentation of climate change impacts on snow and implications for the water resources of central California, Merced River Fair, Riverdance Farm, June, 2010.

Kirchner, P. B. Presentation of Critical Zone Observatory research to University of California, Merced Board of Trustees, February 2010.
Lucas, R. Climate Change: Central Valley Impacts and Implications. Talk presented to Great Valley Center's Institute for Emerging Area Leaders. April 2010.

Lucas, R. Climate Change: A Global Phenomenon with Local Implications. Talk presented to the Central Valley Air Quality Coalition. January 2010.

Lucas, R. Studying Water Processes in the Sierra Nevada. Talk presented to the Great Modesto Area Partners in Science. April 2010.

Lucas, R. Water Crisis: Where are We Headed? Talk presented to the University Friends Circle. March 2010.

Meadows, M. and Sullivan, L. Yosemite Institute hydrology curriculum development day. October 2010.

2009

Bales, R. C. California's water cycle: climate, snowpack & forest management. California Licensed Foresters Association annual meeting. Sacramento. March 2009.

Conklin, M. H. and Kirchner, P. B. Interviews featured in 'California at the Tipping Point' KQED Quest public television documentary on climate change science and California, first aired in April, 2009.
http://www.kqed.org/quest/television/climate-watch-california-at-the-tipping-point-part-one

Lucas, R. Critical Zone Observatory ? Researching Hydrologic Processes in the Southern Sierra Nevada. Talk and symposium presented at the American Geophysical Union, Geoscience Information For Teachers. December 2009.

Kirchner, P. B. Environmental Monitoring for Hydrologic Resources; a look into the future. Presentation at the Geophysical Information for Teachers (GIFT) workshop, American Geophysical Union. San Francisco. December 2009.

Kirchner, P. B. Eastern Sierra Roadside Heritage project, Snow and Ice in the Sierra Nevada, NSF funded video interview and middle school outreach. September 2009. http://www.roadsideheritage.org/index.html

Lucas, R. Climate Change Implications to the Sierra Nevada and the Central Valley Presentation and Panel Member. Sacramento Valley Forum. October 2009.

Lucas, R. Critical Zone Observatory ? Researching Hydrologic Processes in the Southern Sierra Nevada. Talk presented to Merced High School District Excellence in Science. November 2009.

Meadows, M. Southern Sierra Critical Zone Observatory: Integrating measurements for advances in hydrology & geochemistry. Reedley College, NR12 Watershed Ecology class guest speaker. February 2009.

Tague, C. Modeling eco-hydrology under a changing climate, how much do subsurface drainage patterns matter? Berkeley Catchment Science Symposium. Berkeley, CA. December, 2009.

2008

Bales, R. C. Integrating measurements of snowpack, soil moisture, ET& streamflow for understanding the Sierra Nevada water balance. Yosemite Hydroclimate Meeting. October 2008.

Bales, R. C. Hydroclimate, ecosystem links & the Southern Sierra Critical Zone Observatory. Southern Sierra Science Symposium. Visalia, CA. Sept 2008.

Bales, R. C. Sierra Nevada snowcover patterns & watershed processes. Seminar presented at Oregon State University. April 2008.

Bales, R. C. California water, mountain hydrology, & UC Merced. Talk at UC-WRRC synthesis meeting. Woodlake, CA. April, 2008.

Conklin, M. H. and Kirchner, P. B. Interviews featured in 'California Heat' a KVIE View Finder public television documentary on climate change impacts in California, first aired in October 2008. http://www.kvie.org/programs/kvie/viewfinder/california_heat/default.htm

Meadows, M. Sierra Nevada Research Institute: research update. Invited Presentation. California Cooperative Snow Survey Meeting, Bass Lake, CA. November, 2008.

Meadows, M. Southern Sierra Critical Zone Observatory: Integrating measurements for advances in hydrology and geochemistry. Invited Presentation. Society of American Foresters, High Sierra Chapter Meeting. October, 2008.

Journal Publications

Johnson, D.W., W.W. Miller, R.B. Susfalk, R.A. Dahlgren, and D.W. Glass, "Biogeochemical Cycling in Forest Soils of the Eastern Sierra Nevada Mountains", Forest Ecology and Management, p. , vol. , (2009). Published, 10.1016/j.foreco.2009.01.018

Anderson, S. A.; R. C. Bales; C. J. Duffy, "Critical Zone Observatories: Building a network to advance interdisciplinary study of Earth surface processes", Mineralogical Magazine, p. 7, vol. 72(1), (2008). Published,

Hunsaker, C.T., Whitaker, T., Bales, R.C., "Water yield and runoff timing across the rain-snow transition in California's southern Sierra Nevada", submitted, p. , vol. , (2010). Submitted,

Johnson, D. W., Glass, D. W., Murphy, J. D., Stein, C. M., Miller, W. W., "Hot Spots and Hot Moments: Another Look at Nutrient Variability in Sierra Nevada Forest Soils", Biogeochemistry, p. , vol. , (2010). Accepted,

Johnson, D.W., Hunsaker, C.F., Glass, D.W., Rau, B.M., Roath B.A., "Carbon and Nutrient Contents in Soils from the King's River Experimental Watershed, Sierra Nevada Mountains, California", Geoderma, p. 490, vol. 160, (2010). Published, 10.1016/j.geoderma.2010.10.019

Kerkez, B., Glaser, S.D., Dracup, J.A., Bales, R.C., "A hybrid system model of seasonal snowpack water balance", International Conference on Hybrid Systems: Computation and Control, p. , vol. , (2010). Published, Lui, F., Hunsaker, C.T., Bales, R.B., "Controls of streamflow pathways in small catchments across the snow-rain transition in the Southern Sierra, California", submitted, p. , vol. , (2010). Submitted,

Tague, C., "Assessing climate change impacts on alpine stream-flow and vegetation water use: mining the linkages with subsurface hydrologic processes", Hydrological Processes, p. 1815, vol. 23, (2009). Published, DOI: 10.1002/hyp.7288

Kizito, F; Campbell, CS; Campbell, GS; Cobos, DR; Teare, BL; Carter, B; Hopmans, JW, "Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor", JOURNAL OF HYDROLOGY, p. 367, vol. 352, (2008). Published, 10.1016/j.jhydrol.2008.01.02

Malazian, A., P.C. Hartsough, T. Kamai, C.S. Campbell, D.R. Cobos and J.W. Hopmans, "Evaluation of MPS-1 soil water potential sensor", J. of Hydrology, p. 126, vol. 402, (2011). Published, 10.1016/j.jhydrol.2011.03.006

Nasta, P., S. Huynh, and J.W. Hopmans, "Simplified Multistep Outflow method to estimate unsaturated hydraulic conductivity for coarse-textured soils", Soil Science Society America Journal, p. , vol. , (2010). Submitted,

Kerkez, B., Glaser, S.D., and Bales, R.C., "Wireless Sensor Networks for of Hydrologic Measurements: Performance Evaluation and Design Methods", Water Resources Research, p. , vol. , (2011). Submitted,

Bales, R.C., Hopmans, J.W. O'Geen, T.O., Meadoes, M. Hartsough, P.C., Kirchner, P., Hunsaker, C.T., Beaudette, D., "Soil moisture response to snowmelt and rainfall in a Sierra Nevada mixed-conifer forest", journal, p. , vol. , (2011). Submitted,

Fengjing Liu, Martha H. Conklin, Mark E. Conrad, and Glenn Shaw, "Determination of meteoric water contributions from lower and higher elevations to streamflow in the Upper Merced River, Sierra Nevada, California", Journal, p. , vol. , (2011). Submitted,

Johnson, D. W., D.W. Glass, J.D. Murphy, C.M. Stein, and W.W. Miller, "Nutrient hot spots in some Sierra Nevada forest soils", Biogeochemistry, p. 93, vol. 101, (2010). Published, 10.1007/s10533-010-9423-8

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Web/Internet Site

URL(s):

https://snri.ucmerced.edu/CZO
https://eng.ucmerced.edu/snsjho
https://snri.ucmerced.edu/CZO/data.html

Description:

The first is our main CZO url.
The second url is our Digital Library.
The third url is our Data Catalog.

Other Specific Products

Product Type:

Instruments or equipment developed

Product Description:

System and method for measuring water fluxes and partitioning across a landscape. Disclosure & patent application filed; pending. Will be included on UC Merced's report to federal government in June 2011.

Sharing Information:

Scalable water-balance instrument cluster.

Contributions

Contributions within Discipline:

The CZO provides a multi-disciplinary platform for research. Most of the CZO data are available to the community, and other data to CZO cooperators who agree to data-sharing protocols.

Contributions to Other Disciplines:

The CZO fosters multi-disciplinary research. The site is also a candidate for a NEON investment, which could significantly enhance some of our CZO activities.

Contributions to Human Resource Development:

Several graduate students, undergraduates and recent Ph.D. graduates
are involved with the CZO, and are preparing themselves for independent measurement and data analysis work in field hydrology and modeling.

Contributions to Resources for Research and Education:

The CZO is a research platform, i.e. infrastructure for multidisciplinary research.

Contributions Beyond Science and Engineering:

The high profile of our CZO helps communicate water and other critical zone issues to the public, and helps educate agencies about the need to modernize measurement and decision-making infrastructure.

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Special Requirements

Special reporting requirements: None

Change in Objectives or Scope: None

Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Southern Sierra Critical Zone Observatory
Work Plan, updated October 8, 2010

Contents

Topic. **Core CZO measurements, data management and integration**
Updated 2010

Investigator. **Roger Bales & Martha Conklin**

Students & research staff. **Matt Meadows, UG assistant, Xiande Meng, Communications Assistant.**

Scope.

Field installations & support. Core measurements made by the CZO team compliment those done by the KREW team. One focus is the water balance instrument cluster, which is anchored by an eddy-correlation flux tower but with ground measurements extending 1-2 km from the tower. The flux tower will provide point measurements of water, energy and carbon exchange with the atmosphere, which will be extended outward using the meteorological, snow/soil, remotely sensed and other spatial data. The proposed instrument cluster will include three embedded sensor networks, one located in the vicinity of the tower, one at a lower elevation with cold-season precipitation a mix of rain and snow lower met station vicinity) and one at a higher snow-dominated elevation upper met station vicinity). Measurements that are part of the instrument clusters include: snow depth, air temperature, solar radiation (open and under canopy), reflected radiation, soil moisture, temperature and matric potential (multiple depths), sap flow. Across the meadow and stream sections it is planned to measure water level, temperature, electrical conductivity in piezometers. Measurements on the tower include wind speed and direction, atmospheric water vapor flux, CO2 flux, shortwave and longwave radiation (incoming/outgoing), precipitation, relative humidity, barometric pressure.

Data management. CZO data are archived in a digital library: https://eng.ucmerced.edu/snsjho.

Public Education & outreach. We regularly (at least monthly) give talks across the region, to stakeholders with an interest in the Sierra Nevada and its recourses. We attend other planning meetings related to resource management, where CZO knowledge may be applied.

K-12 Education and outreach. One focus is on training instructors of the Yosemite Institute (YI) in critical zone processes, with a particular focus on mountain hydrology. We will focus on activities that stress the mountain water cycle, the role of the Sierra Nevada snowpacks to CA water supply and their vulnerability of the snow to climate change.

University education. We plan to develop at least three university earth science "case studies" using data and observations obtained from the CZO. One module will combine a basic energy balance with state of the art technology, Raman-backscatter distributed temperature sensing, in a montane stream. Concepts to be stressed include the spatial heterogeneity of the stream as well as the role of obtaining system "snapshots" in time. These case studies will provide teaching notes for educators and will be posted on the CZO website; we will also post them on websites provided by professional organizations. These case studies will seek to provide earth science educators and students with current, peer-reviewed material.

CZO integration. The core office will also maintain a web site to facilitate project communications, organize an annual meeting of Southern Sierra CZO investigators, maintain communication with PSW, communicate with the press and stakeholders, represent the CZO at professional meetings (when invited), and coordinate with NSF, the other CZO's and the CZO steering committee.

Funding. Largely CZO.

Schedule, including field work. Ongoing

Manuscripts in progress & planned. TBD

Topic. **Core KREW measurements and data management**
Updated 2008

Investigator. **Carolyn Hunsaker**

Students & research staff. **Tom Whitaker, field hydrologist**

Scope. PSW has agreed to share basic, relevant data with the CZO team and science community. Data that PSW is developing include: stream stage & discharge, meteorology, stream channel characteristics, stream condition inventory, stream physical habitat (macroinvertebrates), erosion & sedimentation, geology, soils & litter, shallow soil water chemistry, snowmelt & rain chemistry, streamwater chemistry, riparian & upland vegetation, fuel loading, algae & periphyton.

Schedule, including field work. Ongoing
Manuscripts in progress & planned. See below.

Topic. **Modeling of water and nutrient cycles**
Updated 2008

Investigator. **Christina Tague**

Students & research staff. **Kyongho Son**

Scope. Modeling will be carried out using RHESSys, a spatially distributed, dynamic model of coupled eco-hydrologic processes. Included in the model are mechanistic representations of vertical hydrologic processes (interception, soil and litter evaporation, canopy transpiration, infiltration, vertical drainage); lateral redistribution of moisture and nutrients and streamflow production; and soil and vegetation carbon and nitrogen cycling (http://fiesta.bren.ucsb.edu/~rhessys/). The CZO provides an opportunity to better integrate field measurements and analysis within a spatial modeling framework. My broad general goals are to collaborate with other CZO scientists and use the model to: i) contribute to the site selection of new monitoring locations by using the model to develop hypothesis about where significant gradients in response variables are likely to occur, ii) contribute to the spatial scaling of measurements by estimating spatial patterns of response variables, and iii) estimate response variables for a range of climate and land-cover scenarios. It will be very important to use field measurement to try to improve the model by: i) reducing uncertainty in model inputs and parameters, ii) contributing to quantification of model uncertainty, and iii) refining where necessary model structure (or representation of specific hydrologic and biogeochemical cycling processes) The general approach will begin with looking at streamflow hydrology, followed by eco-hydrologic processes (e.g. transpiration) and then finally carbon and nitrogen cycling. Initial work will use the model as is - later work will incorporate measured data to try to improve model performance.

Heterogeneity and spatial resolution. At what spatial resolution must we resolve heterogeneity in snow accumulation and melt in order to capture streamflow responses to climate variation and differences in streamflow responses between study watersheds? The first step is to calibrate RHESSys using currently available inputs: DEM, basic vegetation and soils map, meterological station data, to predict streamflow and variation in streamflow between the 4 instrumented watersheds . I will use GLUE type Monte-Carlo approaches for calibration and generate uncertainty bounds around streamflow predictions. I will also use some non-traditional streamflow metrics to try to better constrain model parameters, considering both peak and low flow metrics and year-to-year variation in these. I will also compare model estimates of ET, and storage discharge relationships with those derived by Jim using his hydrograph recession analysis techniques. I will repeat this model analysis using different model resolutions. Ideally it would also be useful to include estimate of very fine (meter) scale heteorogeneity in snow cover and melt rates. The goal here is to examine sensitivity of streamflow predictions to modeling unit resolution and incorporation of variance within finest scale model units.

Streamflow and climate. What is the relationship between modeled streamflow and climate in site watersheds? How will streamflow in these watershed change under a warmer climate? Using the calibrated model of streamflow from above, we will estimate streamflow behavior under a range of climate conditions. Empirical analysis of streamflow data (in progress by Tom Whitaker) can provide a baseline analysis of climate-streamflow relationships. I will compare model predictions to this baseline analysis and highlight model weaknesses. If model performance is adequate, I will then use the model to estimate streamflow behavior under a warmer climate – initially using uniform increases in temperature (based on projections for California). Ideally it would be useful to also drive the model with downscaled GCM data.

Spatial properties of vegetation. How well does current model predict spatial patterns of vegetation LAI throughout thewatersheds? As a carbon cycling model, RHESSys can be used to predict spatial patterns of vegetation leaf, stem and root carbon stores. Evaluation of model performance will help to determine where additional data must be incorporated to come up with reasonable estimates of vegetation productivity. Ancillary data such as remote sensing derived maps of canopy cover, for example, can be useful in estimating where soil depth is sufficient to support vegetation (something that must currently be prescribed in the model). LAI data for comparison can be derived from remote sensing data. It may also be useful to compare model predictions with vegetation surveys by the KREW team.

Spatial variability in ET. How does the modeled relationship between climate and evapotranspiration vary spatially within study watersheds? How well does model capture seasonal and spatial variation in vegetation water use evident from sap flow sensor measurement? I will use the model calibrated using streamflow, with any improvements associated with LAI comparison above, to estimate spatial patterns of ET and their relationships with peak annual SWE and growing season temperature. Results from this analysis could be used to plan addition instrumentation associated with vegetation water use. There should also be a linkage with spatial soil moisture and sap flow.

Nutrient export. How well does RHESSys modeling capture streamflow nitrate export signatures, including seasonal patterns and differences between the watersheds? Can these signatures be used to better constrain model hydrologic parameters? Given that these are fairly "clean" streams this question may not be that informative but is needed as a baseline model run. There may be other tracers that can be used to as part of biogeochemical calibration? Explore this with Fengjing and Carolyn, who are working on 3 papers.

Biogeochemical stores and fluxes. How well does the current model predict dynamics evident in plot scale measurements of biogeochemical stores and fluxes including plot sampling of soil carbon and nitrogen stores, flux tower estimates of NEP and ET etc. Note that it is unlikely that a model that is parameterized based on fairly coarse-scale data (10-m DEM etc.) will be able to accurate estimate point scale measurements of something like soil decomposition rates or soil moisture. There are several options – if there are sufficient, and stratified, samples – then comparison between sample means and modeled data may be reasonable. Alternatively, we can use intensively monitored sites to fully parameterize the model – and test whether, given these parameters the model performs as expected. For example, do equations used to estimate decomposition rates perform well if we assign temperature, moisture and soil carbon and nitrogen stores. Any adjustments based on this detailed analysis can them be incorporated in the model and would improve larger (watershed) scale distributed estimates. Suggestions from ecologically oriented Co-PIs on how this might best be done welcome.

Spatial patterns and aggregation of biogeochemical fluxes. Given model estimates of spatial patterns of these biogeochemical fluxes (NPP, NEP, Nexport, nitrification/denitrification) how representative (in a spatial sense) are these plot measurements likely to be– how reflective are they of basin scale aggregate carbon and nitrogen fluxes. How do model estimates of aggregate basin and spatial patterns of biogeochemical fluxes (nitrate export, carbon sequestration) change as assumptions about vertical and lateral hydrologic connectivity change? This final question is I think is in many ways the most interesting one from a modeling perspective and will be the place where we can use model-measurement relationships to try to say something about the role of flowpaths, macropores, upland-riparian connectivity etc. . Understanding the hydrologic function of the subsurface critical zone is a key challenge – the model provides a mechanistic way of exploring the implications of different conceptual and quantitative models of subsurface hydrology. Measured data can be used to try to suggest which of these different models is realistic.

Funding. Largely CZO.

<u>Schedule, including field work.</u> The first 2 tasks are for year 1.
<u>Manuscripts in progress & planned.</u> Tasks 1-2 will yield 2 manuscripts. The main data sets needed for tasks 1-2 are the streamflow and meteorological data from KREW, the GIS data and soils information.

Topic: **Near-surface soil-water processes**
Updated 2010

Investigator: **Jan Hopmans, UCD**
Students & research staff. The following lab personal have worked on the project.

a. Total hours contributed < 160
Tamir Kamai (Graduate Student) – Datalogger programming and instrument calibration
Gerard Kluitenberg (Visiting Scientist) – Field installation
Toby O'Geen (Collaborator) – Pedology
Dylan Beaudette (graduate student) - Pedology

b. Total hours contributed > 160

Armen Malazian (Graduate Student) – Field installation and instrument calibration.
Paolo Nasta (Postdoc) Field installations, lab work and modeling
Peter Hartsough (Postdoc) – Experimental design, implementation and maintenance
Sara Enders (Graduate Student) – Field sampling
Katya Roudneva – Field and Lab Technician
Jennifer Storch – Field and Lab Technician
Eric Hoang – Field and Lab Intern

Scope.

Progress 2008-2010

In August 2008 we instrumented a white fir (*Abies concolor*) tree (CZT-1) in the SSCZO with soil moisture, temperature, matric potential (MPS) sensors and tensiometers. We placed the sensors in a radial array around the tree to capture the changing dynamics of the water content across the growing season and through the winter season (Figure 1). The tree is located within the Kings River Experimental Watershed (KREW), at an elevation of 2018m. The tree itself was also instrumented with sap flux sensors and time domain reflectometry (TDR) for determination of changes in stem water content. Ninety soil sensors are spread over a spatial array at 30 cm depth and also distributed across 6 vertical pits to a depth of 90cm. Collocated within this plot are four water balance clusters (UCM pits) consisting of additional soil moisture measurements, snow depth and solar radiation. All sensors are autonomously powered (solar panels) and use radio transmission to the P301 Flux tower. From there, data is transmitted by cell modem to UC Davis. Also installed on the CZT-1 site was a camera to monitor changes in snow depth (Figure 2).

Two summers of data show very dry soil conditions at summers end, typical of the Mediterranean conditions at the site. Winter precipitation arrived in December in the form of snow. Moisture conditions in the soil soon reached field capacity (Figure 3), after precipitation and snow melt events. The snowmelt patterns are captured in a time lapse video (http://hopmans.lawr.ucdavis.edu/nsf_czo_experiments.htm). Soil temperature data show that the shallow (15cm) sensors are responding to diurnal fluctuations in air temperature (Fig. 4). Under dry soil moisture conditions, the soil temperature typically decreases with soil depth, whereas in the winter months the soil temperature profile is inverted with the highest temperatures at the larger soil depths. During short periods of snow melt, soil temperature is largely independent of soil depth because of infiltrating melt water.

Soil water storage was estimated by integrating soil moisture profile depth (Figure 5). Using total soil moisture storage (cm) values, tree transpiration rates for the initial 43 day dry period was estimated to be about 0.2mm/day, indicating severe soil moisture stress. The first precipitation of the season fell on 10/4, 3.3cm as measured at the NADP site 2km away. Only approximately half of this rain event was recorded by the soil moisture sensors, with the remainder likely stored in the litter layer and shallow soil above the 15cm sensor. The next precipitation event of 3.7cm on 11/1 increased storage in the upper profile by 2.7cm, perhaps indicating that the lower soil profile was wetted, with changes in soil water storage reflecting precipitation amounts. The following large storm in mid-December falls mostly as snow and the water entering the profile is delayed until melting begins in early January. After the big storms in December and January, there was additional water input into the soil profile, because of soil water drainage after reaching field capacity. The receding limb in the soil water storage plot (Figure 5) is a measurement of the drainage rate out of the profile.

Ongoing research into summer 2010 will involve integrating measurements at the tree, stem water content, sap flux, and stem water potential, with measurements of changing conditions in the subsurface. A Ground Penetrating Radar (GPR) survey was conducted to determine root architecture. Moreover, we will calibrate the soil water potential sensors (MPS) with co-located tensiometers, thereby allowing evaluation of soil water stress and its spatial distribution on tree transpiration. Co-monitoring the tree and the soil across the developing moisture stress conditions of the Mediterranean summer will provide valuable data on the interaction of surface/subsurface water dynamics in a mid latitude alpine forest. Measurements taken at the tree can be scaled up to catchment scale using data from the 50m P301 flux tower adjacent to the plot.

New and Ongoing projects

1. Second Tree Instrumentation

We are currently in the process of instrumenting a second tree at an adjacent site within the watershed (CZT-2). The second instrumented tree is a 20m tall Ponderosa Pine (*Pinus ponderosa*) growing on a 10-15% slope. We selected the second site to better represent some of the thinner and dryer sites within the watershed. The tree is located approximately 300m SW of CZT-1 at an elevation of 2030m, with good southern exposure. The tree is more isolated from surrounding trees and sits on soils that are rocky and generally less than 90cm thick. The soil instrumentation consists of 24 MPS-1, co-located with 24 ECHO-5TE sensors distributed across eight vertical pits, around the critical zone tree and hard wired into a central data logger. Tensiometers were installed in eight locations co-located with the vertical pits at 30-80cm depths. As was done previously, we instrumented the tree with heat pulse sapflux sensors on four sides corresponding to the soil measurements. This site is also wired to a central datalogger located at the tree. From there, the data is sent wirelessly, first to the tower and then on to UC Davis via cell modem.

2. Root excavation

At the end of the 2010 summer, we plan to excavate the root from a tree adjacent to the CTZ-1 to map root structure and location in response to moisture deficit in the soil profile. This tree has been previously characterized using surface geophysical techniques. While we can approximate the spatial distribution of active rootwater uptake, from measurements of soil moisture and water potential around the tree, using an inverse modeling approach, we would benefit from a complete excavation of a tree, to ensure local root architecture and rooting depth. In our monitored tree we have seen the tree switch to water extraction from deeper soil zone or even fractured bedrock as upper layers of soil dried out. Excavation will allow us to confirm the lateral and vertical extent of the root system and provide a better estimate of the area of influence of moisture removal for the tree. We hope to excavate roots down to the saprolite interface, a depth greater than 1m. Soil will be removed using compressed air, leaving roots intact and available for 3-D mapping.

3. Modeling of the Critical Zone Tree

We have developed a quantitative model parameterizing the soil-tree hydrologic system as a dual-porous media, calibrating the reduction of the potential evapotranspiration (through the Jarvis model), and the hydraulic properties of the tree and the root distribution. In this approach, we use a parameter optimization approach to estimate the soil and tree conducting tissues as two interactive independent porous media, each with conductive and capacitive properties that are a function of water potential. The simulations are run using the HYDRUS 2D flow code (Simunek et al., 1999). As data input for the model, we are using measurements made at the tree, meteorological data collected at the P301 flux tower and soil hydraulic properties measured from samples taken adjacent to the tree instrumentation. Data include soil water content and water potential in 3 spatial dimensions in the root zone, tree stem water content and sap flux, canopy water potential, and atmospheric variables such as net radiation, air temperature and humidity.

4.Nitrogen fluxes from soil

See section on Nitrogen fluxes from soil below.

5. Sourcing water accessed by trees using stable isotopes

See section on Nitrogen fluxes from soil below.

6. Depth to bedrock

A soil depth model was built from 57 soil depth observations, collected from the experimental watershed by manual excavation, and a combination of DEM, ASTER, and NAIP data (Figure 6). The model was built using multiple linear regression, with predictor variables selected according parameters that typically affect or are affected by soil depth: surface slope, tree location, and vegetation density. Slope angle was computed from USGS 10 meter resolution DEM data, obtained from the NED website (date). Tree location and vegetation density were approximated with the Normalized Difference Vegetation Index (NDVI), calculated from a ASTER bands 2 and 3n, and the first principal component of a 3-band NAIP scene. The expected non-linear relationship between soil depth and predictor variables was accommodated by generating restricted cubic spline (RCS) basis functions with three knots for each predictor variable. The resulting model accounted for 52% of the variance in soil depth (adjusted r^2), and predictions were characterized by a root-mean squared error (RMSE) of 17.7 cm. Predictions were truncated to the original range of the soil depth measurements (0 to 100 cm), and smoothed with a 5x5-cell mean filter. A revised version of this model that uses a larger dataset of soil depth measurements is in development.

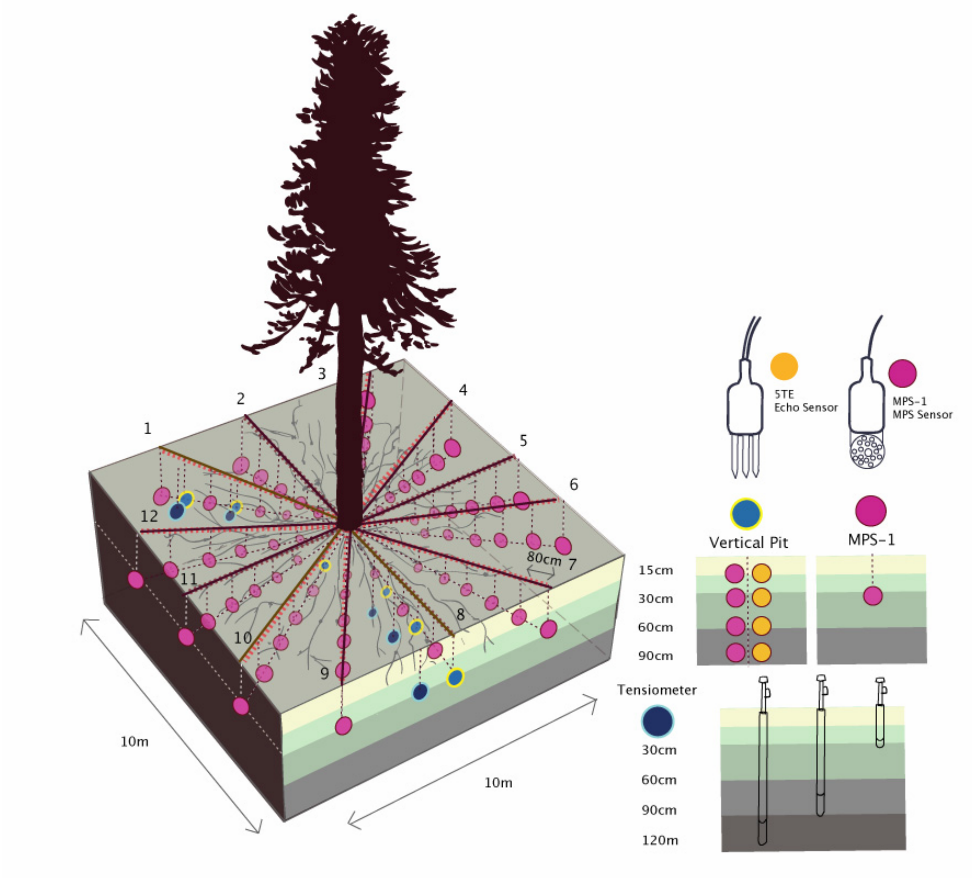

Figure 1. Site Layout showing radial array of soil sensors and locations of vertical pits and tensiometers at CZT-1.


Figure 2. CZT-1 instrumentation

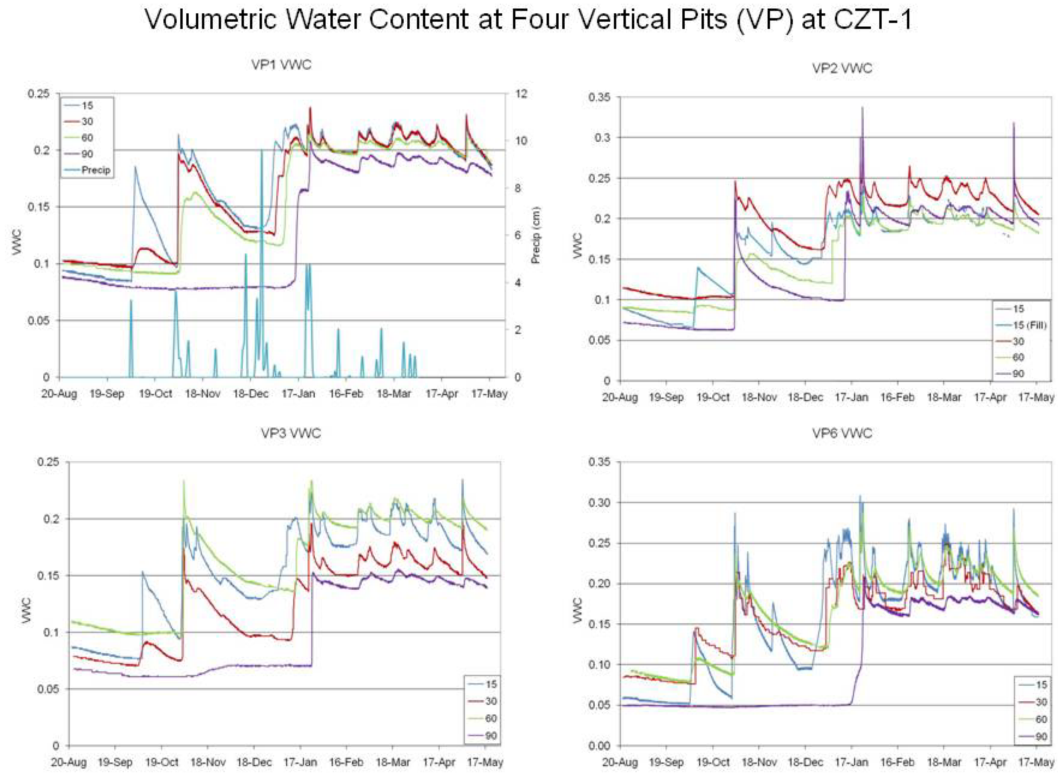

Figure 3. Distribution of soil moisture across four vertical pits. All pits show extremely dry conditions in late summer, even at the 90cm soil depth. Soil profiles are increasing in soil water content, in response to precipitation starting in October and reach field capacity during snow melt in December/January.

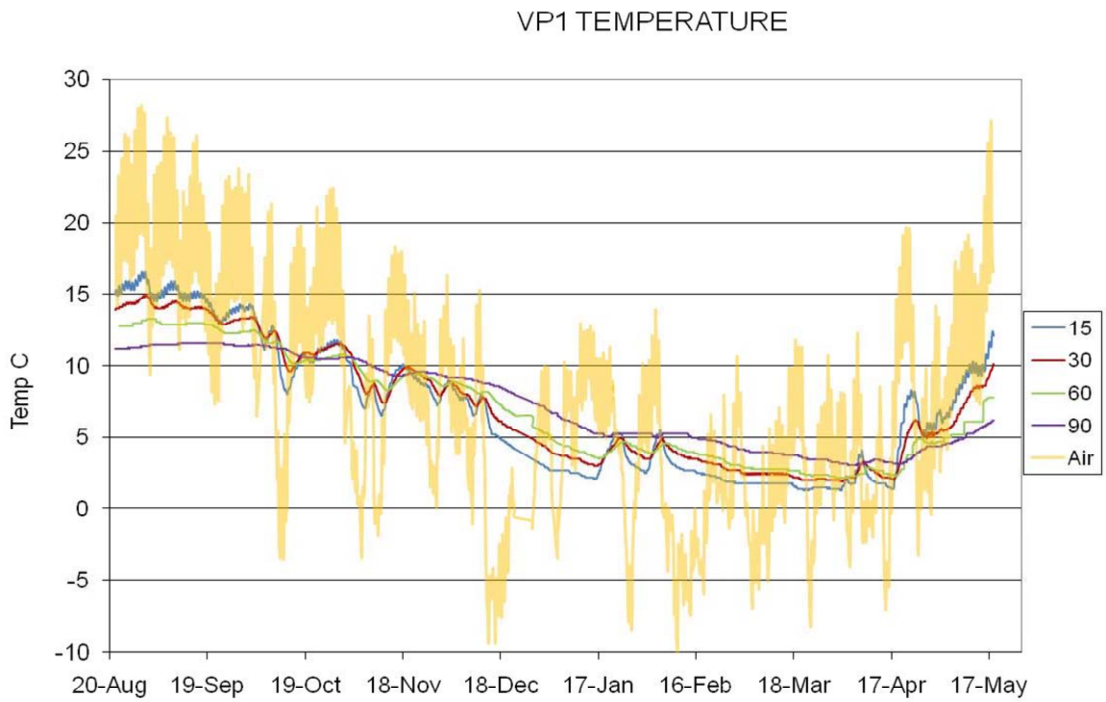

Figure 4. Soil Temperature profile in a representative vertical pit (VP-1). Soil temperature stay above freezing for the entire winter, despite air temperatures falling well below freezing. The shallow (15cm) sensor responds to diurnal fluctuations while the deeper soil temperature are attenuated. During periods of snow cover, soil temperature increases with soil depth. Soil temperature is almost depth independent during melting periods, because of infiltrating cold snow melt water.

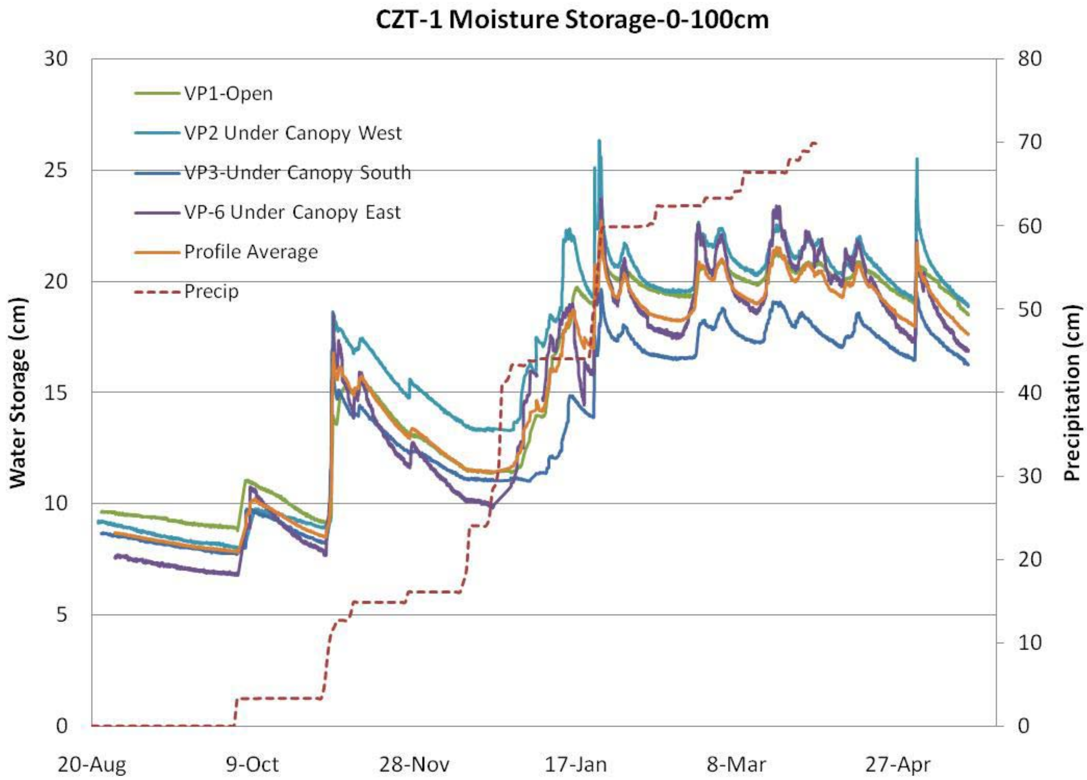

Figure 5. Soil Moisture Storage in the upper 1m surrounding the CZT-1 for summer 2009. Moisture loss from the profile during the initial dry period shows a very low ET rate of 0.2mm/day indicating very little water removed from the upper 1m of the profile. After the big storms in December and January, there is little net change in water stored in the profile for the rest of the winter, indicating soil drainage and lateral water flow downslope contributing to stream flow.

Funding, CZO, with significant leveraging from ongoing NSF Biocomplexity award 0410055-Development of multi-functional heat pulse probe for ecological and hydrological monitoring of plant root zones. Soil moisture sensors will be purchased as part of instrument cluster grant.

<u>Schedule, including field work</u>. On going.

<u>Manuscripts in progress & planned</u>

Kizito, F. C.S. Campbell, G.S. Campbell, D.R. Cobos, B.L. Teare, B. Carter, and J.W.Hopmans. 2008. Frequency, electrical conductivity and temperature analysis of low-cost moisture sensor. J. Hydrology 352:367-378. DOI:10.1016/j.jjhydrol.2008.01.021

Malazian, A., P.C. Hartsough, T. Kamai, C.S. Campbell, D.R. Cobos and J.W. Hopmans Evaluation of MPS-1 soil water potential sensor. J. of Hydrology. (Submitted)

Nasta, P., S. Huynh, and J.W. Hopmans. Simplified Multistep Outflow method to estimate unsaturated hydraulic conductivity for coarse-textured soils. Soil Science Society America Journal. (Submitted)

Hartsough, P.C., A. Malazian, E. Roudneva, T. Kamai, P.Nasta and J.W. Hopmans Monitoring of Critical Zone Processes in a Southern Sierra Nevada Ecosystem (in preparation)

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Topic. **Physical controls on water and carbon exchange and plant production**
Updated 2010

Investigator. **Mike Goulden**, UCI

Students & research staff. **Anne Kelly** (PhD student, UCI); **Greg Winston** (Specialist, UCI)

Background and rational

Our research focuses on the bi-directional interactions between ecosystem function and water balance. The local water balance helps control vegetation type, density, and function through the effects of drought on primary production, plant establishment, mortality, and physiology. The vegetation within an ecosystem helps control the local water balance through the effects of plant physiology and vegetation density on evapotranspiration, snow melt, and soil development. We hope to mechanistically understanding all these interactions, with the long-term goal of determining how climate change will impact montane vegetation, and how changes in vegetation will impact water balance.

Activities

Continuous micrometeorological measurements

We have deployed and are operating four eddy covariance towers to continuously measure the fluxes of water vapor, energy and CO_2. The sites are deployed along a climate/elevation gradient, which is allowing us to understand how climate influences ecosystem structure and function. The sites were installed in 2008-10, and are expected to operate for ~5 years.

Name	Installed	LATITUDE	LONGITUDE	Jurisdiction	Vegetation
San_Joaquin_tower	July 10	37.10872222	-119.7315611	PSW	Oak/Pine woodland
Soaproot_Saddle	Oct 09	37.03106944	-119.2564306	SNF	Ponderosa pine
KREW_P301_tower	Sept 08	37.06767222	-119.1932167	SNF	Midmontane white fir
Courtright_Road	Oct 09	37.06659722	-118.988475	SNF	Subalpine lodgepole

Ecological measurements at tower sites

We are making a range of measurements at the tower sites to better understand the functioning of the local ecosystems. Ecological measurements at each site include sap flow by ~20 trees using Granier type sensors, litter fall collected in ~50 litter traps, and stem increment by ~100 trees using stainless steel dendrometer bands. These ecological measurements will match up with the tower measurements. For example, wood increment measured by dendrometers plus litterfall provides a measure of above ground Net Primary Production, which can be related to the Gross Primary Production determined by the tower. Similarly, the sapflow measured for all of the trees can be related to whole forest Et measured by the tower. Likewise, the sapflow measured for an individual tree can be related to the stem increment of that tree measured by the dendrometers.

Ecological measurements along elevation gradients

We have established a series of plots at intermediate elevations that are being used to better understand the relationships between elevation and ecosystem function, and also to determine whether the tower sites are representative. The elevation gradient plots are located at 400' elevation intervals from 3600' to 8800' and include detailed observations of species composition, along with litter traps and dendrometers. These observations will allow us to further characterize the relationship between elevation and above ground Net Primary Production. Additionally, the gradient measurements will help us to understand the distribution of the various tree species with elevation, as well as the relative rates of growth between species within an elevation, and the relative rates of growth between elevations within a species.

Funding. NSF instrument cluster grant to Merced; NSF CZO grant to Merced; DOE-PER grant to UCI; approx $200k in instruments purchased by previous grants to UCI.

Schedule, including field work.

Summer 2008-2010 – Winston and Merced collaborators install and operate flux towers. Kelly installs ecological measurements at tower sites and establishes elevation gradient sites.

Summer 2010 and beyond – Kelly conducts PhD research. Towers continuously operated.

Manuscripts in progress & planned. TBD. (include data sets used/needed)

Topic. **Surface-groundwater interactions**
Updated 2010

Investigator. **Martha Conklin**, UCM

Students & research staff. Ryan Lucas, grad student; Reza Ganbhari, Post Doc

Scope. A series of meadow experiments and measurement campaigns have been completed or are in progress.

Groundwater exchange in Long meadow. The objective of this experiment is to determine variations in diel temperature change, inflow and outflow of groundwater into the stream, quantify interactions between vegetation and water, and understand the water balance and hydrologic processes in Long meadow, Sequoia NP. In our initial campaign, we will exploited temperature as a hydrologic tracer using a distributed temperature sensor (DTS) and Tidbits, plus use data from piezometers and observation wells (temperature and pressure). The DTS system includes a computer, two 1-km long fiber optic cables and a power source. The DTS system provided stream temperatures with high resolution and high accuracy over the length of the stream for a duration of 5 days. The DTS deployment led to the observations of polymictic pool behavior in the meadow pools. This daily thermal stratification and nightly was further assessed in 2008 and 2009 using Hobo Tidbit temperature loggers, for vertical temperature profiles, and Radon-222 analysis. These data were used in constructing a 2-D model in Fluent, a fluid dynamics equation solver.

In addition to temperature and geochemical tracer activities, evapotranspiration (ET) and ground water level and pressure head measurements have been collected in 2008, 2009, 2010. ET was measured at discrete points in space and time utilizing an ET chamber. These chamber measurements were compared to calculations of ET, calculated using groundwater level data and the White equation, and PET, calculated using meteorological data and the Penman-Montieth equation.

Monitoring well and piezometer analysis have shown that much of the meadow remains saturated well past senescence of the meadow vegetation—soil moisture data from this area indicates that the mineral soil on the surrounding hillslopes is very dry in the late summer early fall. This indicates that there is significant sub-surface water contribution well past snow melt. We think that much of this contribution is from sap rock through flow of the surrounding area. In order to better understand the link between saprock through flow from the adjacent hillslopes and the meadow hydrology, up to 3 sap rock piezometers will be installed in Long Meadow. These piezometers will be screened in the sap rock complex below the mineral soil.

Groundwater exchange in P301 meadow. Most of the wells and piezometers have been installed in the P301 meadow. In addition to the initially planned wells/piezometers, we installed, in summer 2010, three sap rock piezometers. These range from 205 to over 500 cm in total depth and 40-400 cm of screened casing in the sap rock complex. We also installed one stilling well in the stream between the middle and lower meadows; we will install one more stilling well below the lower meadow. All told ther will be 24 monitoring wells, stilling wells, piezometers, and sap rock piezometers installed in the P301 meadow complex.

ET chamber measurements commenced in June 2010 and will continue Fall 20101 and before, during, and after meadow vegetation growing season 2011. ET will be calculated from ground water level monitoring wells using the White method and PET will be calculated using the nearest meteorological data. We would like to compare these measurements and calculations with ET measurements being collected at the nearby P301 flux tower.

Salt dilutions have commenced at the installed stilling well. These will continue in the fall 2010 and recommence after snow melts 2011. Salt dilutions will be start at the second stilling well once it is installed. Salt dilution activities will continue until enough data is collected to establish a sufficient rating curve.

Funding. Largely CZO.

Schedule, including field work. field work in both meaows is ongoing. Saprok pieaometers will be installed in Long Meadow in fall 2010. Total station surveys of both meadows will be completed in fall 2010 or spring 2011.

Manuscripts in progress & planned. TBD. (include data sets used/needed)

Topic.

Spatial variability in the KREW watershed: Effects on nutrient cycling and water quality

Updated 2010

Investigator. **Dale Johnson**, UNR

Students & research staff. Cassandra Woodward, MS student

Scope. (updated 8/22/08) After reconsideration of project priorities/budgets, and consultation with the other investigators, the work plan has been modified from the original plan to manipulate snowpack duration to one that focused on spatial variability in nutrients on several scales and a pilot study to investigate the potential for inconspicuous, nutrient-laden runoff, as seen frequently in the eastern Sierra Nevada. The new work plan consists of four basic components: 1) analysis of soil samples taken from a gridwork across the entire watersheds; 2) a pilot study of runoff in selected locations, 3) an analysis of spatial variability in nutrient availability in the scale of meters or less, and 4) measurement of resin-based fluxes of N and P in conjunction with detailed soil moisture measurements being made by other investigators in the project.

Analyses of soils from the KREW grid. On the broadest spatial scale, funding from this project has allowed the analysis of soils taken from 87 grid points on the KREW watersheds, which, along with data laboriously collected in quantitative soil pits at these grid points, were converted soil nutrient contents to a kg ha^{-1} basis. As of this writing, A paper on this data has been submitted to Geoderma, sent back for revision, and revisions have been submitted (Johnson et al., in revision). We await final work on acceptability of the revision. Results showed that Bull watersheds had significantly greater C, N, and B contents and significantly lower extractable P, exchangeable Ca^{2+} Mg^{2+}, and Na^{+} contents (kg ha^{-1}) and lower pH than the lower elevation Providence watersheds. Soil NH_4^+ and mineral N contents were high in both the Bull and Providence watersheds and could not be related to any measured soil property or attributed to known rates of atmospheric deposition. Nutrient analyses on satellite samples were comparable to those taken from pits when averaged on a watershed or site (Bull and Providence) scale, but quite variable on an individual grid point basis. Elevated Zn values from the quantitative pit samples suggested contamination by field sieving through a galvanized screen. Had the amount of large rocks within the soil sample not been accounted for with quantitative pit analyses, estimates of fine earth and associated C and nutrient contents (kg ha^{-1}) would have been overestimated by 16 to 43%.

This data will not only allow us to place results of the more intensive studies described below into context for the CZO project, but also allow USFS researchers to place the results of several years of nutrient flux data collected with resin lysimeters (Susfalk and Johnson, 2002). The data for soil and rock mass from the quantitative pits has also been shared with Cliff Riebe for his analysis of historical erosion regimes.

Runoff and meter-scale measurements of spatial variability in nutrients. Forests in the KREW watersheds are similar in many ways to those in the eastern Sierra Nevada (see text box for background), including hydrophobicity of mineral soils in summer and lack of rooting in O horizons in many forests. Thus, we hypothesized that:

1. Runoff through the O horizons over the mineral soil will occur in KREW watersheds, as it does in eastern Sierran ecosystems;
2. Runoff will have high concentrations of inorganic N and P, as in the eastern Sierran ecosystems; and
3. Infiltration of nutrient-rich runoff into preferential flowpaths will create hot spots of nutrient availability in O horizons and mineral soils.

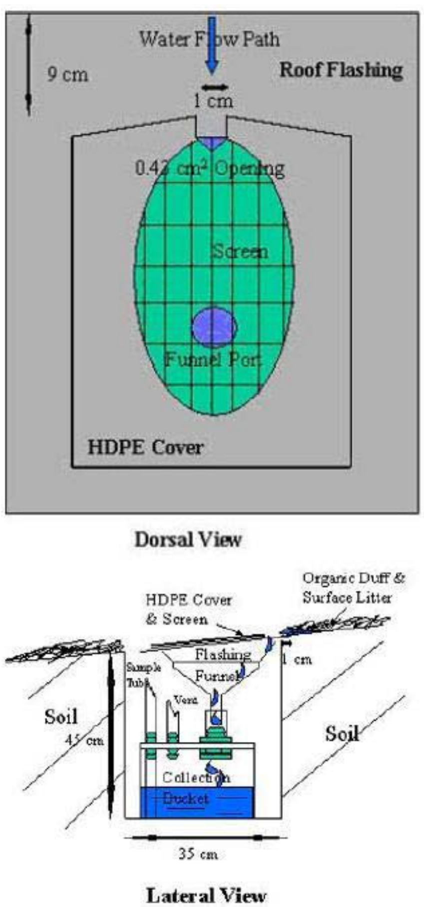

Figure 1—Schematic of runoff collector

In order to test these hypotheses, we are conducting a pilot study which includes runoff collections (Figure 1) and a resin-based study of small-scale spatial variability in O horizon and soil nutrient levels at two sites in the KREW/CZO system: 1) the upper meterological station and 2) Prenart lysimeter site P301. These sites were chosen because 1) they have now or soon will have a substantial amount of ancillary data to compare these results with and 2), of equal importance, they will be accessed frequently during the snowmelt season where frequent sampling of runoff collectors will be necessary. This pilot study includes three runoff collectors at each site and one 6 x 6 m plot within which resin-based nutrient sampling to investigate the possibility of hot spots will be conducted. For the 2008-2009 snow season, twenty-eight grid points in the latter plots have been instrumented with Plant Root Simulator (PRSTM) anion- and cation exchange membrane probes (Western Ag Innovations, Inc) and Unibest mixed bed resin capsules, both places within the O horizon. The gridpoints include 16 on a 2 x 2 m interval and 12 additional grid points in the 12 central 2 x 2 m plot which are placed at a 0.67 x 0.67 m interval, this allowing us to examine spatial variability at two scales (Figure 2). Results from this first year study are being written up for publication, and include the following highlights. First, O horizon interflow runoff does indeed occur at the KREW watersheds and is enriched in nutrients, as is the case in the eastern Sierra Nevada. Secondly, There is ample evidence of nutrient hotspots not only for ammonium and nitrate, but also for ortho-P, K, Ca, and Mg in the plots established in year 1. We found that hotspots for water-extractable cannot be attributed to any traditional measure of soil nutrients, but do resember the chemical characteristics of runoff waters. We hypothesize that these water soluble hotspots are in fact preferential flow paths into which nutrient rich O horizon inteflow enters. For the 2009-2010 snow season, we changed the design somewhat: the new plots had 16 gridpoints, and at each grid point four resin capsules and four resin stakes were installed. Two of the four were removed just after the first precipitation event in the fall of 2009, and the remaining two were removed in June 2010 after snowmelt. With this design, we hope to obtain temporal information on the hot spots (hot moments) that we know occur in these systems. The 2010-2011 plot layout will differ somewhat in that we have installed resin lysimeters (Susfalk and Johnson, 2002) in one grid and in the second grid, we will install not only stakes and capsules, but also prototypes for resin-based O horizon runoff collectors. Finally, we will install a Decagon soil moisture/temperature/electrical conductivity monitoring system in the lower (Prenart) site.

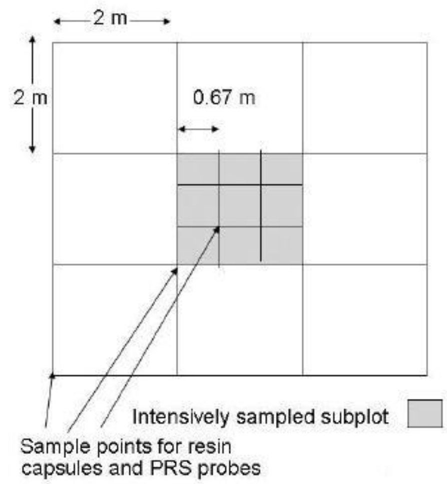

Figure 2—Layout of 6 x 6 m spatial variability plots. A PRS probe and resin capsule was installed at each 2 x 2 m gridpoint in the main plot and also at each 0.67 x 0.67 m gridpoint in the center 2 x 2 m subplot.

Background on spatial variability in nutrients

The measurements of runoff and (sub)meter-scale variability in nutrient availability are closely conceptually linked and therefore are described together. By way of background, Schimel and Bennett (2004) built upon the hot-spot and hot-moment concept described by McClain et al (2003) and others and posed a new paradigm for plant-microbial competition where trees can effectively compete with soil microbes by invading N-rich microsites (hot spots) that exist at least temporarily (hot moments) even in relatively N-limited conditions. Roots, with their elongated structure and exploratory habit can presumably tap into these hot spots and hot moments, and thereby might effectively mine the soil for N over time.

We have found that hot spots and hot moments are characteristic of nutrient cycling in Sierran ecosystems (Johnson et al., in press). However, we also believe that the new paradigm posed by Schimel and Bennett (2004) for plant-microbial competition is moot for the many Sierran forest ecosystems. Because of the extreme summer drought, rooting is often entirely absent in the forest floors Sierran forests; thus, decomposition and vegetation uptake processes are spatially discoupled, and the intense competition for N between roots and decomposers which characterizes the more humid forest soils is absent. Because of this vertical discoupling, nutrients released during decomposition in O horizons are not immediately taken up and can be solubilized by rain or snowmelt to create solutions with very high inorganic N and P concentrations. Miller et al. (2005, 2006) have installed runoff collectors at the O horizon – mineral soil interface at many sites throughout the eastern Sierra Nevada and found that, contrary to common textbook knowledge that runoff in forest ecosystems in minimal, runoff over the mineral soil and through the root-free O horizon and over the top of the mineral soil is very common, not only during snowmelt when soils may be saturated but also during summer storms when mineral soils are extremely hydrophobic. Not only is runoff routinely collected, but concentrations of ionic N and P in these solutions are often extraordinarily high, including NH4+ (concentrations as high as 87 mg N L-1) and ortho-P, (concentrations as high as 13 mg P L-1), ions that are strongly adsorbed to mineral soils and are therefore found in very low concentrations in soil solution only a few cm deeper into mineral soil. We believe that these high concentrations of ionic N and P are a result of mineralization of N and P in the O horizons, and because rooting is absent in the O horizons mineralized N and P is not taken up as it would be in more mesic ecosystems. We also believe that fire exclusion over much of the 20th century in these systems has resulted in litter buildup that has provided an increasing source of nutrients in this runoff, perhaps contributing to the well-documented deterioration of water quality in nearby Lake Tahoe (Goldman, 1981; Miller et al., 2005, 2006). We are not as yet able to precisely quantify the area from which this interflow runoff is generated nor can we pinpoint where it infiltrates. We hypothesize that this interflow could be a major factor in the creation of hot spots if it enters into the mineral soil via preferential flow paths (Burcar et al., 1994a), or alternatively could be a significant source of mineral N to streams, perhaps contributing to the peaks in mineral N concentrations that are sometimes seen during cycles of snowmelt runoff (e.g., Johnson et al., 1998).

Table 1. Schedule of Activities

<table>
<tr><td colspan="5">2008-9</td><td colspan="4">2009-10</td><td colspan="4">2010-11</td></tr>
<tr><td>Activity</td><td>Sum</td><td>Fall</td><td>Win</td><td>Spr</td><td>Sum</td><td>Fall</td><td>Win</td><td>Spr</td><td>Sum</td><td>Fall</td><td>Win</td><td>Spr</td></tr>
<tr><td colspan="7">Analyze KREW soils for C, N, NH4, and NO3</td><td colspan="6">X</td></tr>
<tr><td colspan="7">Analyze KREW soils for other nutrients</td><td colspan="6">X</td></tr>
<tr><td colspan="7">Establish and instrument plots</td><td colspan="6">X</td></tr>
<tr><td colspan="5">Collect data</td><td colspan="4">X</td><td colspan="4">X</td></tr>
<tr><td colspan="3">Analyze data</td><td colspan="4">X</td><td colspan="3">X</td><td colspan="3">X</td></tr>
<tr><td colspan="5">Prelimnary analysis and reports</td><td colspan="4">X</td><td colspan="4">X</td></tr>
<tr><td colspan="5">Re-evaluate and modify designs and re-install equipment for subsequent years</td><td colspan="4">X</td><td colspan="4">x</td></tr>
<tr><td colspan="7">Final report and publication</td><td colspan="6">Begin in spring, continuing to summer & fall 2011</td></tr>
</table>

Measurement of resin lysimeter fluxes in conjunction with detailed soil moisture measurements. The KREW project as well as many others in the eastern Sierra Nevada mountains (Murphy, et al., 2006 a and b) and elsewhere (Johnson et al., 2003; Kjonnas 200x) use resin-based lysimeters as cheap and low-maintenance method of measuring nutrient leaching fluxes. The resin-based methods rely on the ability of resins to capture nutrients that can later be extracted, and, with measurements of the lysimeter collection area, converted to a kg ha-1 flux. While resin-based flux measurements are cheap and convenient, they provide no information as to the relative contributions of water flux and nutrient concentrations in soil solution to the total fluxes measured. Thus, we have installed resin lysimeters of the design described by Susfalk and Johnson (2002) near the “tree” for the last three years now to compare our leaching results with the very detailed measurements of soil moisture are being made there. Specifically, we have installed resin lysimeters at the outer perimeter of 10 of the 12 “spokes” of the wheel of sensors installed around the “tree”. These lysimeters are removed (and replaced) and extracted after snowmelt to see of the fluxes correspond to any indicators of soil moisture status made in the nearby collectors.

Funding. CZO

Schedule, including field work. We have started this research in the August of 2008. After a winter season of data collection, we will evaluate protocols and designs, modify as needed, and re-install equipment during the following summer seasons. The intent is to not only capture data worthy of publication in its own right, but also to continue to refine and develop sampling techniques most suitable for nutrient work in snow-dominated Sierran ecosystems.

Manuscripts in progress & planned:

Johnson, D. W., Glass, D. W., Murphy, J. D., Stein, C. M., Miller, W. W. Hot Spots and Hot Moments: Another Look at Nutrient Variability in Sierra Nevada Forest Soils. *Biogeochemistry* (in press)

Johnson, D.W., Hunsakeer, C.F., Glass, D.W., Rau, B.M., Roath B.A. Carbon and Nutrient Contents in Soils from the King's River Experimental Watershed, Sierran Nevada Mountains, California. Geoderma (submitted and returned after revision)

Johnson, D.W., W.W. Miller, B.M. Rau, and M. W. Meadows. Spatial Nutrient Variability in a Sierran Forest Soil: an Investigation into the Nature and Potential Causes of Nutrient Hot Spots. In prep for Soil Science Society of America, Journal.

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Johnson, D. W., Glass, D. W., Murphy, J. D., Stein, C. M., Miller, W. W. Hot Spots and Hot Moments: Another Look at Nutrient Variability in Sierra Nevada Forest Soils. *Biogeochemistry* (in press)

Johnson, D.W., P. J. Hanson, D.E. Todd, Jr. 2002. The effects of throughfall manipulation on soil leaching in a deciduous forest. J. Environ. Qual. 31: 204-216

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Miller, W. W., D.W. Johnson, T.M. Loupe, J.S. Sedinger, E.M. Carroll, J.D. Murphy, R.F. Walker, D.W. Glass. 2006. Nutrients Flow from Runoff at Burned Forest Site in Lake Tahoe Basin. California Agriculture/University of California, 60: 65-71.

Murphy, J.D., D.W. Johnson, W.W. Miller, R.F. Walker, and R.R. Blank. 2006a. Prescribed fire effects on forest floor and soil nutrients in a Sierra Nevada ecosystem. Soil Science 171: 181-199.

Murphy, J.D., D.W. Johnson, W.W. Miller, R.F. Walker, E.F. Carrol, and R.R. Blank. 2006b. Wildfire effects on soil nutrients and leaching in a Tahoe Basin watershed. Journal of Environmental Quality 35: 479-489.

Schimel, J.P., and J. Bennett. 2004. Nitrogen mineralization: Challenges of a changing paradigm. Ecology 85: 591-602.

Susfalk, R.B., and D.W. Johnson. 2002. Ion exchange resin based soil solution lysimeters and snowmelt collectors. Comm. Soil Sci. Plant Anal.33: 1261-1275.

Topic. Nitrogen fluxes from soil
Updated 2010
Investigator. Ben Houlton, UCD
Students & research staff. Sara Enders (PhD student)
Scope. We will use natural nitrogen (N) isotopic variations in dissolved inputs, soils and stream waters to examine the dominant vectors of N inputs and losses from forested watersheds across an elevation gradient to compare processes at higher and lower elevation watersheds, across the rain-snow transition. Isotope mass-balance approaches are especially useful for modeling hard-to-measure gaseous N fluxes, such as loss via denitrification.

Since microbial denitrification strongly fractionates N stable isotopes, the $^{15}N/^{14}N$ ratio of streamwater N is elevated relative to N inputs when this process is important. We will also use measures of O isotopes in nitrate to further examine gaseous N production in soils and streams. For example, our previous work indicates that denitrification elevates both the $^{18}O/^{16}O$ and $^{15}N/^{14}N$ of nitrate, imparting a slope ~0.6 on these isotope systems. In combination, these isotopic measurements will be used to inversely model N gas fluxes across snow vs. rainfall dominated forests.

For sampling, 8 first order streams in Providence (3) and Duff (1) catchments and Bull (3) and Teakettle (1) catchments will be measured monthly for TN, DIN, and $\delta^{15}N$ and $\delta^{18}O$ of NO_3^- and DON to identify temporal patterns in N isotopes in losses. We will monitor the $^{15}N/^{14}N$ and $^{18}O/^{16}O$ of N deposition inputs based on collectors established at various locations within the watersheds or proximate, such as NADP site CA28. We will measure the isotopic composition of N in plant leaves and soils, and combine these measures with input-output analyses and models to construct budgets of the N cycle. Archive stream, soil, litter, and precipitation samples will additionally be analyzed as available. Finally, we will monitor δD and $\delta^{18}O$ of stream waters at catchment outlets to complement current understanding of rain vs. snow contributions to the hydrology of respective catchments.

Nitrogen isotopic modeling. Combining the isotopic information collected across the various scales of sampling, we will use N budget models such as DAYCENT and DNDC, and integrate N data to integrate with RHESSys to further constrain the flux of N inputs and losses from the watersheds.

Funding. Funding is largely CZO, through Hopmans, with leveraging from UCD.

Schedule, including field work. We began collecting preliminary stream, soil, and foliar samples in July, 2010. An intensive mid-canopy foliar sampling is planned for early September, 2010, in which sun leaves will be accessed by shotgun. Sampling will then intensify over the next two years, shaped by our preliminary findings.

Manuscripts in progress & planned: TBD.

Topic. **Baseline hydrologic, sediment and geochemical characterization**
Updated 2008

Investigator. **Carolyn Hunsaker**, PSW

Students & research staff. Tom Whitaker, Fengjing Liu, others TBD

Scope. Although this work is part of PSW's original KREW project, doing it is essential to progress on CZO research and one or more of the CZO investigators will assist as needed.

Hydrologic characteristics. Elevational transition of mixed rain/snow to snow, seasonal transitions, snowmelt to baseflow, time lags in the system, seasonal responses to precipitation.

Sediment. Analysis of sediment data from sediment ponds, turbidity, sediment fences, headcuts and bank pins. Also modeling.

Geochemical characteristics. Annual cycle of geochemistry, sources of streamflow across catchments, flow paths result in chemical differences, seasonality of streamflow sources. Can mixing models help us determine if KREW is over sampling (frequency), identifying important nutrients to sample for?

Funding. Leveraged, PSW.

Schedule, including field work. Ongoing. Goal is to complete as much related to papers 1-6 during 2008 as possible. Field measurements will continue.

Manuscripts in progress & planned.

1. *Hydrologic response of rain-snow transition and timing of snowmelt and streamflow*. Whitaker and Hunsaker (Bales assist). Uses daily/hourly discharge data, temperature data from met stations, precipitation data.
2. *Sediment basin, turbidity & suspended sediment*. Hunsaker and Whitaker. Annual measurements from sediment basins and continuous turbidity data.
3. *Sediment budget for Providence*. Hunsaker & CSU/UCM collaborators. Need paper 2 plus MS thesis results from Sarah & Abby.
4. *Geochemical response across rain-snow transition: ions, pretreatment – system characterization – gradients in system*. Hunsaker and Liu. Use ion data, 2002-2006; build on first paper 1.
5. *Sources of stream water across rain-snow transition – streamflow generation*. Liu and Hunsaker. Use EMMA, diagnostic tools of mixing models, ion data. Need sampling of wells first.
6. *Nutrient response to streamflow sources; nutrients as reflection on biological activity*. Hunsaker and Liu.

Topic. **Water, geochemical cycles, and upscaling of in-situ measurements**
Updated 2008

Investigator. **Roger Bales**, UCM

Students & research staff. Peter Kirchner, PhD student

Scope. In cooperation with KREW researchers, we will estimate components of the water and geochemical cycles in the Providence catchments, as noted above. Parallel observations will take place at the Wolverton watershed of Sequoia National Park for cross comparison between the rain snow-transition and snow-dominated ecosystems.

Patterns of snowcover and soil moisture. It is our hypothesis that spatial variations in tree canopy cover are as important as slope and aspect for variability in snowcover and soil moisture. An implied hypothesis is also that soil moisture patterns will be influenced by patterns of snowcover accumulation and depletion in a predictable manner (the Hydrus 1D model will be used to aid in interpretation of soil moisture data). Soil moisture measurements will also help to discriminate snow versus rain. Our spatially dense measurements of snow depth and soil moisture are placed to capture the variability in physiographic features and vegetation across the catchments as part of our core measurement program. Radiation will be quantified by using a combination of insitu sensors and a portable canopy imager such as the CI-110 by CID, Inc. We will also place tidbit temperature loggers on grid and ordinal patterns in key locations to provide a mesoscale record of snowmelt. It is also thought that soil moisture and ET respond systematically to differences in water inputs and energy balance along gradients of elevation and aspect. That is, distributed system responses to seasonal transitions, changes in soils and vegetation, and longer-term climate changes are predictable based on physiographic features and soils/vegetation characteristics. However, within those gradients, heterogeneity caused by differences in bedrock and vegetation not captured by modeling will limit that predictability.

Upscaling of forest snowcover and soil moisture distribution. Scaling depends to some extent on how well distributed measurements capture the inherent variability across a catchment. The high frequency and spatially dense core measurements will provide the basic data for this. Synoptic measurements conducted at mesoscales will provide the ability to bridge these high-frequency data to larger scales. Synoptic surveys of snow soils, and bedrock using non-invasive geophysical methods, will be used, to characterize the snow covered area and the vadose zone on a broader spatial scale. These findings will provide a basis for linking our high frequency temporal measurements with high spatial resolution satellite images.

Evapotranspiration. In addition to flux tower and sap flow measurements, we will examine ET by analysis of diel variations in streamflow across seasons following the approach outlined previously by J. Kirchner. In addition to data analysis, we will use the RHESSys watershed model to integrate data, investigate partitioning between ET and streamflow, and predict watershed behavior, as noted above.

Geochemical processes. It is our hypothesis that the distribution of soil moisture throughout the catchments controls the extent of coupling among the carbon and nitrogen cycles, as well as the weathering and mobility of ions. Because soils beneath the snowpack normally remain moist and unfrozen, snow-dominated sites will have higher rates of litter decomposition, nutrient cycling and solute production compared to rain-dominated sites, where soil drying limits decomposition and weathering rates and thence coupling (this is not explicitly planned to be part of P. Kirchner's dissertation).

Funding. Largely CZO.

Schedule, including field work Ongoing. Core instrumentation in the Wolverton watershed was completed in 2007. Mesoscale surveys of snow distribution, and soil moisture were conducted in 2007 and 2008 and will continue through 2009. Real-time communication links with data loggers are planned for late 2008.

Manuscripts in progress & planned.

1. Hydrologic response of snowmelt, streamflow, and evapotranspiration in a snow dominated forested catchment. Kirchner, Bales. Uses CZO core measurement data from the Wolverton watershed: discharge, meteorologic parameters, snow depth, precipitation, soil moisture, and sap flow. Water chemistry data collected 2006-present will also be used.
2. Snow accumulation and melt distribution in forest ecosystems. Kirchner, Bales. Uses CZO core measurement data from the Providence and Wolverton watersheds: radiation, snow depth, precipitation, and soil moisture, coupled with synoptic surveys of depth and snow water equivalent and long-term data collected at the snow courses and pillows.
3. Mesoscale representation of snow and soil moisture in forested ecosystems. Kirchner, Bales. Uses same datasets as above in addition to repeated geophysical surveys conducted at target locations throughout the Wolverton watershed. If LIDAR or hyperspectral imagery of the study areas becomes available prior to publication they will be used also.

Topic. **Physical erosion and chemical weathering**
Updated 2010

Investigators. **Clifford S. Riebe**, U Wyoming; **James W. Kirchner**, UCB, WSL, ETH. The base of operations for lab work and analyses will be the University of Wyoming. Analysis of cosmogenic nuclides by Accelerator Mass Spectrometry (AMS) will be conducted at Prime Lab (Purdue University) where we have an ongoing collaboration. Riebe will be the primary investigator and advisor of graduate and undergraduate students. Kirchner will be involved as an advisor throughout the project. **Bryan Shuman** and **Steven Holbrook**, two experts in geophysical methods for shallow subsurface characterization will be involved in advisory roles. CZO investigator **Carolyn Hunsaker** will be involved in interpretation of sediment yield data, collected as part of the core KREW measurement program.

Students & research staff. This work will be conducted over the course of three years and will employ a team of researchers including one Masters student (who will be responsible for the day-to-day operations of the project), and several undergraduate assistants (who will be involved in field and lab work). Update as of August 2010: Riebe has completed two field seasons with his Masters student, **Barbara Jessup** and has had several undergraduates working part time on preparation of samples collected so far.

Scope. A combination of measurements, including cosmogenic nuclide concentrations, a solid-phase mass balance of catchment soils, and shallow (<10 m) geophysical imaging, will be used to (1) document how long-term rates of erosion and weathering vary across the Southern Sierra Nevada Critical Zone Observatory, and (2) test a series of hypotheses about variations in rates of erosion and weathering across a range of spatial and temporal scales. These measurements will be integrated into other elements of the CZO work plan as outlined below.

Comparisons of short-term and long-term rates of physical erosion

To measure long-term (*i.e.*, millennial timescale) erosion rates of the CZO catchments, we will collect stream sediment from each of the CZO catchments for analysis of cosmogenic radionuclides (CNRs) in stream-borne quartz. These measurements will allow us to infer spatially averaged erosion rates for the sediment contributing areas (e.g., Binnie et al., 2006; Granger et al., 1996). Including replicates, and samples from other KREW-monitored catchments to the south (i.e., Bull and Teakettle), we will need to analyze 15 sediment samples for CNR concentrations. Because CNRs accumulate over thousands of years, as minerals are eroded through the upper meter or so of soil to the landscape surface, CNR-based erosion rates reflect long-term averages that can be used as benchmarks for comparison with the present-day (multi-year average) rates that are currently being measured from sediment traps as part of the core-KREW measurement plan. We will need to coordinate extensively with Carolyn Hunsaker in interpreting the data from the sediment traps.

As part of this work, we may be able to assess the importance of fire and post-fire responses by comparing flux measurements in the thinned versus control and the burned versus unburned catchments. However, in light of funding constraints, it remains to be seen whether the thinning and burning experiments will be conducted as planned. If they are, then the long-term measurements based on cosmogenic nuclides will used to test for site-to-site differences in "background" rates of erosion and weathering between the burned and unburned catchments, and thus will be vital for quantifying the effects of burning (the and differences in background rates need to be accounted for in the analysis of short-term fluxes from the treated and untreated slopes).

We envision several plausible outcomes of the comparisons between short-term and long-term rates of physical erosion:

Outcome 1: Episodic erosion dominates. Our working hypothesis, based on a similar study in forested catchments in Idaho (Kirchner et al., 2001), is that the long-term averages from the cosmogenic nuclides will be significantly greater than the short-term averages from the sediment traps. We expect that the sediment trapping record may be too short to incorporate the full effects of episodic erosion from landslides and post-fire erosion; although these erosion events may be infrequent, they are likely to be important contributors to sediment flux over the long term.

Outcome 2: Anthropogenically accelerated erosion dominates. If the effects of episodic erosion are minimal and if land use has accelerated erosion in the recent past, then long-term averages of erosion rates could be systematically lower than the short-term averages. Such a pattern would suggest that anthropogenic factors (e.g., logging or grazing) are important contributors to the modern erosional flux. If this is the case, then it may be reflected in CNR profiles within soil columns; when the surface of a well-mixed soil is stripped away, the CNR profile will be truncated to a degree that reflects the depth of stripping (Granger and Riebe, 2007). Hence, if long-term erosion rates are slower than short-term averages, we should be able to test whether accelerated erosion of the recent past was accompanied by significant stripping of surface soils. This would have important implications for the biogeochemistry of the catchments, because of the tendency of nutrients to be concentrated in the upper levels of the soil profile, which are most prone to stripping. Hence these results should inform interpretation of soil nutrient data collected in other phases of the CZO project (e.g., by CZO Investigators **Dale Johnson** and **Ben Houlton**)

The possibility of soil stripping will need to be investigated in any case, because stripping has the potential to expose material with low cosmogenic nuclide concentrations that do not accurately reflect the long-term, background rate of erosion. To spot check soil profiles, and ensure that their CNR inventories are consistent with measurements from stream sediment, we will need to take an additional 8 samples of soil and saprolite for cosmogenic nuclide analysis.

Outcome 3: Erosion rates are roughly similar across time. If erosion rates are broadly similar at short and long timescales, it may suggest that there is little diversity in erosional processes. For example, it may be that the incremental day-to-day erosion measured in the sediment traps is able to persist steadily over the long term, without significant contributions from episodic erosion or recent anthropogenic disturbances. However, this seems unlikely given the diversity of processes in the catchments today and the history of land use in the region. For example, there are signs within the catchments of diverse processes such as shallow landsliding, headcut erosion, tree-throw, and down-slope creep (via bioturbation and freeze thaw), which should contribute sediment periodically to streams over a range of timescales, both long and short. Moreover, anthropogenic factors are likely to have perturbed erosion somewhat over the recent past. Taken together, anthropogenic factors and the apparent diversity of erosional processes make it unlikely that erosion rates will agree over the cosmogenic and conventional measurement timescales.

The Soil Production Function

The presence or absence of soils in mountainous landscapes reflects the interplay between erosional removal of soil and its production from saprolite at depth (Dietrich et al., 1995). Cosmogenic nuclides in saprolite and soil can help shed light on this interplay (Heimsath et al., 1997). If soil removal exceeds production, soils will become increasingly thin and eventually vanish, leaving exposed saprolite or rock. Conversely, thick sequences of soils can develop if soil production outpaces removal. Soil production and removal may also be balanced such that soil depth remains roughly steady over time.

Whether soils tend to become thinner, thicker, or have steady thickness over time has profound implications for watershed hydrology and biogeochemistry, because bare rock (exposed when soil removal exceeds production) is able to quickly shed meteoric water, whereas a soil with steady or increasing thickness may retain water and thus make it locally available for biogeochemical processes and enhanced weathering. Decades of theoretical considerations (e.g., Gilbert, 1877) and modeling (e.g., Cox, 1980; Dietrich et al., 1995) suggest what field studies (e.g., Heimsath et al., 1997) have only recently been able to confirm—that the rate of soil production in hilly, temperate landscapes may often depend on soil depth. However, recent work by Dixon et al. (2009) suggests that soil production rates do not vary systematically with depth in the CZO landscape. Instead, the rate of soil production is nearly uniform, within uncertainties, over depths ranging from <20 cm to >100 cm both within the CZO (along a hillslope transect in the Providence Creek drainage) and at other localities nearby. Although the range of depths considered by Dixon et al. (2009) is nearly as broad as the range we have observed at the sight, her data do not shed light on whether denudation rates for bare rock are higher or lower than denudation rates of soil mantled terrain. We expect that bare rock erodes much more slowly than soil mantled rock, and will test whether this is the case using CNR analyses of 20 samples of bare rock to characterize soil production rates under the condition that soils are absent.

Soil production rates, when integrated over the entire catchment, should roughly equate over long timescales with sediment delivery rates to channels and streams. We should be able to test whether this is the case by comparing our catchment-wide average erosion rates (from cosmogenic-based measurements of stream sediment samples) with catchment-integrated soil production rates. We expect that the most significant difference in soil production rates will be in a contrast between rates of production on bare rock and rates of production under a soil cover. Hence, to effectively integrate soil production rates over each catchment we will need to estimate the abundance of bare rock in each of the watersheds. Together, our data on soil production rates and bare rock abundance will also help us compare the catchment-wide soil production rate with short-term erosion rates inferred from sediment trapping data collected by **Hunsaker** in the core-measurement program for KREW watersheds.

Stepped topography of the Sierra Nevada: quantifying hydrologic controls on weathering rates
The Southern Sierra Nevada Critical Zone landscape exhibits both bare bedrock (typically near the ridges) and soil-mantled topography (typically at midslope and lower, near channeled and unchanneled valley axes). This juxtaposition of bare and soil-mantled topography is common in granite (the underlying bedrock at the CZO), despite the apparent tendency towards steady soil thickness in other granitic landscapes (Heimsath et al., 1997). The dichotomous presence of bare granite and granitic soil (or gruss) was cited as an explanation for the apparent broad-scale organization of Sierra Nevada topography into an inter-fingered set of steep "steps" and gentle "treads," that account for step-wise increases in elevation to the east (Wahrhaftig, 1965). More specifically, Wahrhaftig (1965) proposed that this so-called "stepped topography" arose due to hydrologic control of weathering rates.

Hypothetical mechanism for developing stepped topography. According to Wahrhaftig (1965) bare rock sheds water more quickly and therefore does not weather as quickly as soil-mantled rock. Over time, he argued, this should drive the formation of a series of bare steps that shed water, never develop a soil, and thus erode relatively slowly (and thus become more pronounced in relief) compared to the more gentle treads which remain soil covered and thus can more effectively hold moisture (which in turn promotes further weathering and thickening of the soil). Although Wahrhaftig's (1965) hypothesis has been invoked to help explain the juxtaposition of steep and gentle terrain elsewhere in granitic terrain of the Sierra Nevada (Granger et al., 2001), it has never been tested in the "type" section of Wahrhaftig's observations, in the southern Sierra Nevada. In this study we will be able to readily test Wahrhafitg's (1965) hypothesis in the very heart of the "steps," because it encompasses the Southern Sierra Nevada Critical Zone Observatory catchments. The soil moisture data, collected in other phases of the CZO project (e.g., by **Hopmans, Johnson,** and **Bales**), will be crucial in investigations of this hypothesis, because of the insight the data will yield about the proposed link between moisture and weathering rates.

Verification of the existence of the steps. As part of this analysis, it will be crucial to first test whether there really is a topographic signature of stepped topography that needs to be explained. Do the steps and treads actually emerge from an objective, computational analysis of the topography? If so, are they as regular and pervasive as Wahrhaftig (1965) suggested? In the early 1960's, when Wahrhaftig was drafting his paper, methods for analyzing topography were crude and much more subjective than the methods we have at our disposal today. It is possible that Wahrhaftig's (1965) maps of the steps exaggerate their pervasiveness. For example, many of the biggest (i.e., highest relief) steps are shown to occur along river canyons (Wahrhaftig, 1965). This potentially misrepresents the mechanism of canyon formation, which presumably depends on river incision, rather than any moisture-driven differences in weathering rates on slopes. To quantify the existence and pervasiveness of steps we will reduce Digital Elevation Model (DEM) data from the landscape into a series of topographic indices. If the stepped topography is as pervasive as Wahrhaftig (1965) suggests, we expect the landscape should group roughly into three zones. On steps we expect to see roughly planar slopes (i.e., with high hillslope gradient and low curvature). At step-tread transitions, we expect to see high curvature and intermediate gradients. On treads, we expect to see low gradients and low curvature. Hence, if the steps are pervasive, the landscape should be roughly organized into three zones on a gradient-versus-curvature plot. By itself, such a three-zone plot would not be uniquely diagnostic of "stepped topography." To corroborate the supposedly ubiquitous existence of alternating steps and treads, there would need to be an identifiable eastward-trending cyclicity of topographic parameters, from high-gradient/low-curvature to intermediate-gradient/low-curvature to low-gradient/low-curvature and so on, marking steps, step-tread transitions, and treads (respectively) in sequence. To complete this task, we would ideally need 1-m LIDAR data for the watershed. However, it may be possible (given the purportedly large (~100 m) scale of the steps) to conduct this analysis with 10-m DEM data.

The soil production function and soil depth as a test of the stepped-topography hypothesis. If it turns out that the steps are as salient as Wahrhaftig (1965) suggests, and if he was correct in suggesting that hydrologic control of weathering is the mechanism behind the stepped topography, then we should expect to see a particular pattern of soil production rates as a function of depth. Namely, we expect that steps should be eroding significantly slower than treads. We will need to analyze an additional 20-30 samples for CRN, to determine whether this is the case.

We should also be able to leverage soil moisture measurements from other facets of the CZO project (**Johnson, Hopman,** and **Bales**) for improved understanding of controls on variations in rates of soil production and chemical weathering across the watersheds. (Methods for measuring long-term chemical weathering rates are described in the next section.) This should enable a direct test of the Wahrhatig's (1965) hypothesis about hydrologic (i.e., moisture-related) control of erosion and weathering in soils in the region.

Taken together, the combination of topography, soil depths, soil moisture, and CNR measurements will set this study apart as an important test of Wahrhaftig's (1965) long-standing hypothesis about hydrologic controls on weathering rates.

Chemical weathering rates from solid phase mass balance
We will also compile a suite of long-term, baseline measurements of chemical weathering rates for each of the catchments within the CZO. These measurements rely on the bulk chemistry and mineralogy of samples of soil, saprolite, and protolith to quantify weathering losses that occur as minerals are exposed to meteoric water during exhumation to the surface (Riebe et al., 2001; Stallard, 1985). In earlier versions of the work plan, we expressed initial concerns that our approach to making long-term weathering rate measurements would be hindered by site-to-site heterogeneity in the underlying bedrock composition across the CZO. We estimate that we will need to sample and analyze approximately 600 samples of soil, 200 samples of saprolite, and 200 samples of rock by XRF (to measure bulk chemistry) and XRD (to measure mineralogy). We will also need to prepare 100 thin sections for characterization of bedrock mineralogy.

Finally, with the in-kind support of a new collaborator, **Tony Dosseto** (University of Wollongong, Australia), we should be able to employ new isotopic methods (Dosseto et al., 2008) to yield a new quantitative perspective on the timescales of weathering in the CZO. Although the cosmogenic nuclides techniques described above represent a powerful approach for interpreting rates of landscape denudation and soil production from saprolite, they do not generally yield any information about the timing of the initiation of weathering at the regolith/rock interface, which is often meters below the surface, below the penetration lengthscales of cosmic radiation. In contrast, recent applications of U-series isotopic dating shows promise in the quantification of weathering timescales (Dosseto et al., 2008) and we are fortunate to have enlisted one of the field's leaders for support in some preliminary U-series analyses at the CZO. No analysis costs are required for this in-kind support, but we will cover Dosseto's expenses for one field visit in August 2010.

Funding Mostly CZO with some leveraging from ETH and U. Wyoming (in the form of on-site measurements) if possible.

Schedule, including field work. Collection of soil, rock and stream sediment samples, beginning Summer 2009 (initial pilot samples have already been collected); analysis of topographic data beginning fall 2009 and continuing through 2010; analysis of samples beginning winter 2010; GPR and shallow seismic surveys beginning fall 2010; additional sampling of rock and soil as needed in summer 2010. Fall 2010 continued analysis and interpretation of data.

Manuscripts in progress & planned. TBD. Need data from core measurement program and need to coordinate with Carolyn Hunsaker for access to sediment trapping data. Data from moisture probes also needed.

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Topic. **Snow processes**

Investigator. **Noah Molotch**, UCLA

Students & research staff. Keith Musselman, PhD student

Scope.

Wolverton basin snow distribution. Snow surveys and mapping.

Providence Creek studies. TBD

Funding. Largely leveraged

Schedule, including field work. Wolverton Creek in progress. Providence Creek TBD.
Manuscripts in progress & planned. TBD (include data sets used/needed)

Topic. **Biogeochemical processes/cycling**

Investigator. Discussions with additional investigators in progress

Students & research staff. TBD (graduate fellowship available at UC Merced)

Scope. TBD.

Schedule, including field work. TBD

Manuscripts in progress & planned. (include data sets used/needed)

Activities

Background. The Southern Sierra Critical Zone Observatory (CZO) was established in 2007 as a community platform for research on critical-zone processes, and is based on a strategic partnership between the University of California and the Pacific Southwest Research Station (PSW) of the U.S. Forest Service. The CZO is co-located with PSWs Kings River Experimental Watersheds (KREW), a watershed-level, integrated ecosystem project established in 2002 for long-term research to inform forest management.

The conceptual science model for the CZO is built around bi-directional links between landscape/climate variability and water/material fluxes across the rain-snow transition. Ongoing research focuses on water balance, nutrient cycling and weathering across the rain-snow transition; soil moisture is an integrating variable. Science questions currently being addressed include:

- How does landscape variability control how soil moisture, evapotranspiration and streamflow respond to snowmelt and rainfall?
- How is soil moisture linked to topographic variability, soil formation and weathering rates?
- What physiological mechanisms are controlling how vegetation distribution and function vary with climate?
- How do vegetation attributes influence cycling of water, energy, CO_2?
- What is the link between soil heterogeneity, water fluxes and nutrient availability?

The Southern Sierra CZO is located at elevations 1750-2100 m, across the rain-snow transition, in a productive mixed-conifer forest, with extended measurement nodes at elevations 400-2700 m. The main CZO site includes 3 headwater catchments with a dominant southwest aspect (37.068^{o}N, 119.191^{o}W) (Figures 1-4).

Soils within the watersheds developed from residuum and colluvium of granite, granodiorite, and quartz diorite parent material. Soils are weakly developed as a result of the parent material's resistance to chemical weathering and cool temperatures. Upper-elevation soils are at the lower extent of late Pleistocene glaciations. Shaver and Gerle-Cagwin soil families dominate the watershed. Soils are gravely sand to loamy sand, with a sand fraction of about 0.75. Soils are shallow (< 50 cm) in parts of the watershed with low tree density and many rock outcrops. Soils in more gently sloping terrain with linear or convex hillslopes are moderately deep; and landforms with the deepest soils (>150 cm) supporting a high tree density.

The area has a high forest density, with canopy closures up to 90%. PSW plans to thin and/or carry out controlled burns in two of the three headwater catchments of the CZO, to inform forest managers about impacts of thinning on ecosystem services. Five more nearby, similar headwater catchments are part of this USFS research. The area has limited recreational use, e,g, hunting and OHV use.

CZO research is carried out by students, faculty, staff and postdoctoral researchers from nine campuses, plus other collaborators who are making use of our data for comparative studies with other locations. There is both a wide range of disciplinary focus and critical-zone time scales represented in these investigations, from the response of the seasonal water cycle to perturbations, to the formation of soils to the weathering of the Sierra Nevada. There is also a high degree of integration between investigators. The main institutions with faculty students/postdocs doing research focused at the CZO include: UC Merced, UC. Davis, UC Berkeley, UC Santa Barbara, UC Irvine, UCLA, U. Nevada Reno, U. Colorado, U. Wyoming.

Research activities include: i) measurements of water, carbon, and nutrient cycle fluxes and states, ii) measurements of weathering over annual and longer time scales, and iii) hydrologic and biogeochemical modeling. It is planned to initiate further studies of critical zone form, formation and structure.

Core CZO measurements, data management and integration. Core activities provide common data to investigators and help integrate the research of the multiple scientists involved. There is also a vigorous outreach and education component. The PI supervises 2.5 staff (field hydrologist, data manager, outreach and communications scientist) and coordinates with the KREW PI to provide essential infrastructure and communications for the CZO. The CZO field hydrologist works closely with the KREW field staff to maintain a core measurement program, and coordinate field campaigns involving the various CZO researchers. The CZO data manager works closely with the PI and other scientists to archive, serve, and carry out quality control on data. The outreach and communications scientist, co-supervised by the Co-PI in charge of education and outreach (M. Conklin), assists with project management, engages in hands-on outreach with both stakeholders and K-12 audiences, and is active in communicating CZO results to multiple audiences.

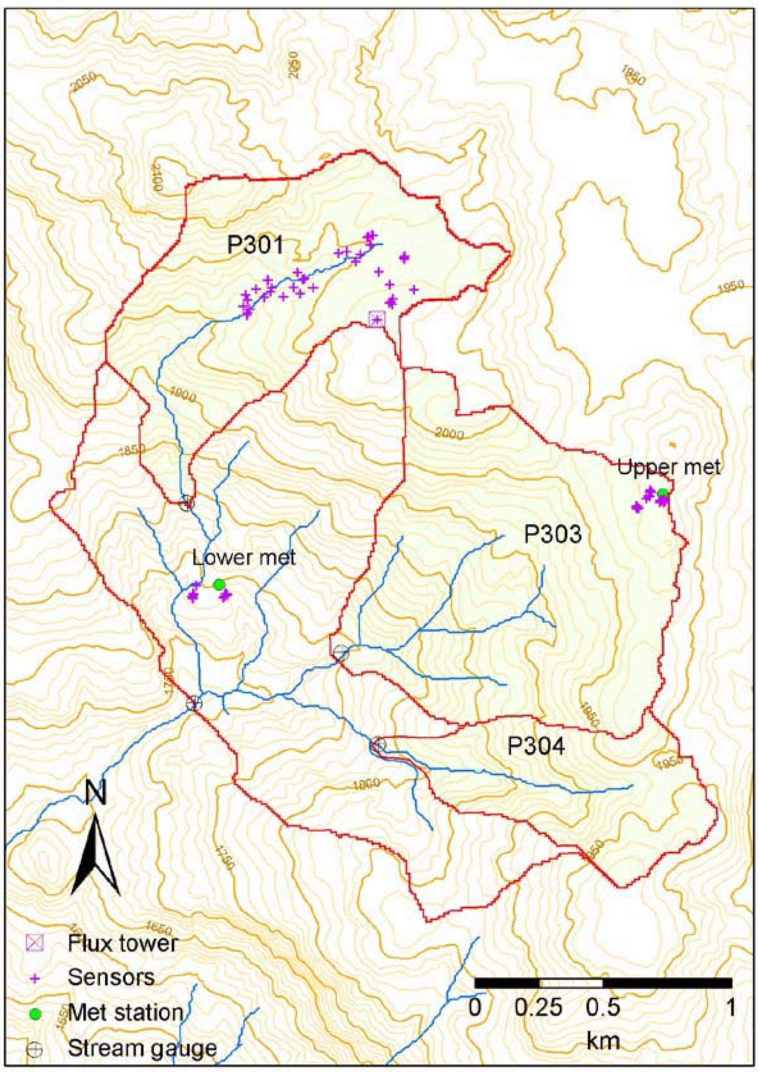

Figure 1. Instrument cluster design at KREW CZO site. Instrument node locations, strategically placed to capture variability in elevation, aspect and vegetation properties.

The water-balance instrument cluster at the main CZO site, the Providence catchments, is in its fourth water year of operation (Figure 1). The instrument cluster includes over 380 individual sensors, placed around 13 trees, in three meadow transects, at three aspects and different elevations. The sensors in P301 form a wireless sensor network (WSN). An eddy-covariance flux tower is in P301, with three additional towers forming an elevation transect. Towers are at the San Joaquin Experimental Range (SJER) (420 m), Soaproot Saddle (1080 m), Providence (1950 m), and Shorthair Creek (2670 m). The elevation gradient on the west side of the Sierra characterizes the change in precipitation (from rain to snow-dominated) and ecosystem types which are specific to different elevation bands.

The water-balance instrumentation is producing consistent data, which are archived in our digital library, subjected to quality-control procedures, and made available to our CZO team and the broader community. The Wolverton baseline instrument cluster also continues to produce quality data. Data are currently being processed to Level 2 (outliers removed, formatted, calibrated) for publishing at the national CZO site. Our digital library and data catalog are updated at least semi-annually. Level 3 data are also being produced (e.g. gaps filled, averaged hourly and daily). The SSCZO website is updated at least monthly, or more often as developments warrant.

The DUST wireless sensor network and EME Systems dataloggers have continued to operate in the P301 ground-based water-balance instrumentation (Figure 2). The DUST wireless network is distributed, self-assembling, and self-healing, meaning that if links in the network go down unexpectedly, alternative links form to ensure data will continually transmit. The WSN currently consists of 60 radio motes, and links over 250 of the sensors to a central data hub. All of our systems use solar power.

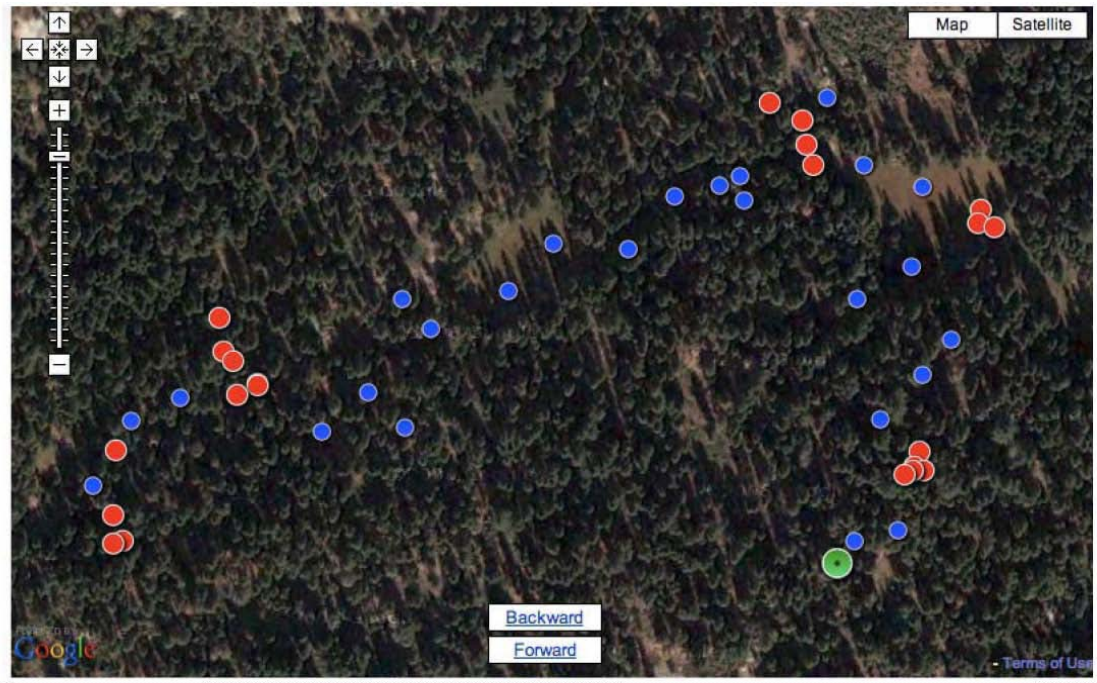

Figure 2. Locations of DUST wireless network radios. The green dot indicates the mother computer, the red dots indicate sensors, and the blue dots indicate hopper radios.

The wireless nature of the systems permits for data to be sampled at a large scale, and subsequently to be piped to a central location, aggregated for easy collection, and transmitted off site via cellular modem. This would not have been possible with conventional wired setups. The infrastructure for the WSN was set in 2009 to test communications for a robust network. An above-average snowpack and higher than average winds caused some damage to the interim infrastructure and identified weak points in the deployment. The WSN has since undergone reinforcement and installation as more permanent infrastructure. We are currently experimenting with wireless Ethernet technology that can connect multiple locations over distances of 30km. This will allow us to incorporate data from other sites within the Providence basin to the central communication hub.

Core KREW measurements and data management. Streamflow, meteorological, turbidity, and sediment measurements and data analysis have continued. Collaboration between USFS and SSCZO personnel is ongoing and will continue in the production of the series of manuscripts discussed in the Workplan, which is appended to this description of activities. The SSCZO is working with KREW in order to combat USFS budget cuts that have lead to a loss of personnel and a reduction in KREW field activities. Turbidity measurements have ceased for WY 2011, due to staffing and USFS budgetary cuts. See Figures 3 (a) and (b) for a typical stream control section in CZO/KREW catchments.

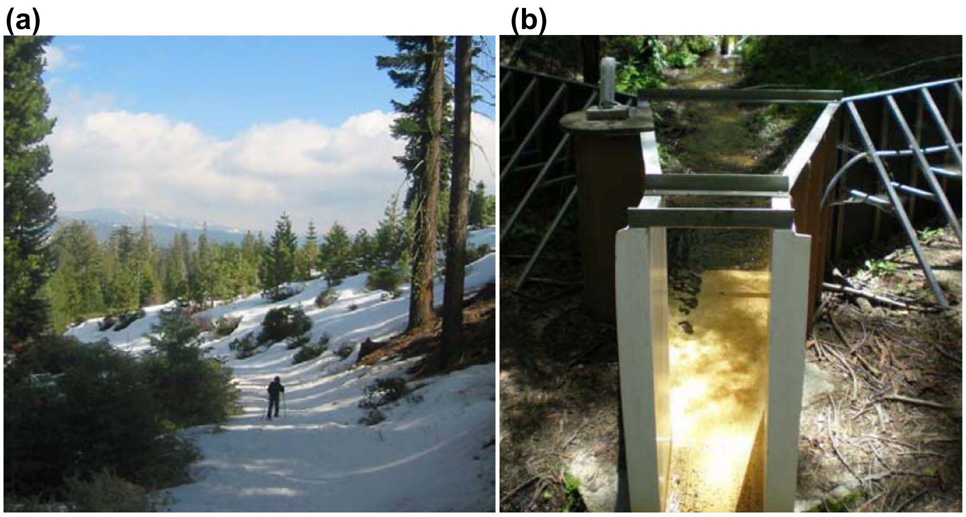

Figure 3. a) Road into CZO in early spring. **b).** Looking upstream of a typical stream control section in the CZO/KREW catchments.

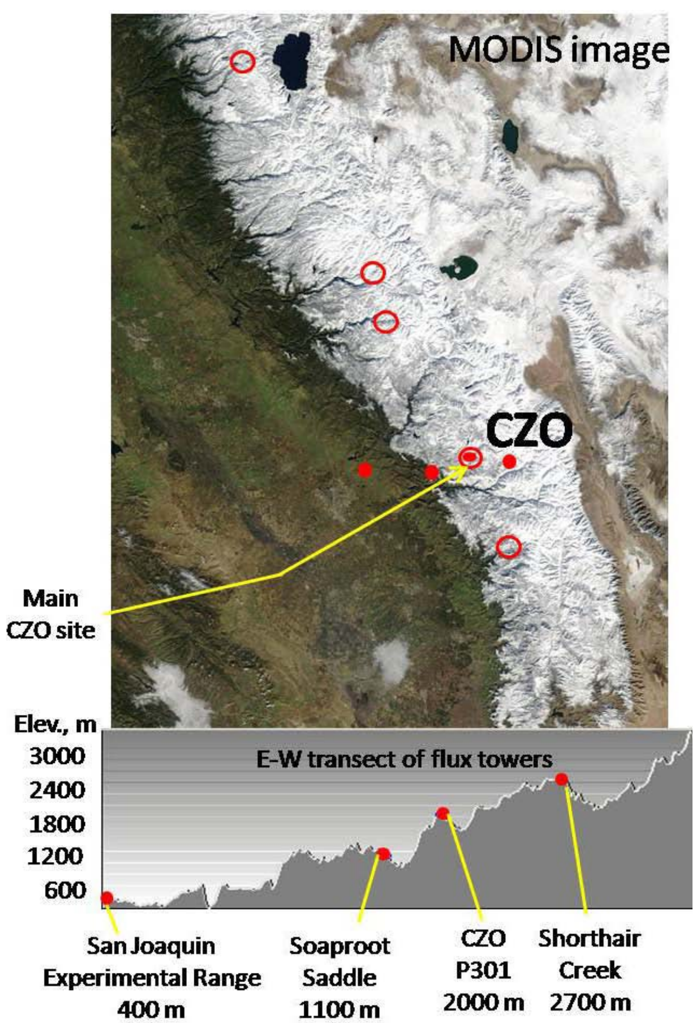

Figure 4. East-west topographic transect of flux towers, from 400 m to 2700 m elevation. Flux tower sites are throughout the Southern Sierra Nevada.

Airborne LiDAR was flown for the broader CZO installations, including Providence, Bull, Teakettle, Tokopah, and Wolverton catchments, as well as the San Joaquin Experimental Range (SJER), Soaproot Saddle, and Shorthair flux tower sights (Figure 4). Bull and Teakettle, not shown on Figure 4, are intermediate between the main CZO site (Providence) and the Shorthair Creek tower. Bull and Teakettle are part of the KREW project and provide additional locations for higher elevation SSCZO monitoring. Flights were conducted mid-March 2010 near peak snow accumulation and again in the summer 2010 when snow was melted. LiDAR data will provide spatial distribution of snow depth, leaf area index, canopy structure, and a high resolution digital elevation map. DEM data are available now; and canopy data are being processed for distribution in fall. New watershed boundaries were delineated for the Providence basin, and will be field-validated this summer.

Wireless sensor network. The past year featured a number of notable upgrades to the SSCZO Wireless Sensor Network to improve durability of physical hardware, and maintain reliable network communications. The network is made up of *sensor-nodes* (Figure 5, radio, data logger, and sensors), and *repeater-nodes* (only radio for network redundancy). Based on analysis of network data, we have redesigned the network by improving the location of current repeater-nodes and adding more repeater-nodes. The present network configuration (Figure 6) ensures communication path diversity, while reducing needless retransmission. This has led to a significant boost in battery lifetime. Figure 7 is a snapshot of the diversity of all possible radio links on which data can be transmitted for a subset of the network.

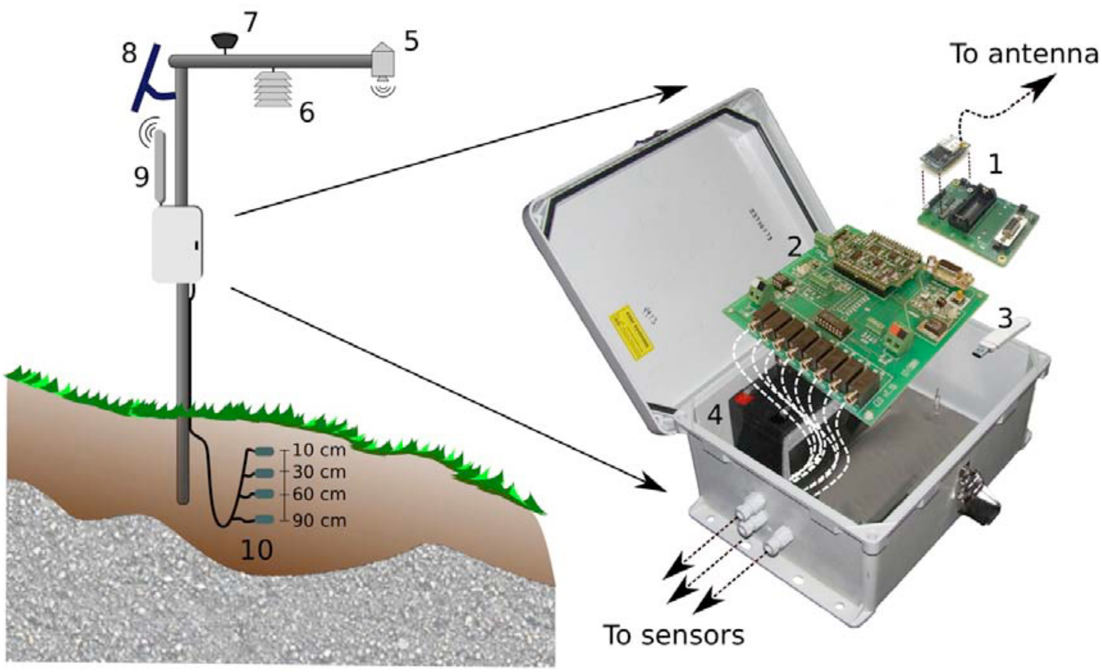

Figure 5. Sensor node architecture: (1) mote, (2) custom data-logger to interface the sensor array, (3) on-site memory storage, (4) 12V battery, (5) snow-depth sensor, (6) humidity and temperature sensor, (7) solar radiation sensor, (8) 10W solar panel, (9) external 8dBi antenna, (10) four soil moisture, temperature, and matric potential sensors at varying depths.

All of the sensor-nodes are now equipped with *Sensirion* humidity and temperature sensors (Figure 5). From a hydrologic perspective, humidity will be an important indicator of the snow-rain transition zone; the readings will also permit us to study the effects of RH on 2.4 GHz low-powered radio communications, a significant issue which has not been studied for general WSN deployments.

Until recently real-time data was only available through a sporadic mobile phone connection. Optimization algorithms have been written to synchronize only newly acquired data, minimizing the power required for off-site transmissions. We have added a node with a much more reliable GPRS connection using long-range 900MHz transmitters to tie the WSN to a nearby met-site. This met site has more reliable mobile phone communications and will feature a new WSN, integrating the latest wireless hardware. This new WSN will integrate readings from an already existing network of Campbell Scientific data loggers, aggregating multiple WSNs over long distances, and will set the stage for a *network-of-networks* paradigm. The integration of WSN technology with Campbell Scientific data logging technology will also permit researchers at the other CZO site to parlay their existing field instrumentation into wireless sensor networks for little effort and cost.

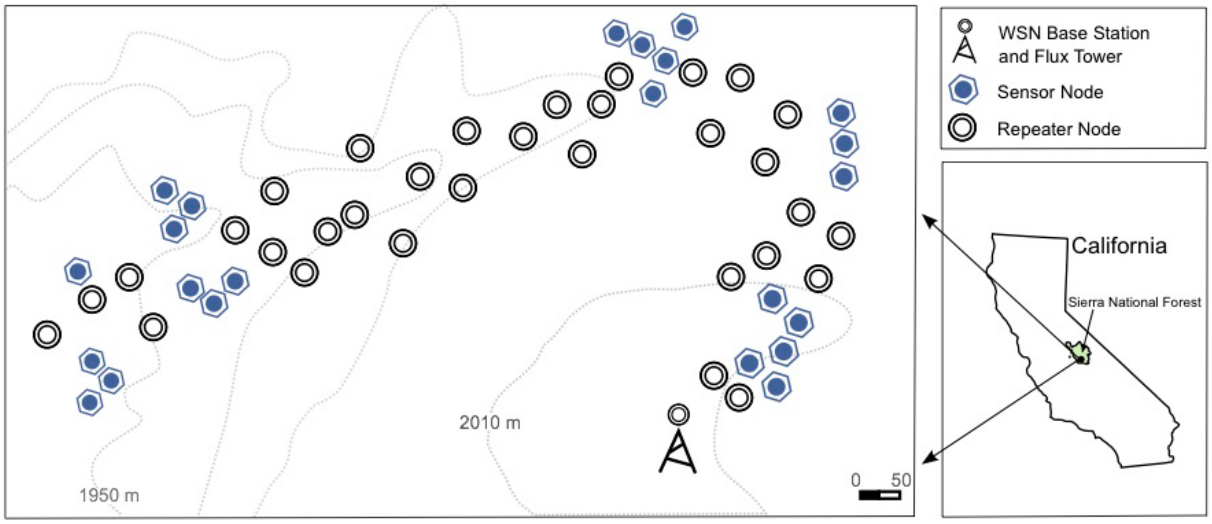

Figure 6. Current layout of the SSCZO wireless sensor network.

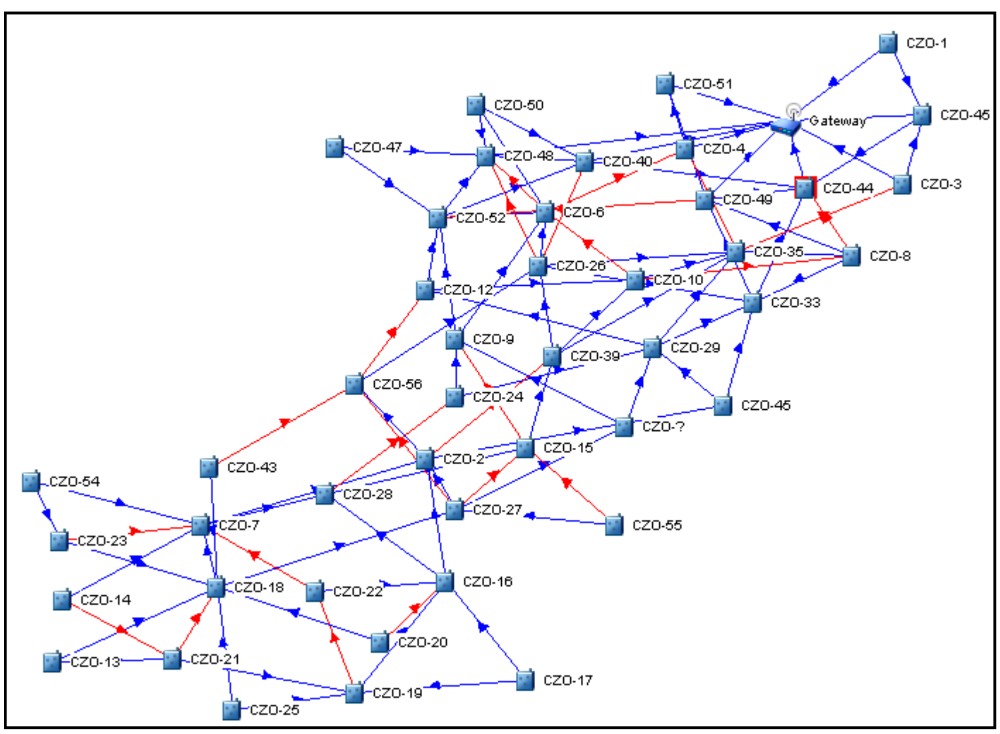

Figure 7. A snapshot of the state of a subset of the SSCZO WSN. Lines indicate paths between nodes. The reliable mesh ensures multiple Connections between nodes.

The PhD student working on the project, Branko Kerkez, has had the opportunity to present at multiple forums. He was awarded a Best Student Paper Award at the 2010 AGU meeting. He has traveled to Sweden, Finland, and Germany presenting his work and helping install wireless sensor platforms. A MS student has joined the team, working on hydrology and wireless sensor networks. He is expected to stay on for his PhD. We hired an undergraduate computer science student from Cal State East Bay to work on a number of low-level problems with data interpretation and network development.

His experience led to his being hired as a software/hardware developer at a startup in San Francisco when he graduated. He was the only CS student to get a job out of his graduating cohort.

Snow and soil processes. LiDAR flights at Providence occurred in WY 2010 for both snow on and snow off conditions. These data are currently being used to create new watershed boundaries for the basin, with field validation occurring in summer 2011. The LiDAR data are also being used to verify snow depth observations made by the water balance instrument cluster. Basin-wide snow depth estimates will be modeled using the 50 site water balance instrument cluster and compared with the LiDAR observations.

The WY2011 snow survey of Providence basin occurred on March 13-16. The main survey consisted of 206 gridded snow depth measurement locations throughout the basin (Figure 8). A subset of sample locations were analyzed for snow density using a federal sampler, five snow pits were analyzed for snow density and snow-water nutrient analysis, and several intense high density snow depth sampling grids. The high intensity sampling grids were in locations with high predicted snow depth variability based on the WY2010 observations and modeling (see Findings Figure 8). A series of snow surveys were also carried out in the Wolverton basin for the fourth consecutive year.

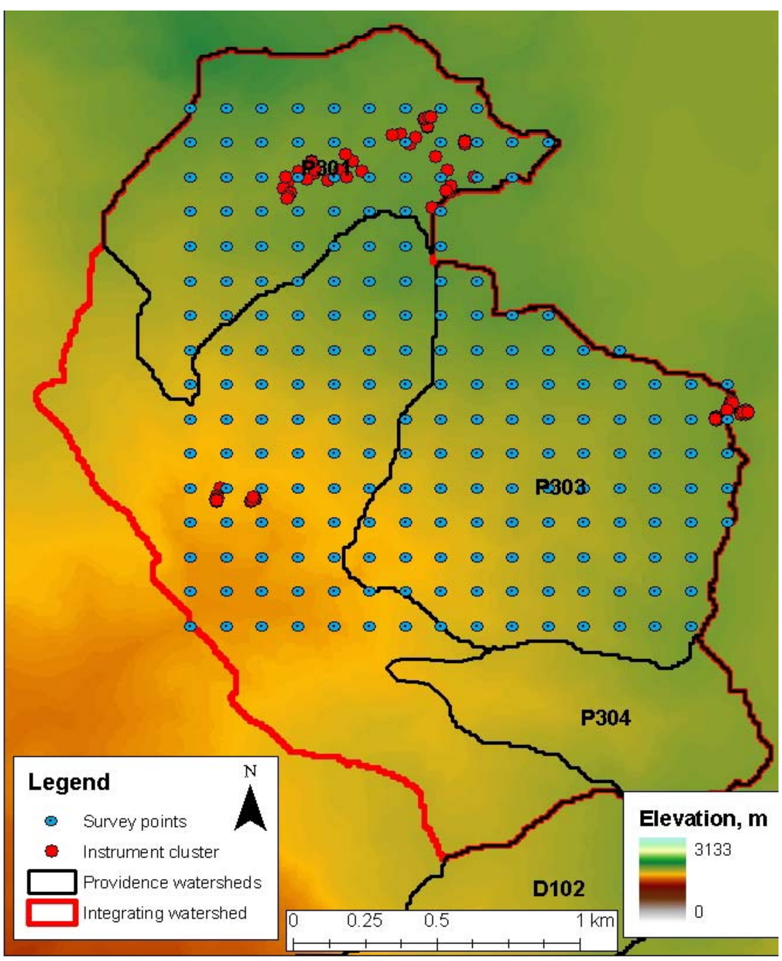

Figure 8. Snow and soil survey locations, with ground-based instrument cluster.

Two soil moisture surveys were completed in the Providence basin in 2010; after snow melt (June 14-17) and after the summer dry period (September 6-10). Shallow soil moisture measurements were taken at the same grid locations used in the snow survey. Representative soil samples were taken for laboratory analysis. The multi-parameter synoptic soil survey consisted of measurements of soil volumetric water content across a grid of over 200 points (this grid coincided with the synoptic snow survey conducted in April 2010), tree trunk moisture, and leaf water potential measurements were taken at a subset of the grid points. Soil moisture surveys for WY2011 have been planned for the beginning of summer, midsummer, and pre-winter. The beginning of the summer soil survey was completed on June 28, for a partial coverage of the upper Providence basin. Ninety-eight sample points were observed before the survey was interrupted by an unexpected rain event. Observations were made using two handheld volumetric water content tools, used to measure moisture content of the upper 20 cm of soil. Twenty representative soil samples were taken for laboratory analysis at a subset of these sample locations. These observations will be compared with instrument cluster observations and model predictions of basin soil moisture.

Based on discussions from the SSCZO team and participants at the March 2011 CZO All Hands meeting, we have started to address a lack of understanding of deep vadose zone processes and how they relate to basin scale water balances. We have started a monitoring effort, the Deep Vadose zone Project (DVP) to instrument and make observations deeper than 1m based on the desire for deep soil monitoring. We successfully augured down to 4m next to CZTree-1 and instrumented the pit with matric potential sensors at 1m intervals. Additionally, the deeper vadose zone monitoring will utilize measurements of volumetric water content (Decagon 5-TM) and soil water potential (Decagon MPS-1 and tensiometers) to determine the soil water status at depths of 150, 200, and 250 cm. The 5-TM and MPS-1 sensors will be used determine water fluxes and soil water status at depth throughout the year. Our basin-wide soil depth observations have previously been limited to 1m. On June 27th we started auguring and probing throughout the basin on the 125 m grid used in the snow and soil surveys (Figure 8). This will provide much needed data to improve our soil depth model, and better inform us of the critical zone processes that occur below 1m depth.

We installed two Cosmic-ray soil moisture observation systems (COSMOS) at our Soaproot Saddle and P301 flux tower sites on June 9-10. The COSMOS installation is part of collaboration with University of Arizona. Soil samples were collected for laboratory analysis and calibration of the sensors. These sensors report hourly averages of volumetric water content for approximately 0.28 km^2 surrounding the flux towers. We have also started to install a soil monitoring transect in conjunction with each tower. This transect includes observations of shallow volumetric water content along with matric potential measurements to a maximum depth of 2 m. These soil monitoring transects are being installed at all four flux tower locations during summer 2011. Further soil moisture monitoring and sampling is currently planned within the footprint of the COSMOS sensors for better calibration throughout the soil drying period. Hourly COSMOS data for the Soaproot Saddle and P301 tower site are currently available online via the University of Arizona website: http://cosmos.hwr.arizona.edu/Probes/probemap.php.

Water, geochemical cycles, and upscaling of in-situ measurements. Measurements from the Wolverton basin and the Teakettle Experimental Forest in the Red Fir zone of the southern Sierra Nevada (2,300-2,600 m elevation) were used to evaluate our hypothesis that topography and vegetation cover are the most important variables affecting snowmelt and soil moisture. The global variables of slope, aspect, and topography influence large scale patterns of snow and soil moisture but vegetation also has a significant influence on the small scale distribution of both. The forest canopy has multiple effects on the accumulation and ablation of snow resulting in a heterogeneous snow cover and the subsequent soil moisture. Snow, as opposed to rain, represents > 90% of the annual precipitation received by these ecosystems and demonstrates a clear seasonal signal in vadose-zone recharge. Our strategy is to combine synoptic surveys and instrumental data from both sites to describe these processes across broad temporal and spatial scales.

Day of snowcover melt out was measured around a north aspect and a southeast aspect tree in the Wolverton baseline watershed in 2007-2009. Using a 500 x 500 m grid, 270 depths were collected within the basin. Synoptic snow surveys were also conducted in the Wolverton basin within 4 days of April 1st from 2007-2009 using a 600 x 600 m area. In addition, depth and density were measured at 36 grid points, four times, once in each cardinal direction, under the canopy of the nearest mature Red Fir tree, and 3-4 times in the closest canopy gap. Radiation measurements of incoming short and longwave radiation were made in 2010 over three days using paired radiometer arrays placed on previously studied north and south facing plots in patterns radiating out from tree stems.

Critical Zone Tree (CZT) monitoring and root excavation. Continued monitoring of CZT-1 and instrumentation of CZT-2 were completed in August 2010. We have now intensively instrumented two trees with over 300 sensors measuring fluxes of water in the soil and in the trees themselves. In September 2010 we excavated the roots of a white fir adjacent to CZT-1 using pressurized air to remove the soil around the roots down to 2 m. Terrestrial LiDAR was used to scan the exposed roots and provide a 3-D model of the root system. Measurements on **t**he intensively instrumented white fir (*Abies concolor*) tree (CZT-1) in the SSCZO continue, with soil moisture, temperature, matric potential (MPS) sensors and tensiometers (Figure 9). CZT-1 has been operational and collecting data for over 30 months. Sap flux sensors and time domain reflectometry (TDR), for determination of changes in stem water content, have been producing data and shown response to fluctuations in air temperature and solar radiation. A Ground Penetrating Radar (GPR) survey of the root structure of a similar, nearby white fir tree was conducted in fall 2009 to better determine the point locations of moisture extraction by the tree. Due to uncertainty in the GPR root scan, it was decided to physically excavate the entire root system to the tree. Excavation of a white fir tree similar in size and location to CZT-1 (GPR tree) was conducted in September 2010 followed by the Terrestrial LiDAR root scan (Figures 10-11). The analysis underway will provide the opportunity to produce a detailed root structure map with respect to various soil structural units.

The second intensively instrumented tree, CZT-2, a ponderosa pine (*Pinus ponderosa*) (Figure 12). The two sites—CZT-1, flat, deeper soils and dense canopy cover, and CZT-2, shallow, sloping soils, and more exposed—complement each other in capturing watershed variability.

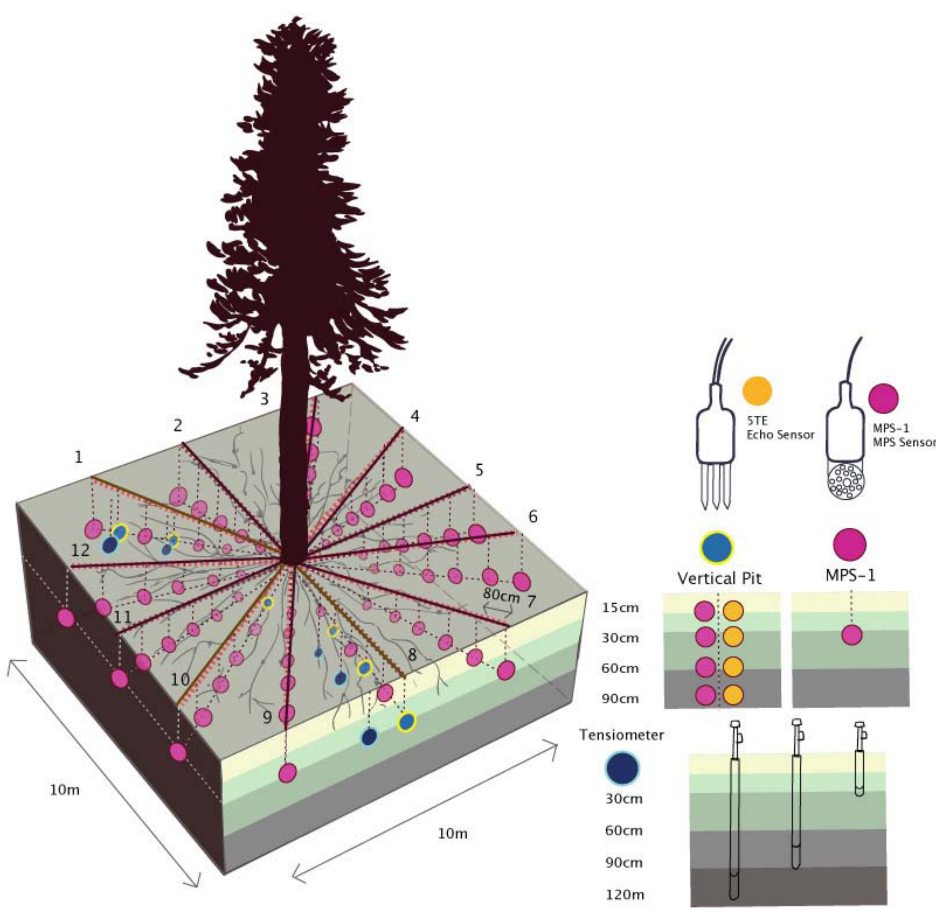

Figure 9. Layout CZT-1 including location of Echo-5TE, MPS, locations, vertical soil moisture/temperature pits, and tensiometers.

a)

b)

Figure 10 a and b. Excavated root system of a mature white fir tree. The soil was removed pneumatically, using an "air knife," down to 2 m, leaving the roots undamaged. We found a dense mat of roots from 30-50 cm and then a general decline in root density with depth. Very few roots extended below the soil/saprolite interface at 1.5 m, and only those directly beneath the trunk.

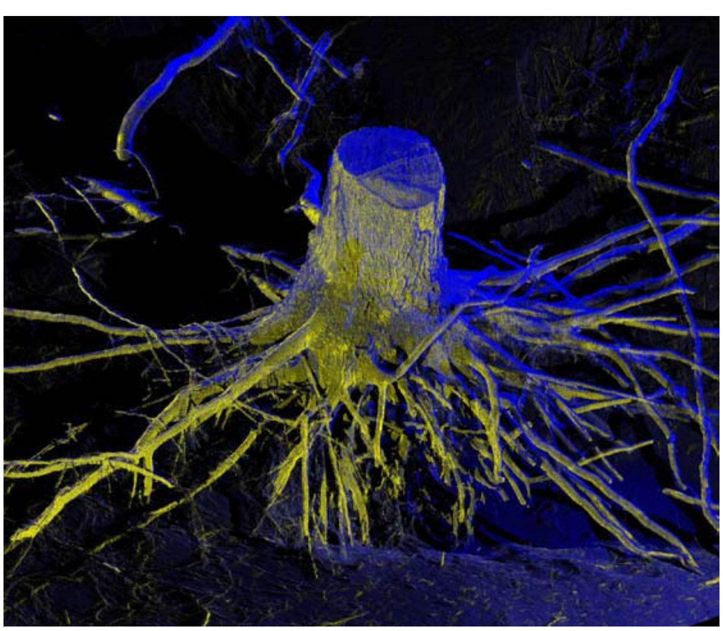

Figure 11. Terrestrial LiDAR image of the excavated root system of a white fir tree. Analysis in process will allow for precise mapping of root location with respect to the soil surface and the various soil horizons, calculation of root volume and partitioning of roots by size fraction.

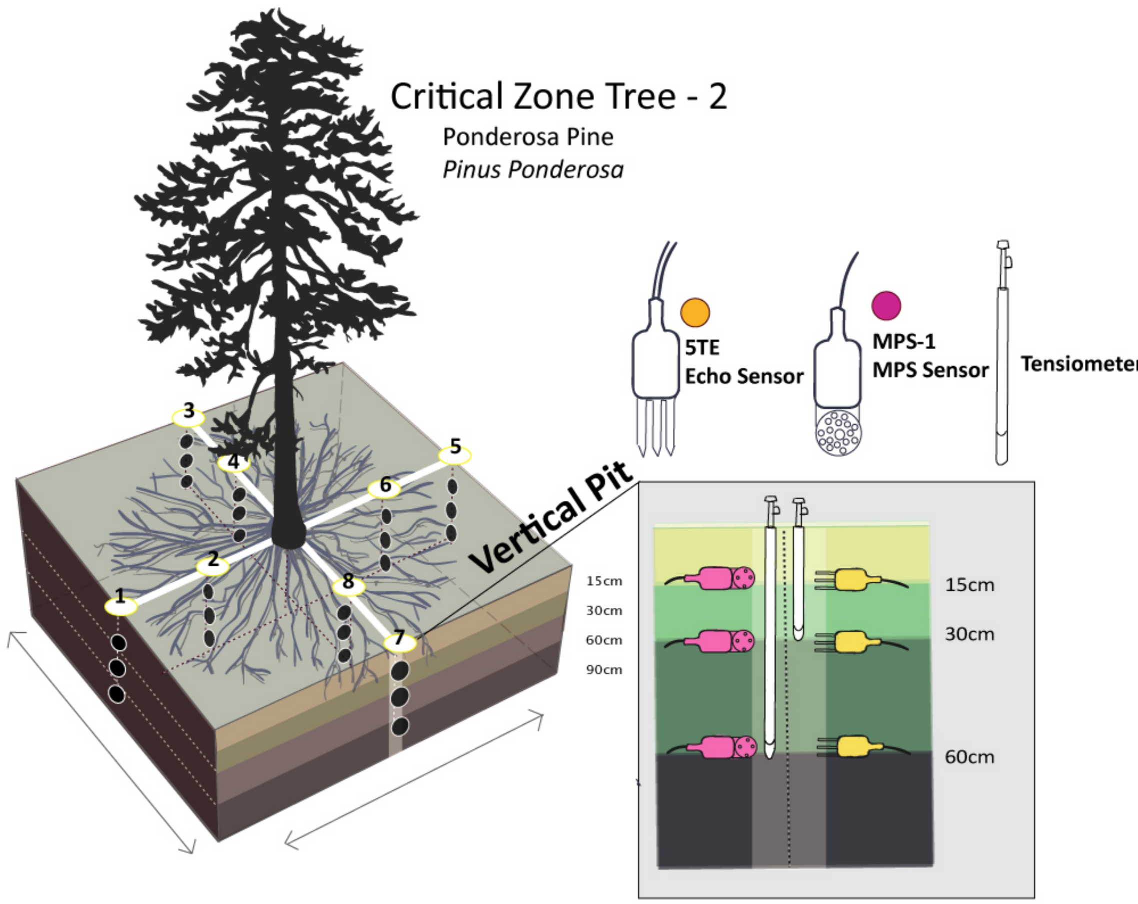

Figure 12. Layout CZT-2 including location of Echo-5TE, MPS, locations, vertical soil moisture/temperature pits, and tensiometers.

Critical Zone Tree (CZT) modeling. We have continued to develop a coupled model of the soil/tree/atmosphere continuum of CZT-1. Using measured data from the site, a forward model of root water uptake at the tree has been developed (Figure 13). This model is driven by spatially distributed potential evaporation in the canopy and includes reduction factors based on soil moisture stress at the root level. There is still great uncertainty about deeper soil water exchange and this model will be expanded to include additional deeper soil units as data from the Deep Vadose zone Project (DVP) becomes available. The next phase of the project already underway is to build an inverse model to do parameter estimation of soil and tree hydraulic properties, as well as refine knowledge of root water extraction depths and magnitudes. Finally, this model will be coupled with the root model from the excavated tree to better understand fine scale root water uptake and redistribution dynamics at the plot scale. Plot scale modeling will be scaled up to the watershed scale using relationships developed with ET measurements taken at the adjacent P301 flux tower.

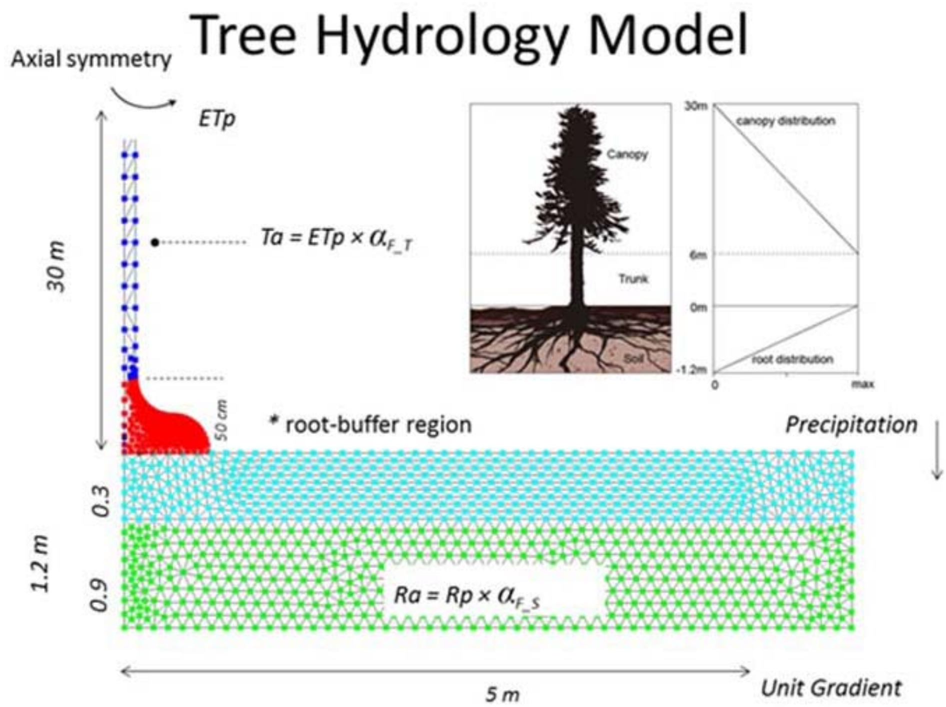

Figure 13. Coupled Tree soil model using the HYDRUS model. Model is driven by PET which is applied to the roots in the soil model and to the tree canopy in the tree model.

Surface-groundwater interactions. The meadow transects in the P301 watershed have been completed. Three additional monitoring wells were installed at the meadow-forest border. These wells were drilled into the sap rock using a gas powered auger engine and concrete coring bits and range from 2 to 5 m in depth. Two stilling wells were installed in the P301 stream—one in the stream between the middle and lower meadows and one downstream of the lower meadow.

Chamber evapotranspiration measurements were conducted in the summer 2010. These measurements will be coupled with groundwater (GW) level data from the monitoring wells, pressure head data from the piezometers, and stream flow data from the stilling wells in order to obtain a water balance for the time of the chamber measurements. Data from the wells and piezometers are currently being analyzed; salt dilutions have been and will continue to be conducted in order to establish rating curves for the two stilling wells.

We improved our modeling efforts of thermally stratified pools in Long Meadow in the Wolverton basin. We used pressure head data from the meadow piezometers to provide accurate ground water gradient and velocity for the time interval we are modeling. We used flow measurements coupled with surveyed cross sections to calculate a range of stream velocities for use within the model. Finally, we incorporated measured dissolved organic carbon concentrations into the light attenuation coefficients used in the model. A paper on behavior and modeling of pool stratification is in preparation.

Well and piezometer data from Long Meadow were further analyzed for evapotranspiration (ET) signals, ground water gradient and flux patterns in the meadow. Rating curves have been applied to the two gauging locations along Wolverton Creek near Long Meadow—one location upstream and one location downstream of where Long Meadow discharges into Wolverton Creek. These new discharge data have been analyzed to produce a calculated discharge from Long Meadow. Additional chamber ET measurements were collected in the 2010 to compare seasonal variation in ET. Two additional wells were installed at the meadow/forest boundary. These wells were set into the sap rock using a gas powered auger engine and concrete coring bits and range from 2 to 4 m in depth. We have observed nighttime air temperatures in the meadow significantly colder than recorded at the nearby meteorological station in the forest. In order to further assess the potential cold air drainage, Hobo tidbit temperature loggers were deployed in the meadow to measure air temperature in and around the meadow. A manuscript on spatial and temporal soil moisture patterns and groundwater connectivity is in preparation.

Physical controls on water and carbon exchange and plant production. We are using the climate gradient of four eddy covariance towers to understand the mechanistic interactions between climate, soil development, species distribution, biotic production, and hydrological balance (Figure 14, Table 1). Our main activities during the last year were: i) the installation and operation of the Soaproot Saddle eddy-covariance tower at 1200 m, which completes the transect, ii) the year-round operation of the three original flux towers, and iii) the establishment of additional in-situ measurements, including plant primary production and sap flow.

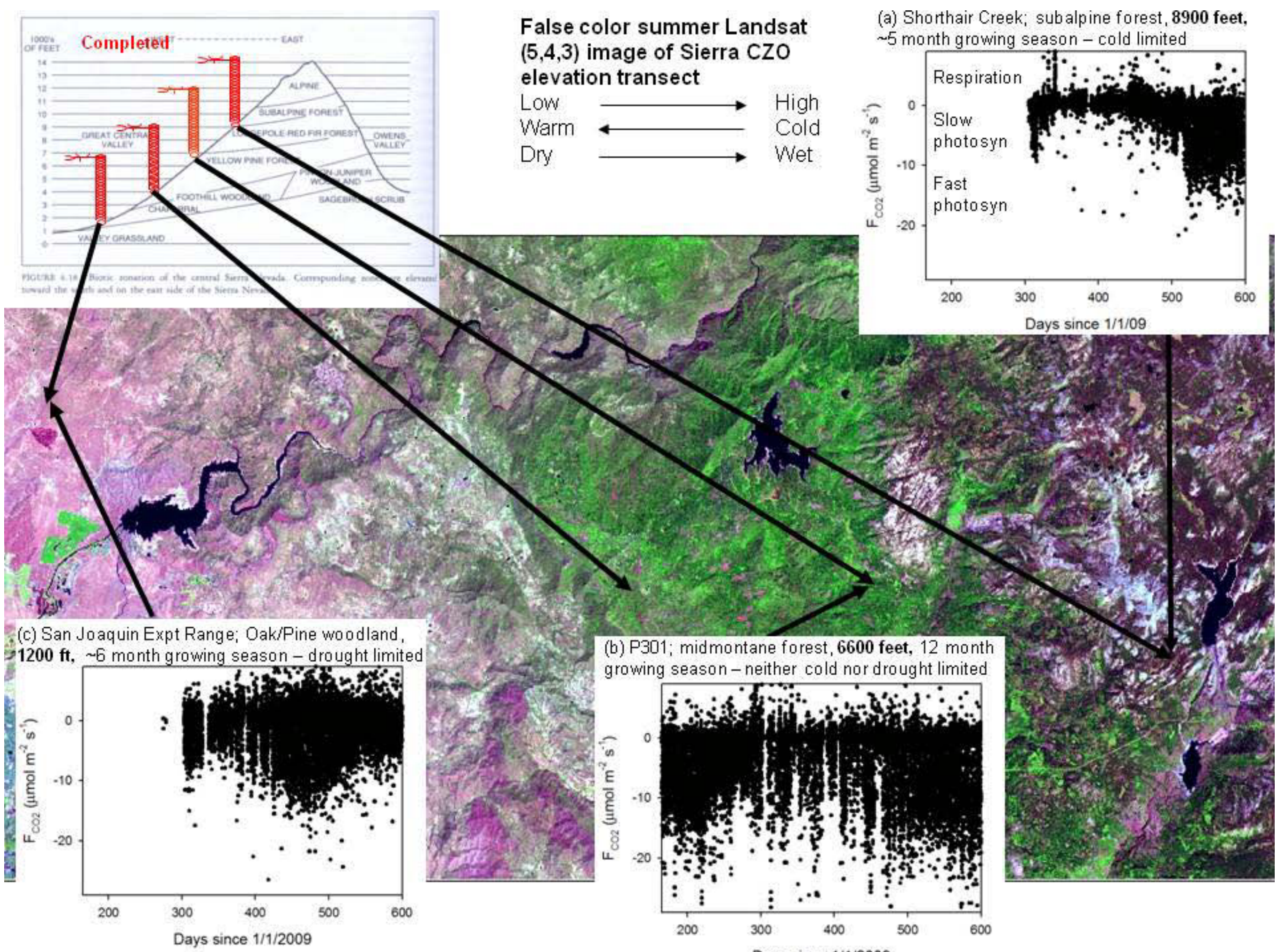

Figure 14. False color Landsat image with locations of the four completed eddy covariance towers. Plots of seasonal CO2 uptake at each of the completed towers are included. Winter occurred from Day of Study 330 to 520, and summer from day of study 540 onwards. Data points are 30-muinute covariances, with negative fluxes indicating daytime net CO_2 uptake (photosynthesis) and near zero or positive fluxes indicating net respiratory CO_2 uptake (either at night or during periods when photosynthesis was dormant).

Table 1. Climate and forest properties at the four primary sites. Climate data are annual means from PRISM (2000-2009) or from tower data when available.

Site	Precip., mm	T, ^{0}C	Hypothesized climate limitations	Biomass, tC/ha	Tree NPP, tC/ha/yr
Oak woodland (382 m)	506	18.2	Severe summer drought	18.6	0.4**
Yellow pine (1204 m)	794	13.2	Summer drought	60.5	3.6**
Mixed conifer (2017 m)	922	10.8	Neither drought nor cold	95.3	6.3
Lodgepole (2709 m)	1064	4.3	Severe winter cold	83.4	1.5**

**Preliminary estimates from less than one year of data

The towers transmit a subset of observations hourly, which allows us to keep an eye on system function. The complete data set is collected manually every month and transferred to UCI via the internet. These data are then processed and posted on the digital library at UCM. The P301 tower has been collecting data for 3 years; the SJER and Shorthair towers have been collecting data for 2 years; the Soaproot Saddle tower has been collecting data for 12 months. The tower sites were also surveyed and instrumented to measure individual tree productivity and water use. One hectare plots were mapped within the footprint of each tower. Dendrometer bands and biomass collection traps are measured every 1-2 months to obtain aboveground NPP. Sap flow sensors measure transpiration on 12-20 trees at the upper three tower sites. Finally, an additional set of plots was established at 120 m elevation intervals between the tower sites to provide finer resolution information on production and species composition variation with elevation.

Dynamic spatial modeling of water and nutrient cycles. RHESSys (a coupled model of hydrology and ecosystem biogeochemical cycling (Tague and Band, 2004; http://fiesta.bren.ucsb.edu/~rhessys/) was calibrated for 3 sub-catchments (P301, P303 and P304). Using RHESSys we demonstrated the use of a top-down sampling design approach for soil moisture and sapflux based on initial predictions of ecohydrologic variables from this calibrated model. The sampling strategy, implemented in summer 2010, complements that initially laid out in the CZO and is explicitly designed to capture the effect of inter-annual climate variability on ecohydrological response. The model was used to generate spatial-

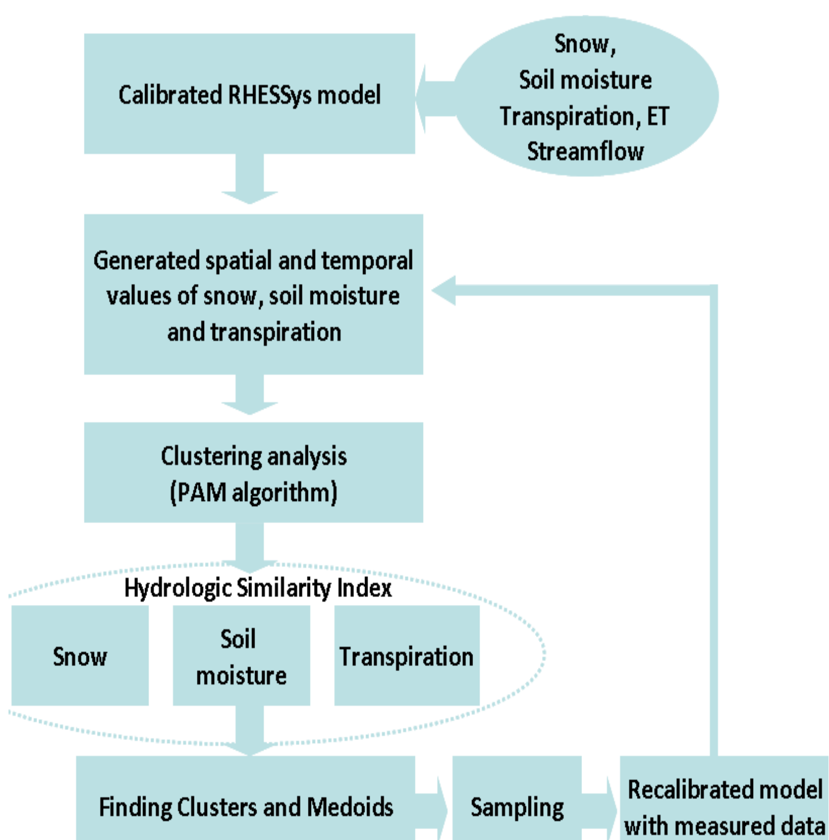

Figure 15. Conceptual framework for top-down sampling design approach for soil moisture and vegetation water use.

temporal patterns of snow, soil moisture and transpiration under historical and projected future climate scenarios. These patterns were then clustered to identify areas of hydrologic similarity, where similarity was defined by inter-annual mean and variation of a suite of hydrologic indicators (e.g. seasonal trajectories of snowmelt, root-zone soil moisture storage, and evapotranspiration). Figure 15 shows the conceptual framework and procedures for our soil moisture and sapflux sampling design. A supplemental grant was awarded by the Kearney Foundation to support additional soil-moisture measurements and soil sampling in the SSCZO catchments.

Physical weathering rates. Sampling of SSCZO soil and rock materials was completed and geochemical analysis is continuing (85% complete). These samples and analysis have been used with prior KREW quantitative soil pit, sediment yield trap, and soil survey data. New data from cosmogenic radionuclides in sediment have also been used in a broader analysis of landscape evolution in the CZO and surrounding landscape. New work was started on characterizing the seismic velocity structure of the subsurface (to ~30 m depth) as a way to constrain weathering and water storage potential at depth. Shallow geophysical work will continue in fall 2011; the shallow seismic survey will be expanded to new sites, and proof of concept surveys by GPR, resistivity, and microgravity will be initiated.

Baseline hydrologic, sediment and geochemical characterization. In July 2010 we submitted a manuscript examining geochemical controls of streamflow pathways in the 8 KREW catchments, including the 3 CZO catchments. The manuscript addressed 3 main questions including; i) what are the end-members contributing to streamflow in these catchments, ii) did these end-members vary with elevation, and iii) can these results give any insight into predicting streamflow when using hydrologic models?

Between 2003 and 2007, bi-weekly stream water samples were collected at the watershed gauging stations using ISCO samplers. In addition, soil water (13-26 cm depth), piezometer water (~1.5 m depth), snowmelt, spring water, and deep groundwater (drinking well) samples were collected from nearby sites and at various times prior to 2009. Analysis of samples included major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (Cl^{-} and SO_4^{2-}). By means of statistical methods, end-members were determined by isolating conservative tracers and using end-member mixing analysis (EMMA). The fractional contribution and correlation with topography of each end-member was also determined.

Organic carbon in streams. Sampling for organic carbon in the KREW streams commenced in April 2009 continued until April 2010. Samples were collected monthly at the KREW gauging stations; sampling has coincided with the bi-weekly major ion sampling conducted by the Forest Service KREW field team. Along with the organic carbon samples, water isotope samples have been collected. The collected organic carbon samples have been sent to Elizabeth Boyer at Pennsylvania State University for analysis. Water isotope samples are being processed at UC Merced.

Soil Nutrient Contents. In addition to the two papers already published, we submitted a third paper on nutrient hotspots to Soil Science in March 2011 (Johnson et al., in review). This paper summarizes the results of the first year data described in the previous report. See the publication list for details. Year three samples were pulled and soil cores were extracted and analyzed for nutrient concentrations. Year four collectors were established, including experiments where O horizon runoff barriers were placed.

In addition to hotspot investigations on the intensive plots, Johnson has been analyzing resin lysimeter and O horizon data collected by C. Hunsaker, Johnson, and helpers over the past 8 years.

Nitrogen fluxes from soil. KREW research was designed to evaluate a nitrogen budget and fluxes both before and after forest restoration treatments. This research was established in 2002 before the SSCZO began, however, synergy with CZO research has enhanced it. Nitrogen (N) as nitrate and ammonium is measured in precipitation (both rain and snowmelt), stream water, shallow soil water, and the flux from ground to shallow mineral soil (26 cm). More details than we present here can be found in the KREW Research Study Plan at www.fs.fed.us/psw/programs/snrc/water/kingsriver.

One Prenart vacuum lysimeter is located in each of the four Providence watersheds; each Prenart has 6 tips that sample at the 13 cm mineral soil depth and 6 tips that sample at the 26 cm mineral soil depth. Enough water can be collected every two weeks during the wet season (November through June) for chemistry analyses of these waters. The Prenart lysimeters provide an indication of temporal variability during the wet season at these intensively monitored locations. Co-located with the vacuum lysimeters are bulk (wet and dry deposition) snowmelt samplers (6 under the forest canopy, 1 open); these samples are collected at the same frequency as the Prenart samples. A large array (150-m grid spacing between sample points) of resin lysimeters are deployed across the watersheds to get the annual spatial variability of N at ground level and at the 13 cm mineral soil depth: P301 has 44 sampling points, P303 has 60, P304 has 39, and D102 has 54. The chemistry of incoming precipitation is measured by an Aerochem sampler (CA28) located at watershed P301 that is part of the National Atmospheric Deposition Network (NADP); this sampler provides a weekly composite water sample. All of these measurements started in 2002 except the Aerochem which started in 2007. Aerochem measurements are continuing, but the other measurements were ended in 2009 pending the implementation of the forest thinning and underburning treatments. KREW has collected seven years of extensive N data to evaluate N deposition to the forest soil and N flux into the shallow mineral soils.

A subset of the resin lysimeters are co-located near the 87 quantitative soil pits for which Johnson et al. reported nutrient analyses in 2010 (*Geoderma* 160).

Photo credits. Figure 3: Ryan Lucas**.** Figure 10: Peter Hartsough.

Findings

Summary. Results from the CZO research over the past 3 years are described in several papers that are published, submitted and in preparation (year 1 was a start-up year with only partial funding). Some highlights of more-mature results follow.

- The water-balance instrument cluster, with its over 380 individual sensors and other characterization, is giving an unprecedented window on the catchment-scale water cycle. Snowpack, soil moisture, evapotranspiration (ET), runoff, and catchment water yield all vary systematically across the elevation (temperature) gradients of the rain-snow transition in the Southern Sierra Nevada.
- The deeper regolith (below mapped soils) is critical for supplying water for ET and baseflow in streams for several months each year. At least the saprolite layer is important for water storage, as roots extend into this layer.
- End-member mixing analysis confirms that streamflow is dominated by a combination of near-surface runoff and baseflow, with storm runoff being a much smaller contributor.
- Sap flow in intensively instrumented trees tracks soil moisture and matric potential from spring through late summer each year.
- Our water-balance instrument-cluster design, using strategic sampling, can capture both the spatial average and spatial patterns of water-balance variables. This design is being replicated at other locations.
- Vegetation transpires year round, in contrast of climatalogical indices of water deficit that predict significant summer shutdown as soils dry and winter shutdown due to sub-freezing air temperatures.
- Spatial patterns of snow accumulation, snowmelt and soil moisture depend in a systematic way on temperature and solar radiation, as indicated by elevation, aspect, slope, and canopy cover.
- Meadow groundwater levels and ET respond in a coordinated way with the water balance in the surrounding forest, indicating a high-degree of year-round hydrologic connectivity despite travel times for water that are much longer than response times.
- Cosmogenic nuclides and terrain analysis of the stepped topography of the CZO area show that the steps are often soil-mantled as often as the treads, and that erosion rates of treads are lower than erosion rates on steps. This is directly counter to the classical hypothesis for formation of the stepped topography.
- Nutrient hotspots in soil, or a high degree of heterogeneity in nutrient fluxes, were found to be present for all solutes studied, and were not correlated with locations of preferential water flow.

Core CZO and KREW measurements and data management. Measurements of precipitation, snow accumulation and melt, streamflow, soil moisture and meteorological variables from a multi-year database have undergone analysis to assess the hydrologic and geochemical response of rain-dominated versus snow-dominated catchments.

Figure 1 shows the measured snow water equivalent (SWE) and cumulative precipitation measured for the upper, snow-dominated Bull watersheds and the lower, rain-dominated Providence watersheds for 2005 and 2006. For both years, cumulative precipitation is similar for the upper and lower watersheds. Snow at lower elevations exhibits multiple accumulation and melt cycles throughout the cold season. Snow at higher elevations exhibits a single main melt period in spring. The Bull watersheds show a greater fraction of cumulative precipitation comes in the form of snow.

Figure 2 presents cumulative discharge for all eight of the KREW watersheds. The lower watersheds, depicted with dashed lines, indicate that mean cumulative discharge occurs earlier than in the upper watersheds, depicted with solid lines, in both the wet and dry precipitation years presented. Earlier runoff in lower elevation catchments reflects the greater proportion of rainfall.

Figure 3 shows a subset of the ground-based water balance instrument cluster data; soil moisture and temperature at 11 instrument nodes. These data show soil wetting and drying cycles and corresponding soil temperature at different depths. Soil moisture declines rapidly in the first week after snowmelt has ceased, followed by a more-gradual decline thereafter.

Local difference in the timing of soil drying between north versus south aspects and shaded versus open sites are about one month, comparable to elevation differences in the average response. These responses are related to variability in snow melt timing at the instrument cluster sites. Water content measurements recorded at the instrument nodes as part of the water balance transects are doing a good job of capturing the variability of the Providence watersheds (see Snow and Soil Processes section).

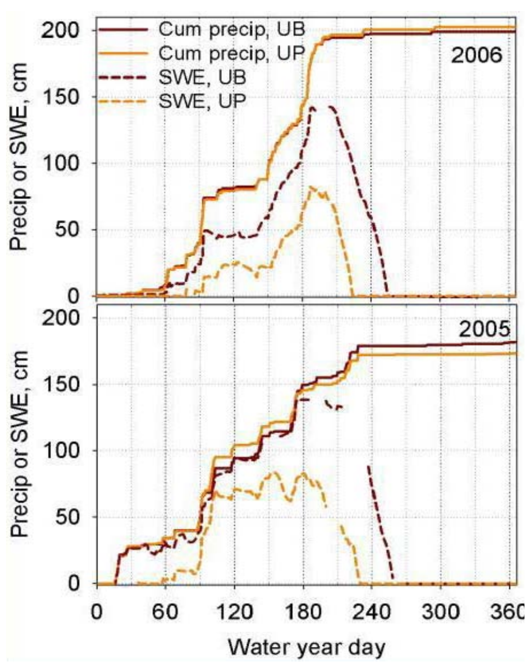

Figure 1. Cumulative precipitation and SWE for Bull and Providence watersheds.

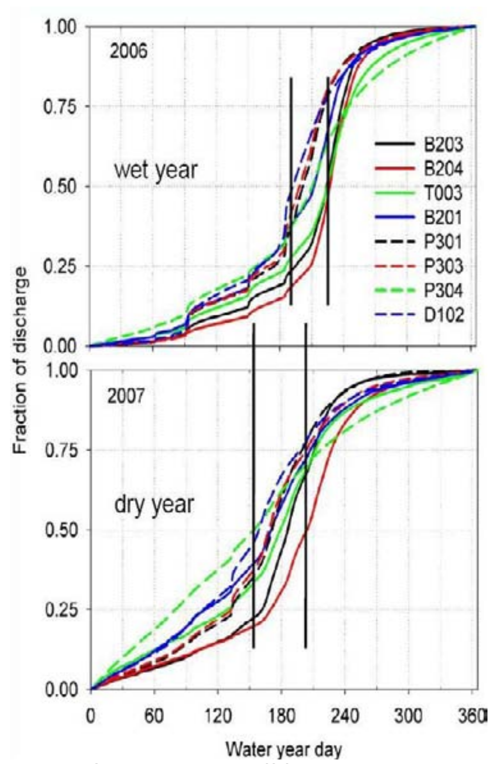

Figure 2. Cumulative runoff for the upper (solid lines) and the lower (dashed lines) elevations.

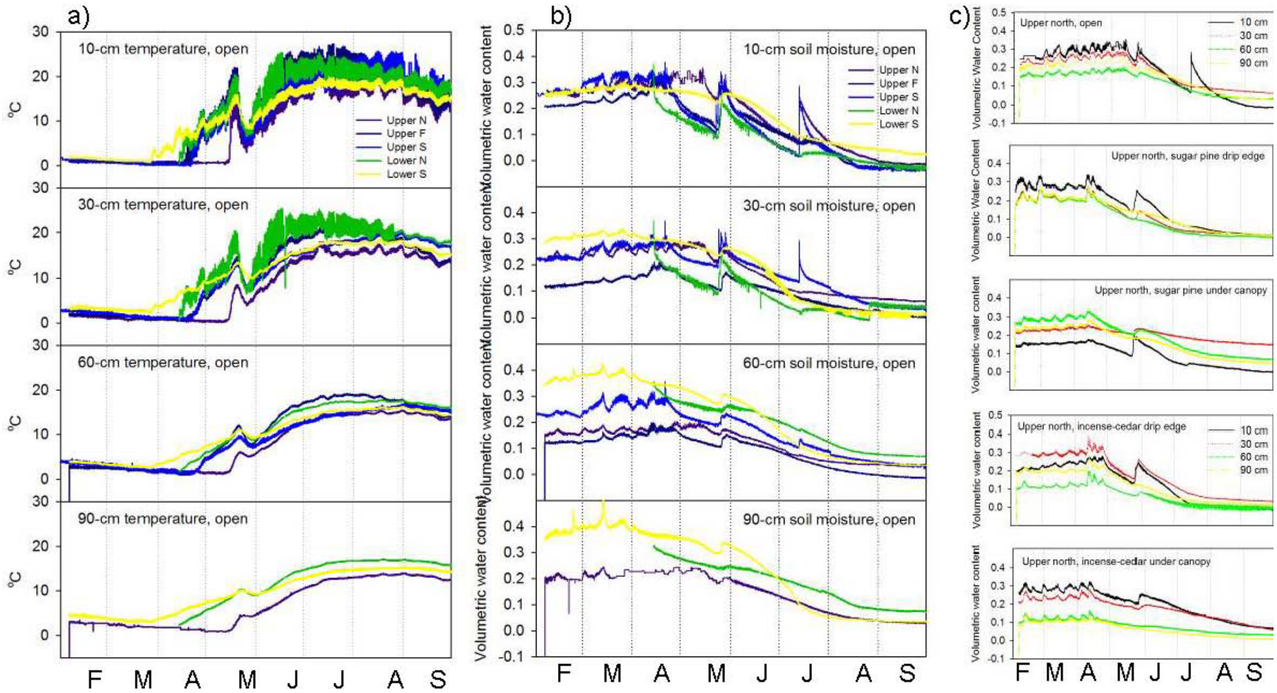

Figure 3. Soil temperature (a) and soil moisture (b) data collected 11 instrument nodes at 3 aspects and 2 elevations in 2008. Vertical soil moisture profiles from nodes located at the upper elevation and north facing aspect (c) in 2008.

Wireless Sensor Network. We have derived a novel snowmelt model which makes use of the dense spatiotemporal data from the CZO (Kerkez et al., 2001a). The paper was well received at a prestigious computer science conference (<15% acceptance). Detailed results from the CZO were presented at the AGU fall meeting, and was received with a best student paper award. Analysis of network data permits derivation of set of core heuristics that permit for flexible, reliable, and rapid WSN deployments. This will aid us in future deployments, and provides other researchers with the tools necessary to conduct scalable, reliable, and rapid WSN deployment using off-the-shelf components.

The ability of the network to capture the variability of snow-depth and soil moisture has been validated by comparing WY2010 measurements, with those made during comprehensive synoptic surveys and LIDAR flight. The sensor-node locations were originally selected to reflect catchment-wide distributions of physiographic parameters (slope, aspects, and canopy cover). The network accurately reflected the mean and variability of snow-depth and soil moisture (Figure 4), when compared to the LIDAR and synoptic survey, thus validating the general sensors placement strategy.

Temporal analysis of snow-depth and soil moisture also revealed significant variability with regard to snow depth (Figure 5a), showing differences in peak accumulations, as well as melt timing for each sensing location. Similar trends were observed for soil moisture, with major fluctuations in volumetric water content being driven by snowmelt (Figre 5b).

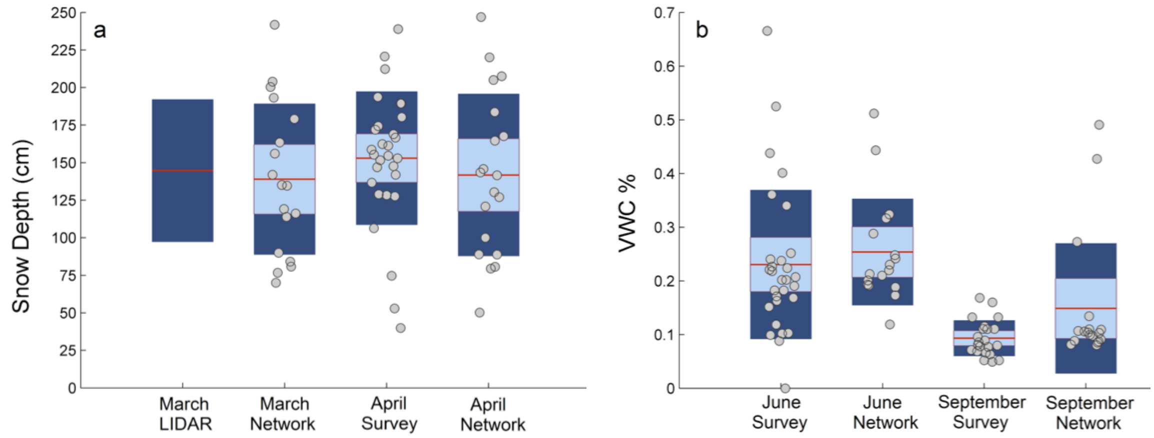

Figure 4. Mean and variability of snow depth, and VWC on four survey dates. Measurements are shown as grey circles (except for the large number of points in the LIDAR data set). The line denotes the mean; the dark region denotes one standard deviation, and the light region denotes the standard error of the mean.

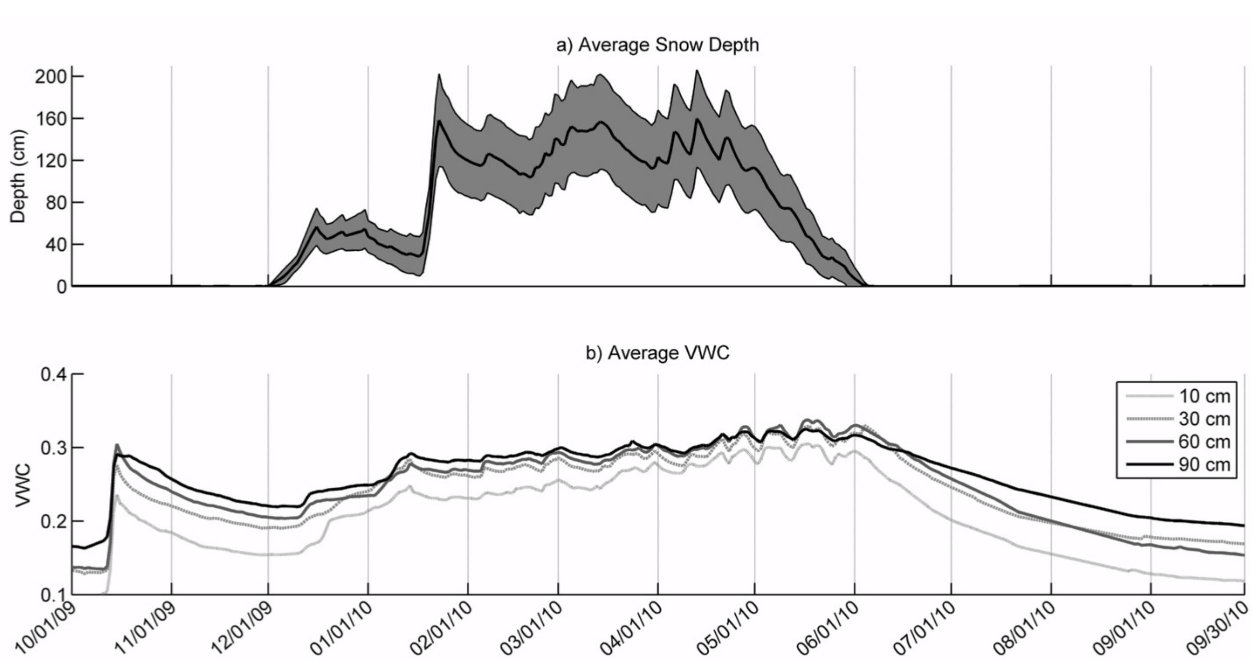

Figure 5. Variability of catmint-wide parameters for WY2010: a) average depth snow depth, b) soil moisture ad varying depths.

We have submitted a manuscript to WRR that investigates optimal sensor placement and estimation techniques, quantifying the effect of placing further sensors on prediction accuracies (Kerkez et al., 2011a). The paper demonstrates that there is a limited amount of information to be gained with the placement of each additional sensor. A second manuscript (Kerkez et al 2011b) shows that the spatial distribution of optimal sensor locations follows a non-uniform pattern that is guided by topological parameters and site-specific covariance structures.

We have presented our work as a novel interpretation of structural health monitoring in March at the 2011 SPIE conference (Kerkez and Glaser, 2010), as well as the Western Snow Conference. We have presented our work at a Sensor workshop organized by Glaser at the Technical University of Munich in June of 2010. Kerkez has worked with Centria Univerist, Ostrobothnia, Finland. He visited in September of 2010 in order to teach the local researchers the theory of wireless sensor networks and help them install the network of our design.

We have been featured in multiple stories and interviews in the press. The articles and clips are available at snri.ucmerced.edu/CZO/news.html. This has led to multiple inquiries about our methods and hardware from both scientists and commercial end users.

Snow and soil processes. Observations made during the three snow surveys and two soil moisture surveys from WY2010 have been compared to observations made by the ground-based water balance instrument cluster. Figure 6 shows that the variability in snow depths observed during the surveys were also observed by the sensor network. Approximately 30 cm of melt occurred between the first and last survey. The mean snow depths observed by the network were 131, 107, and 101cm, while survey means were 137, 121, and 103 cm. The network means were within 2 to 14 cm of the survey means, with the smallest difference occurring during the April peak accumulation survey.

During the April 7, 2010 survey, snow depth observations ranged from 20 to 239 cm, while the Network ranged was 8-222 cm. Observations during the March 14th and March 20th, 2010 surveys included no-snow observations. However, the network did not observe any zero values.

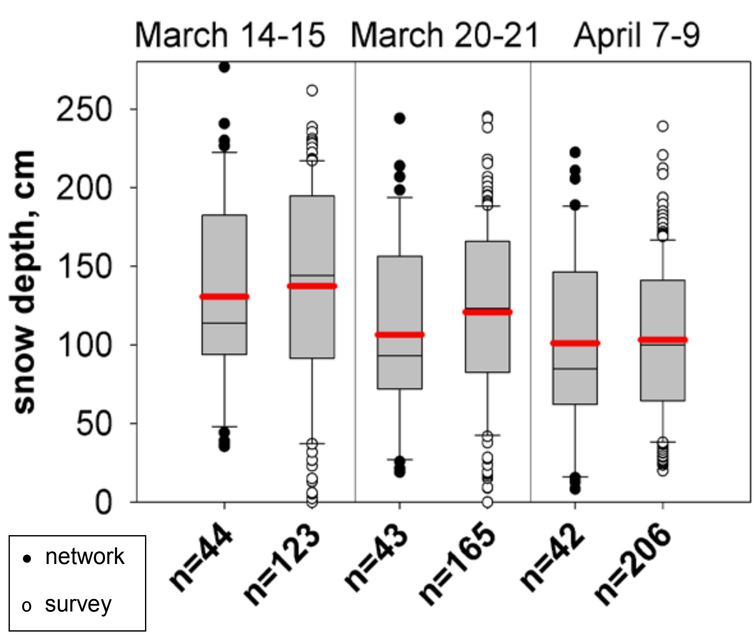

Figure 6. Snow depth observations made by the ground-based instrument cluster and survey observations. The horizontal black line in each box represents the median snow depth value, while the red line indicates the sample mean. Three separate surveys occurred, indicated by the dates above each network/survey pair. Sample sizes are indicated on the x-axis.

Figure 7 shows that the variability in soil moisture observed during the surveys were also observed by the sensor network. The instrument cluster observations are from 10 cm probes, while survey observations are from integrating over top 20 cm of soil. Some of the outliers with high volumetric water contents were located in meadows or near streams. Both the network and the survey observations were about 11% drier during the September survey. The mean volumetric water contents observed by the network were 22 and 11%, while survey means were 19 and 9%. The network means were within 2 to 3% of survey means, which is within the error of the soil moisture sensors. Zero values reported during the survey are from grid points located on bare rock. Ignoring the zero values the June survey ranged between 2 and 67% volumetric water content and the September, 2010 survey ranged between 4 and 43%. The network volumetric water content observations ranged between 6 and 52% in June, and

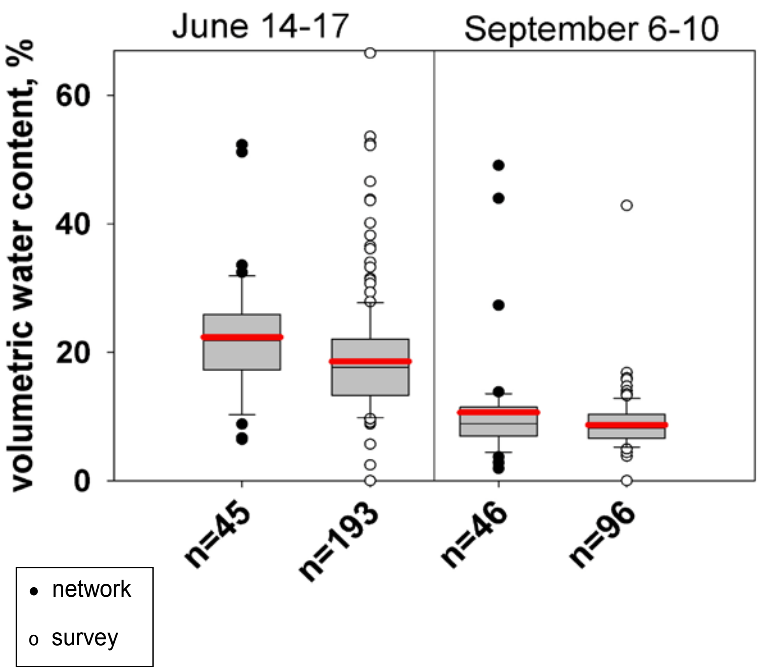

Figure 7. Soil moisture observations made by the ground-based instrument cluster and survey observations. Instrument cluster observations are from 10 cm probe, survey observations are from integrating over top 20 cm of soil. The horizontal black line in each box represents the median soil moisture value, while the red line indicates the sample mean. Two separate surveys occurred, indicated by the dates above each network/survey pair. Sample sizes are indicated on the x-axis.

between 2 and 49% in September, 2010.

For the April 7-9, 2010 peak-accumulation survey, we used a Gaussian process non-linear regression model to predict snow depth throughout the basin. The model used a 30-m DEM along with our network observations to model the snow depth distribution and is based on variables that include: solar radiation, slope, aspect, elevation, and northness (Figure 8). We estimated the error of this model by comparing the model predicted snow depths to the snow depth survey observations (Figure 9). Spatial proximity to sensors is not indicator of model performance. Rather, prediction error is directly tied to ability to capture the physiographic features of solar radiation, slope, aspect, elevation, and northness with the instrument cluster observations. The average predicted depth was 106 cm with a mean error of 35 cm. That said, the preliminary result from the model gives about 33% error while using less than 50 network observations. Because a 30-m DEM was used for this analysis, multiple sensor nodes are incorporated into a single pixel, which reduces our usable number of network observations.

We have captured the dynamics of the soil profile desiccation at various depths beneath the snow pack as it transitioned from saturated to very dry conditions. Tensiometer data within the plot shows the cessation of drainage out of the root zone by early July, leaving an extended period (3+ months) of drying of the soil profile and an estimate of actual ET (Figure 10). Through monitoring of sap flux and periodic leaf water potential measurements, we tracked the activity of the trees as they responded to changing available moisture in the root zone. Water content, temperature, and soil water potential were measured in six vertical pits across the site. Soil water mass balance was used to estimate ET rates using average VWC from the vertical pits. We found remarkable similarity between independent estimates of ET in the trunk and of water removal from the soil. More than 40% of annual ET takes place during this period where soils <90cm are extremely dry (Figure 11). On an annual basis, soil moisture removed from this shallow layer accounts for only a fraction of the total mass loss. Root zone excavation results show limited root extension into deeper layers. How are the trees accessing this deeper moisture? One possibility is that the trees themselves, or successive generations of trees, have created depressions in the saprolite, through chemical activity, where water can be stored locally. Limited measurements seem to indicate an increase in soil depth beneath the trees (Figure 12).

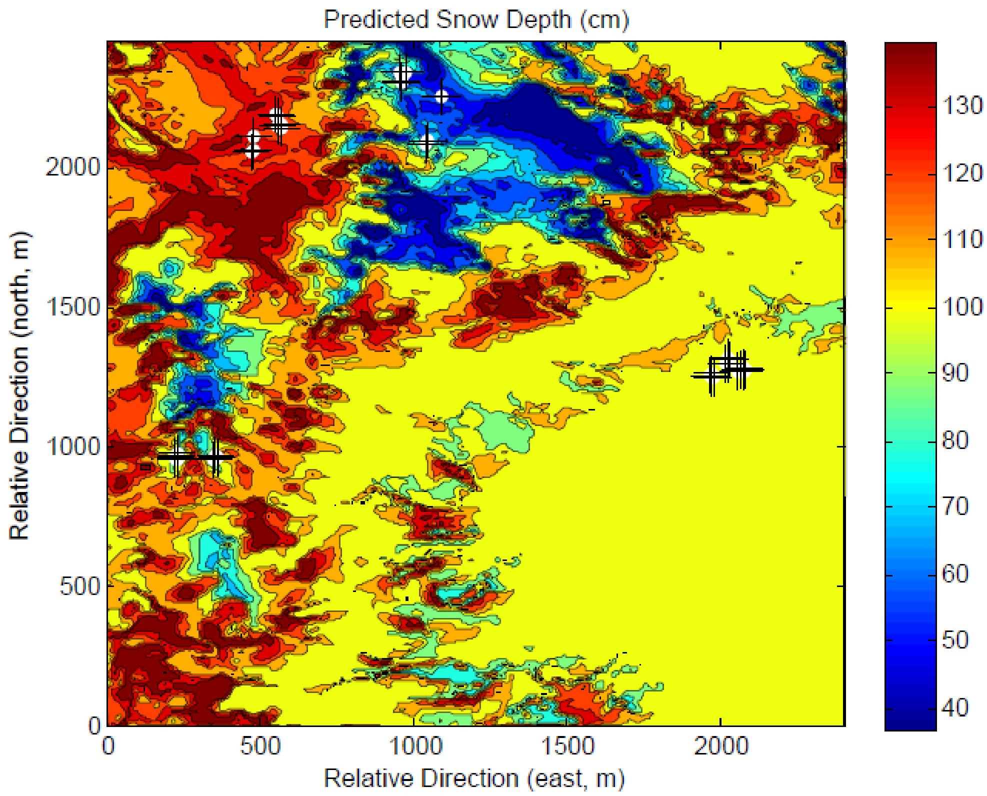

Figure 8. Predicted snow depth based on Gaussian process model. The sensor network locations are indicated with black crosses. Red indicates deep snow and blue is shallow snow.

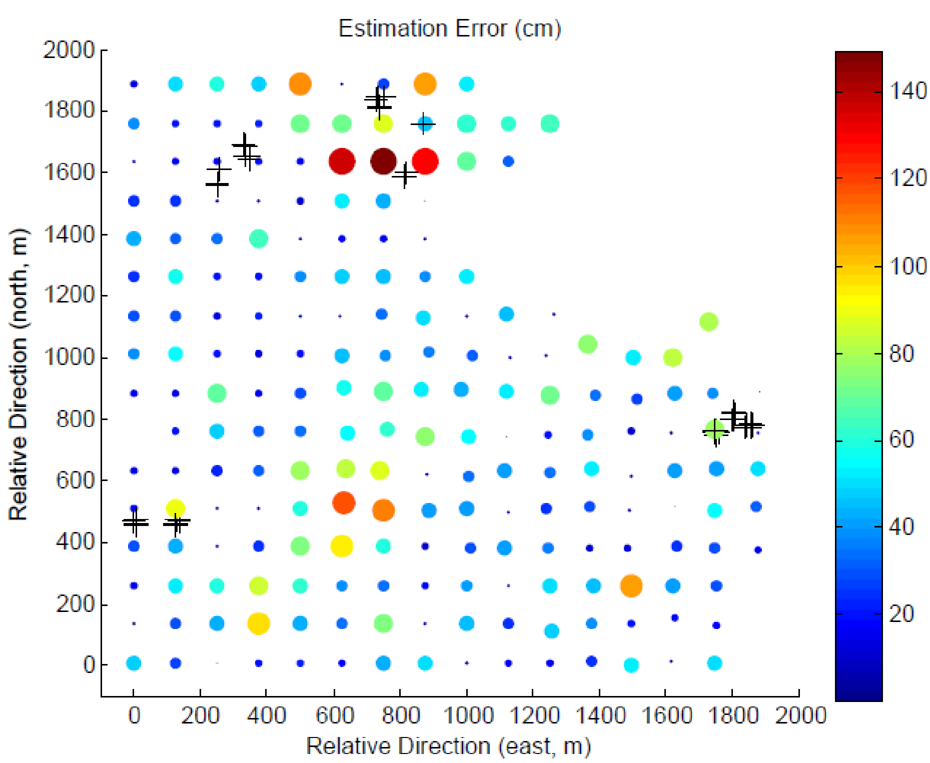

Figure 9. Estimation error of predicted snow depth based on Gaussian process model. The sensor network locations are indicated with black crosses. Big-red circles indicate locations with high error and small-blue indicate locations with low prediction error.

Figure 10. Water content, temperature and soil water potential measured in six vertical pits across the site. Measurements are shown at multiple scales, for a 2-year period (above) and a shorter, 3-day time frame (below).

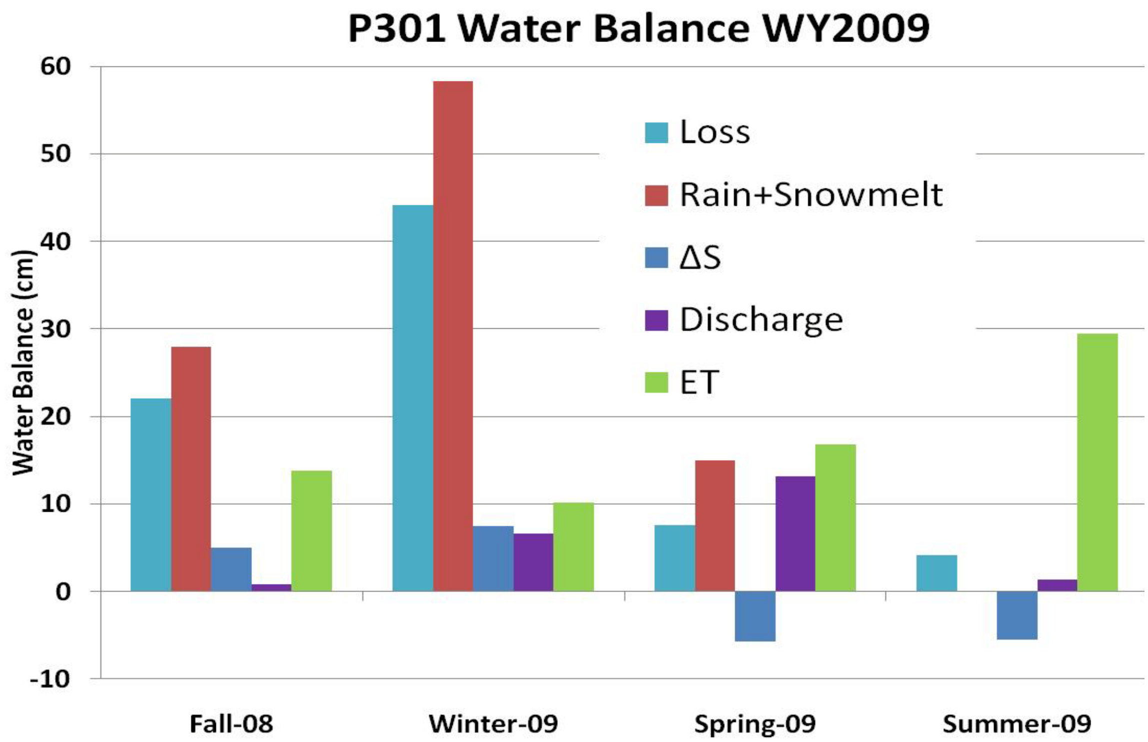

Figure 11. Water balance based on CZT-1 and water balance instrument cluster data for WY 2009.

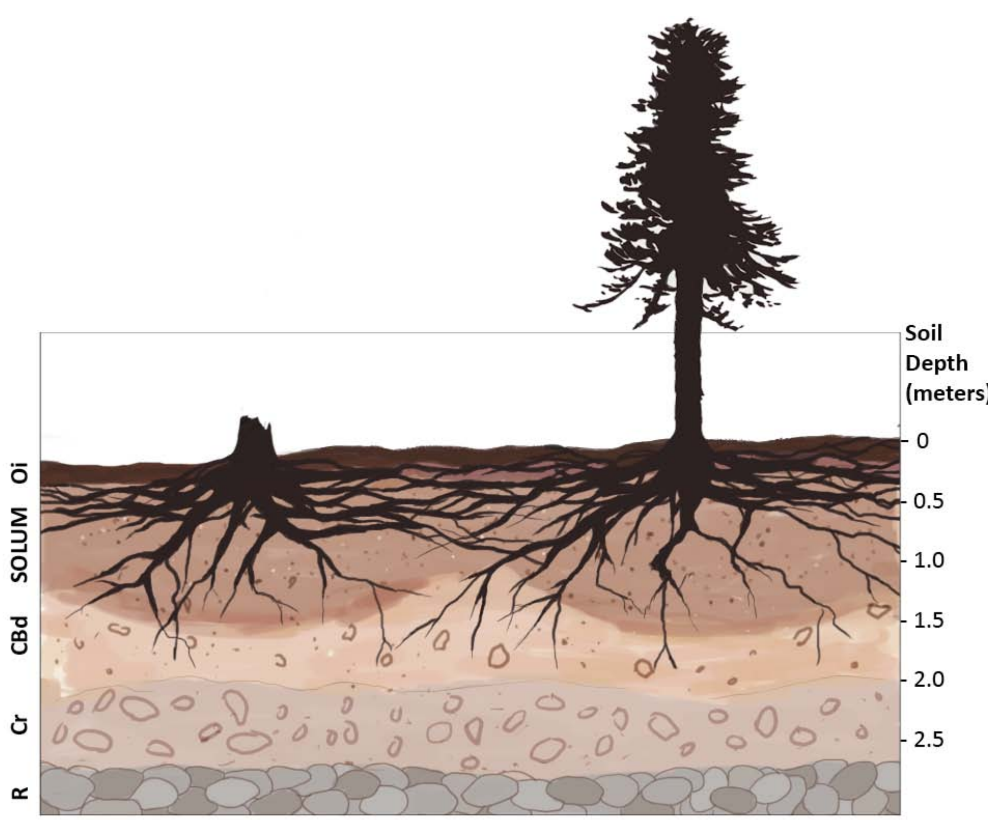

Figure 12. Schematic layout of the excavated tree with inferred root architecture. Diagram shows root density decreasing with depth and the potential for soil depth to be influenced by the tree directly beneath the footprint.

The sensors were reactive to moisture and temperature variations on multiple timescales. Data show the dynamic response of soil moisture to precipitation, snow melt, and changes in vegetative demand. We demonstrate here the initial two years of a multi-year deployment of soil moisture sensors as a critical integrator of hydrologic/ biotic interaction in a forested catchment as part of a wider effort to document ecosystem response to changing environmental inputs. Sap-flow sensors were responsive to fluctuations in air temperature and solar radiation and values declined along with soil moisture availability. Each tree was instrumented with four sensors and variability was seen around the stem. While the magnitude of total flux may contain considerable uncertainty, the timing is very consistent and can be used to determine when trees are transpiring (Figure 13). Leaf water potential values were measured over a 24 hour period, once per month during the summer drying period and corresponded to changes in available soil water.

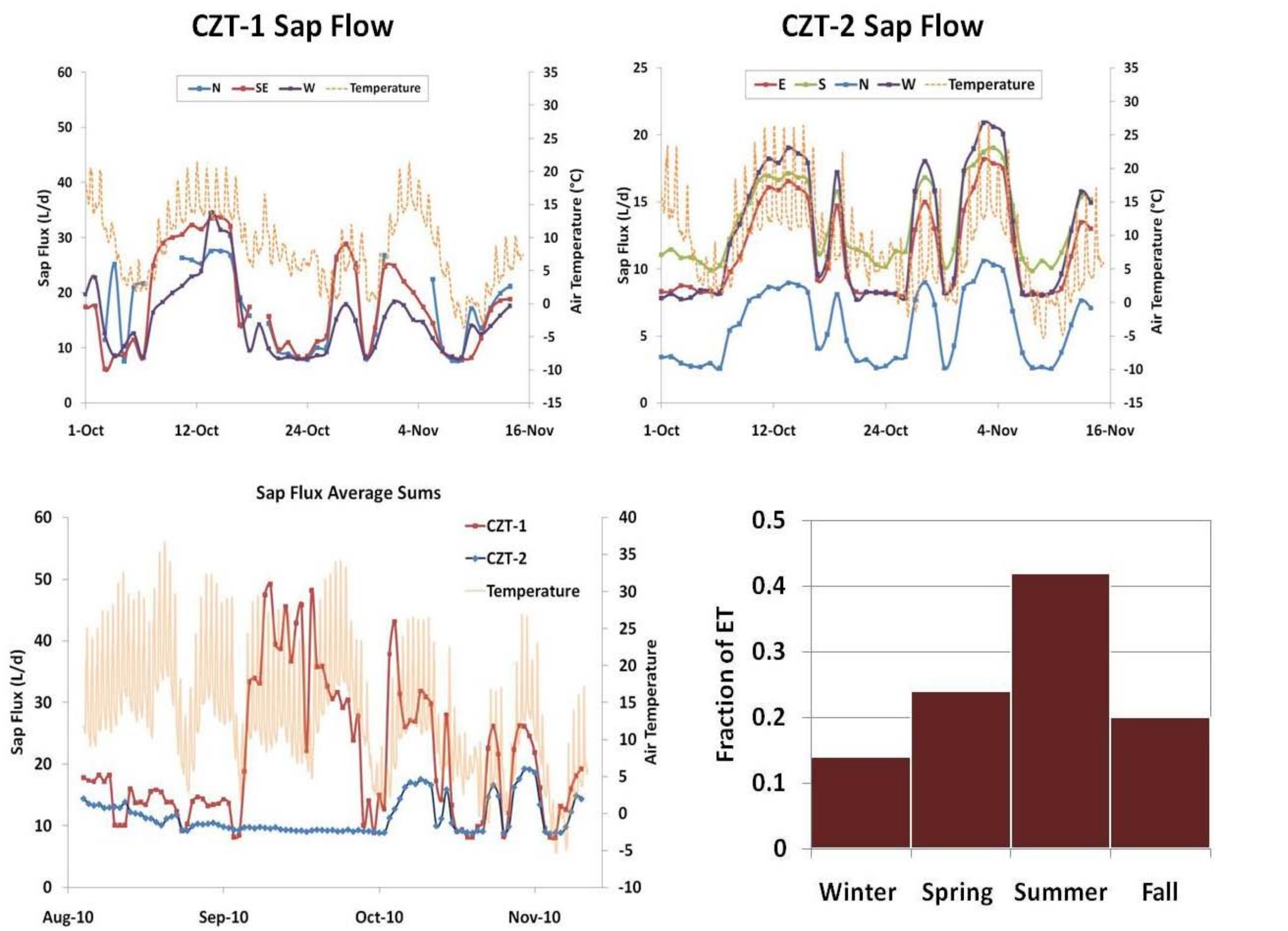

Figure 13. Sapflow sensors at both sites showing response to air temperature. Also shown is the near cessation of sap flow at CZT-2 in Fall 2010 due to thin soils and lack of available soil water. Seasonal timing of sap flow can be estimated as a faction of annual ET taken from the water balance.

Water, geochemical cycles, and upscaling of in-situ measurements. Day of snowcover melt out measured in the Wolverton basin ranged 55 days with the mean being 10 days earlier for the aspect tree and then the north aspect tree (Figure 14). Data from three years of surveys was analyzed for snow depth difference between under canopy and open locations (Figure 15). These surveys indicate greater variation in depth occurs in seasons with less snow suggesting decreased snowpacks will result in greater spatial variability. Similar spatial patterns persist each year with patterns being most pronounced in the very dry 2007 water year and least pronounced in the wettest water year analyzed (2008). Data from the California

Cooperative Snow Survey course located in the study area indicate precipitation was below average in 2007, above in 2008, and close to average in 2009. The mean depth for all measurements was 74.5 cm, 191 cm, and 135 cm, respectively, with 51, 24, and 35 percent difference between the under canopy and open measurements. Soil moisture records indicate melt started prior to the snow surveys in 2007 (March 10-27) after the survey in 2008 (April 10-May 15) and close to the time of the surveys in 2009 March 25 – April 18).

Spatial heterogeneity in snow depth, density, and soil moisture infiltration are influenced by orientation to and proximity with tree canopies. Differences between the open and under canopy are most prominent in locations that have high solar incidence during ablation. Conversely, snow lingers in forest gaps that are shaded by large canopies. Density measurements are higher by up to 40% in some under canopy locations suggesting snow melting off canopies and refreezing in the snowpack during the accumulation period.

Figure 14. Day of snowcover melt out around a Southeast aspect tree and a North aspect tree.

Figure 15. Percent difference between snow depth measured under canopy and in the open for 2007-2009. Percent difference between under canopy and open depth are arranged for comparison with 75 year mean snow course depths to demonstrate a progression to earlier and more variable melt dates.

Spatial interpolation of the percent difference between open and under canopy depth measurements show the largest differences between under canopy and open snowpack on April 1st are found in locations with the highest solar insolation following the last major storm of the accumulation period. However, modeled clear-sky irradiance does not fully explain the distribution because the effects of forest structure and canopies are not taken into account. Canopy interception and redistribution of snow and their influence on the energy balance are also important.

Long and short wave radiation plots for south and north aspect trees are presented in Figures 16 and

17. Future work will focus on using established relationships between canopy cover and incoming radiation to predict under canopy ablation to enhance the accuracy of snow cover prediction made in forested areas using Moderate-resolution Imaging Spectroradiometer Snow Covered Area images.

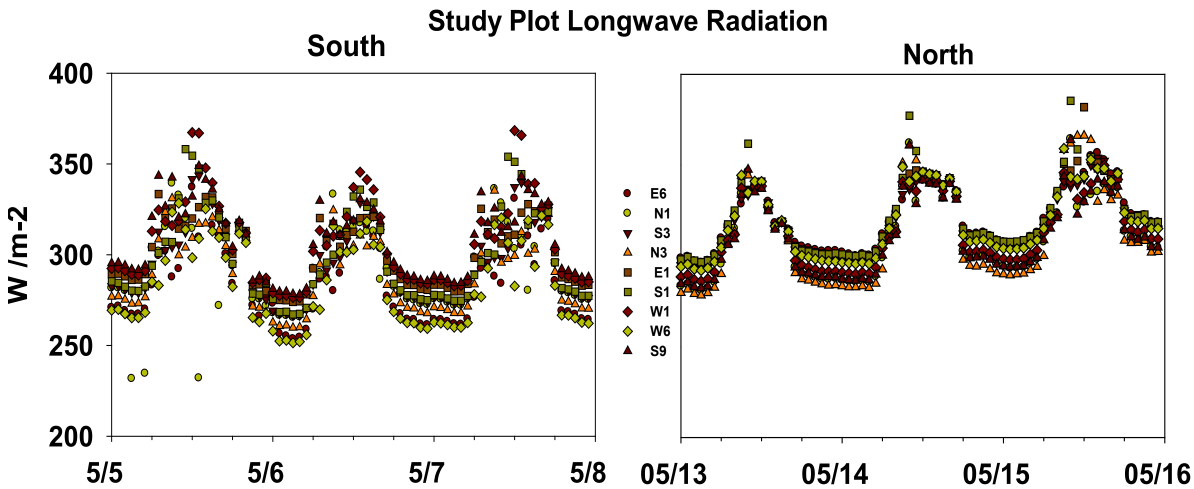

Figure 16. Longwave radiation plot for south and north aspect tree for 6 days during May 2010.

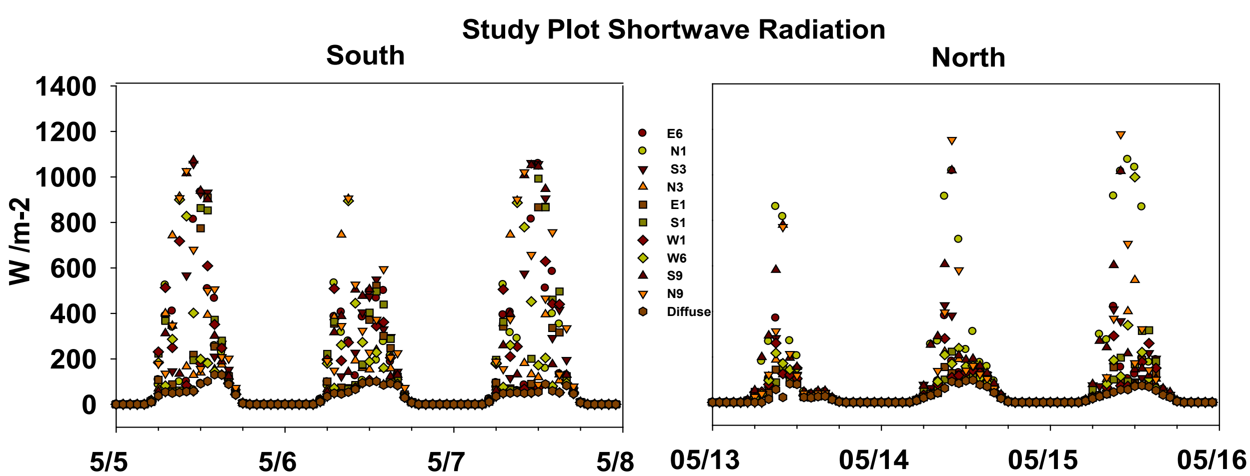

Figure 17. Shortwave radiation plot for south and north aspect tree for 6 days in May 2010.

The percent snow cover determined by MODSCAG from peak accumulation and melt out during the 2008 and 2009 water years were compared to ground observations of both forest gaps and under canopies. Ground based measurements indicated that under-canopy melt out of snow-covered area began earlier and ended 1 to 4 weeks after that indicated by satellite observations, which can only view snow in forest gaps. In our study ablation rates, snow cover duration, leaf area index, canopy closure, and Incoming short and long wave radiation were measured on north and southeast facing plots in a subalpine red fir forest. Results from regression analysis yield an R^2=0.99 between modeled and measured short wave radiation and an R^2=0.82 between leaf area index and the difference between open and under canopy thermal infrared radiation. Canopy cover and leaf area index were also found to be good predictors of observed melt rates and the melt off date of snow under tree canopies. This approach provides a basis for estimating under canopy ablation and, in conjunction with MODSCAG estimates of snow covered area in forest gaps, an accurate prediction of total snow cover in forested areas.

Critical Zone Tree (CZT) monitoring and root excavation. Key science findings include: seasonal water content changes, measurements of ET and drainage from the plot, estimates of changing snow depth and soil moisture contents based on canopy cover and interception, and comparison of soil/tree water relationships between two sites with varying species, slope and aspect. Soil-water balance data contributed to a better understanding to watershed scale water balance. The radial network of shallow MPS-1 sensors shows a distinct pattern of shallow soil water depletion over the course of the summer (Figure 18).

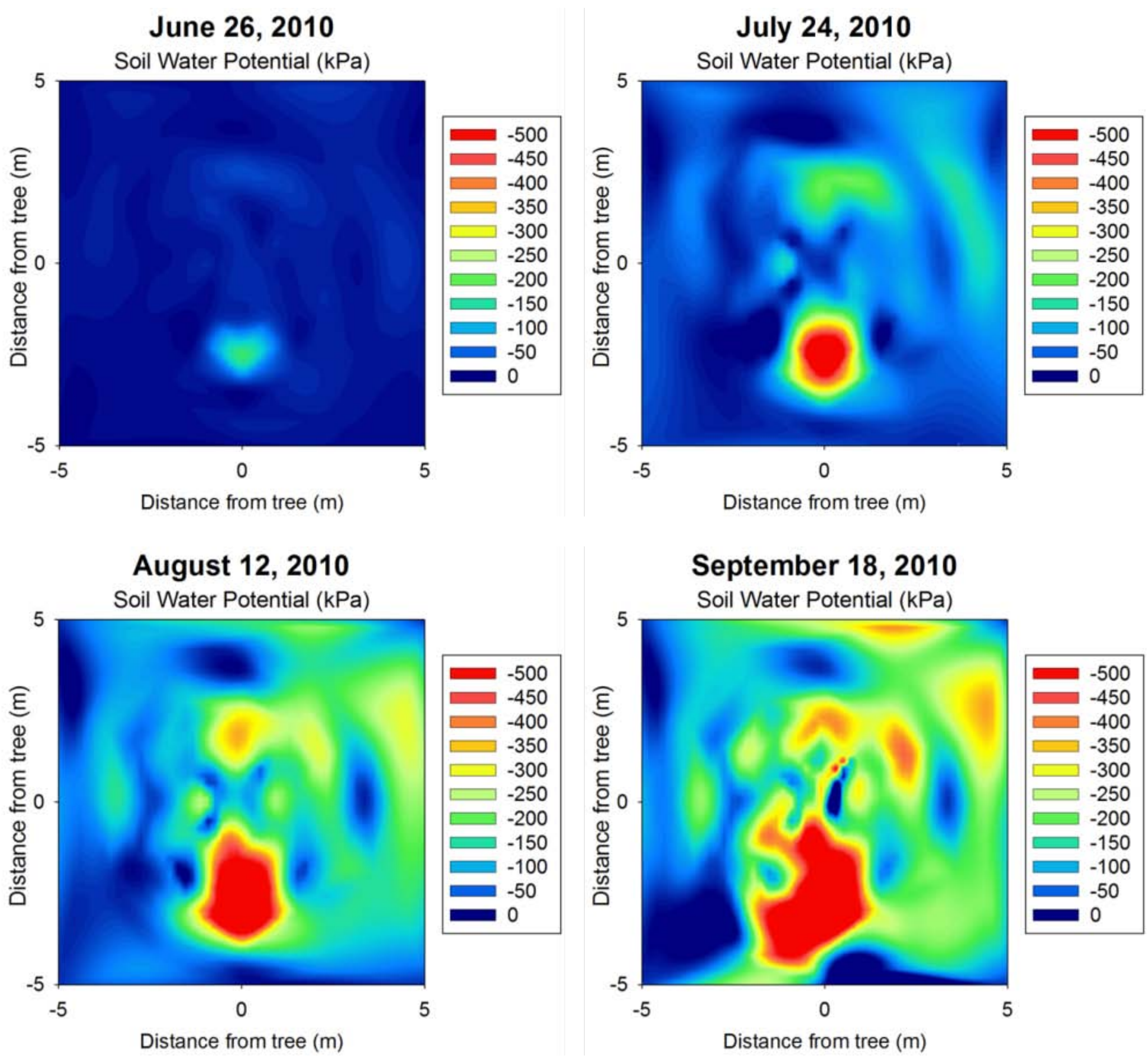

Figure 18. Plots tracking spatial results of the radial array of shallow MPS-1 sensors measuring soil matric potential as root roots deplete shallow soil water over the course of the summer.

We determined that the majority of the roots and nearly all of the fine roots were in the top 60 cm, with the root density highest from 30-60 cm. The root distribution was axial symmetric around the tree. Most (>90%) of the roots were contained within the 5-m radius of the excavation and within the 2 m of soil beneath the tree. Below 2 m, the soil quickly graded to saprolite in various states of weathering, which was difficult for the tree roots to penetrate. Figure 19 shows the preliminary results of the root

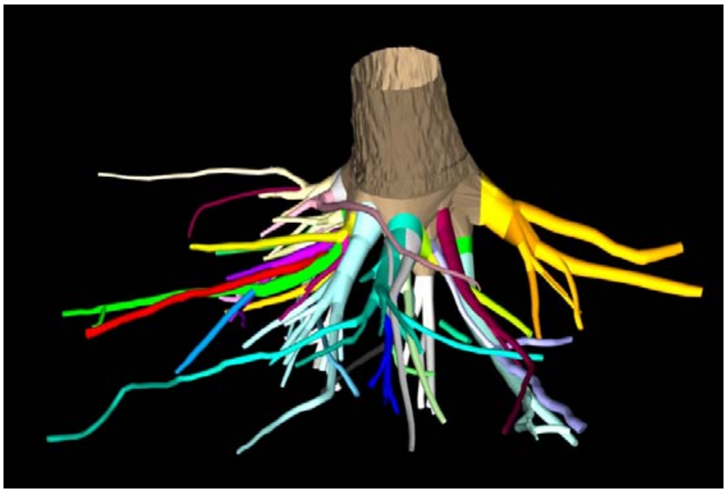

Figure 19. Results of the root model made from the LiDAR data of the root scan.

model constructed from the LiDAR of the excavated roots. The forward model, using a root distribution taken from the excavated tree, has thus far been able to predict water depletion from the soil from ET and deep drainage (Figure 20). The next step will be to build deeper soil and saprolite water storage into the model to fully account for shallow and deep soil water redistribution. The model predicts that the trees remain free of water stress in the later summer by accessing the deeper moisture pools.

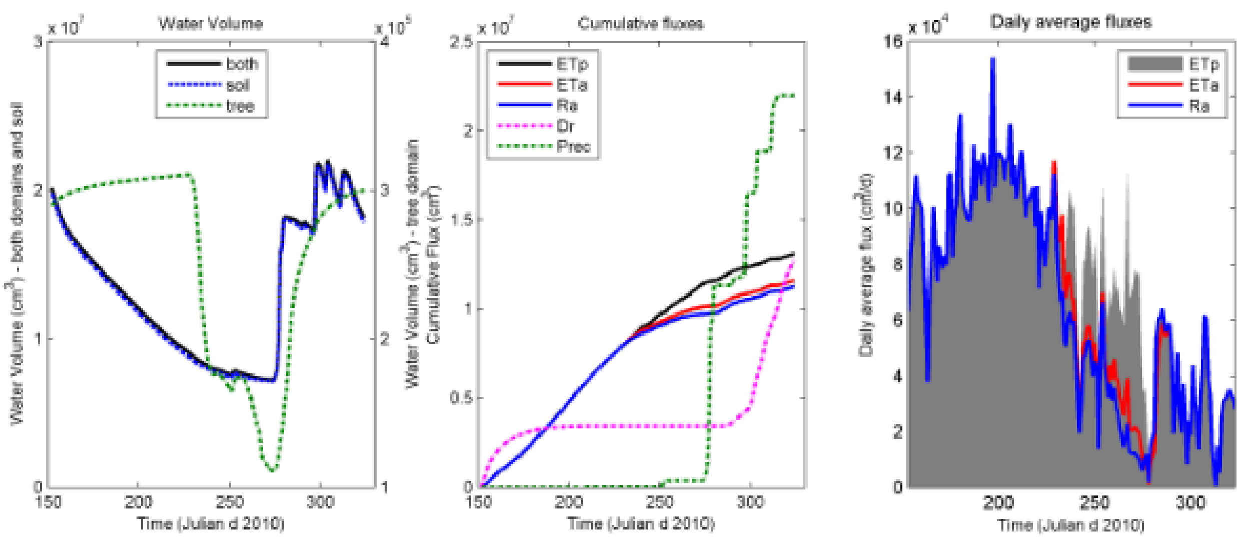

Figure 20. Coupled model results.

Surface-groundwater interactions. Results from analysis of the Wolverton Creek discharge data for July to November, 2008 are presented in Figure 21. The calculated groundwater discharge from Long Meadow indicates a significant groundwater contribution from Long Meadow. Calculated groundwater discharge, also presented in Figure 21, indicate that groundwater is discharged from the center of the meadow throughout the dry season and from the slope of the meadow for most of this time frame, while a negative flux persists at the meadow edge.

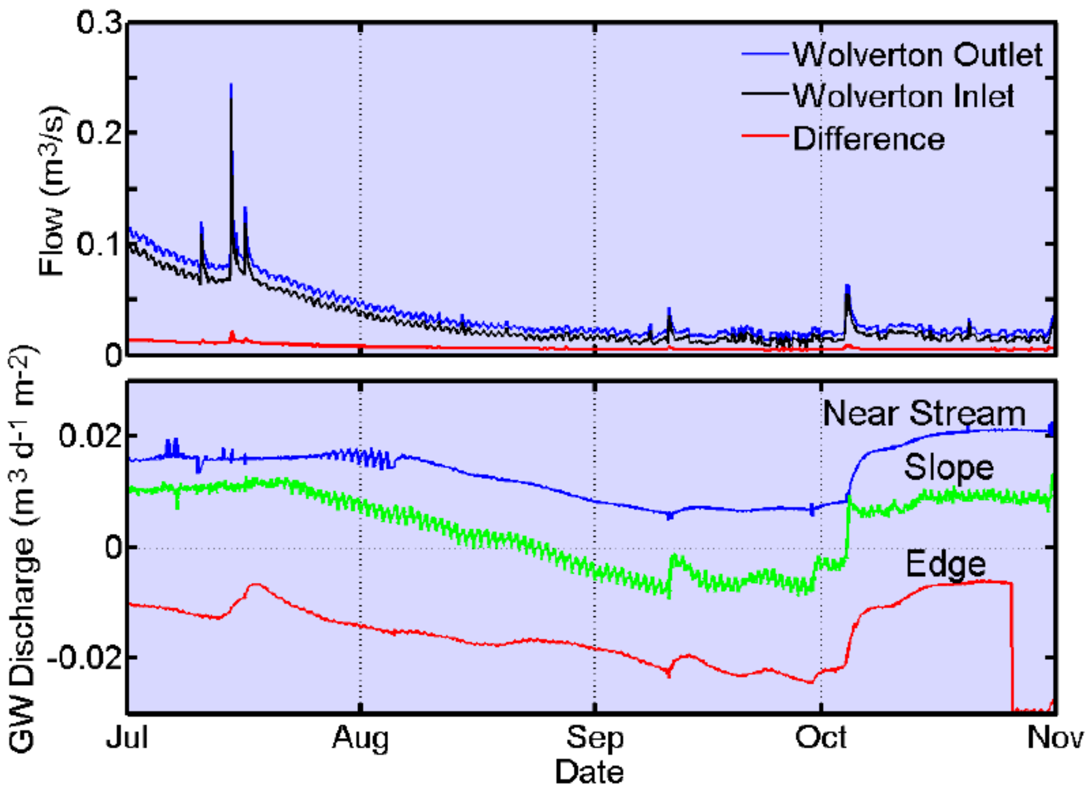

Figure 21. Stream Flow at Wolverton Intel, Outlet, and calculated discharge from Long Meadow (top); and groundwater flux from calculated from piezometer clusters in Long Meadow (bottom), 2008.

Groundwater flux at each location shows a quick response to the precipitation event that occurred in early October. This event is reflected in the discharge data. Evapotranspiration (ET) data calculated from the meadow wells is presented along with chamber ET measurements, calculated potential evapotranspiration (PET) from the nearby Wolverton meteorological station, and recorded precipitation for July to October, 2008 are presented in Figure 22. These data indicate that the edge and slope well calculated ET capture the chamber measured ET in July 2008. These values are higher than the PET calculated from the forest met station; the PET values from the forest met station may be low due to variation in solar radiation, air temperature, relative humidity, and wind speed. The well near the meadow stream underestimates ET in July but captures the chamber measurements in August and September. All three of the wells and the chamber measurement show strong ET signals after PET falls off and well after meadow vegetation senesces. This indicates that the meadow groundwater is connected to the ET behavior of the forested hillslopes adjacent to the meadow.

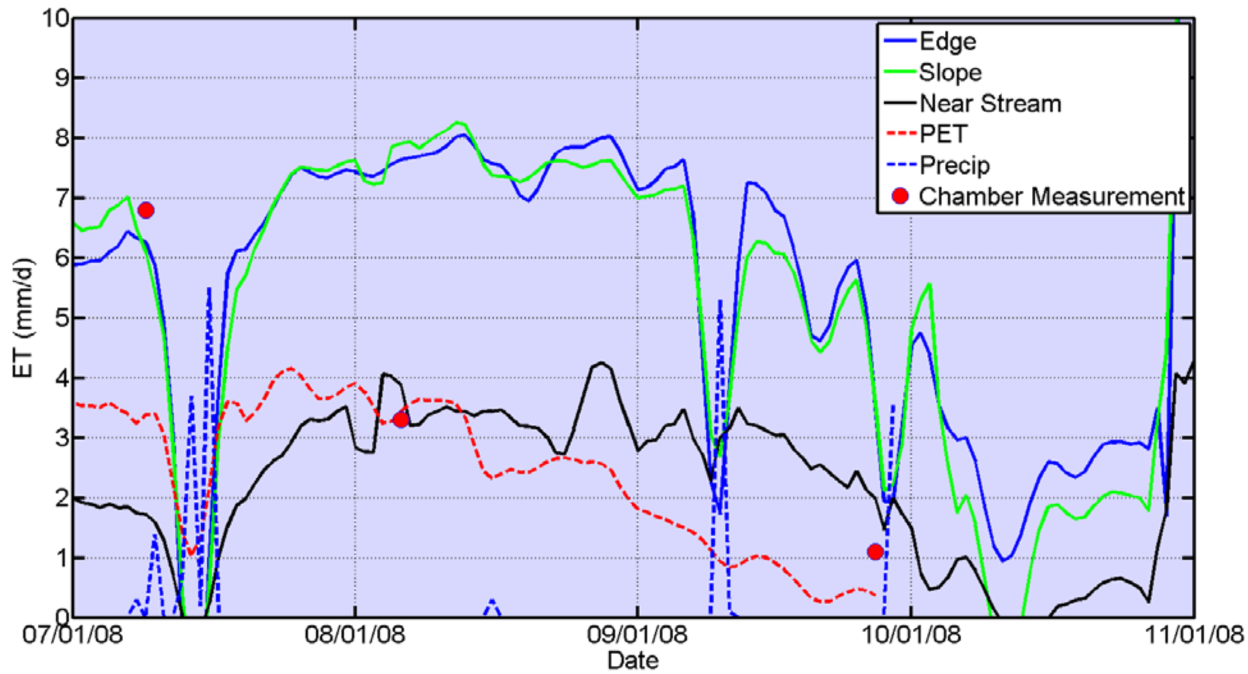

Figure 22. ET calculated from meadow monitoring wells, chamber measurements, PET calculated from the Wolverton Met Station, and precipitation, 2008.

Initial calculations of groundwater flux, ET, and meadow discharge are presented in Table 1. The results indicate that subtracting ET from groundwater flux results in a stream discharge on the order of magnitude as the discharge calculated from the Wolverton Creek data.

Table 1. Calculated ET and groundwater flux from 3 meadow well/piezometer clusters.

	Full meadow area Jul-1 to Nov-1	Sans ski shop meadow Jul-1 to Nov-1	Sans ski shop meadow Jul-1 to Oct-1	
SM1 (edge)	-1.32×10^5 m^3	-9.90×10^4 m^3	-1.32×10^5 m^3	Flux
SM5 (near stream)	4.33×10^4	3.25×10^4	1.60×10^4	
SM4 (slope)	1.68×10^4	1.26×10^5	8.35×10^4	
SM1 (edge)	7.00×10^4	5.25×10^4	3.16×10^4	ET
SM4 (slope)	6.36×10^4	4.77×10^4	4.12×10^4	
SM5 (near stream)	2.64×10^4	1.98×10^4	1.80×10^4	
	Stream Discharge	8.13×10^4	6.52×10^4	

Relative groundwater elevation from one of the installed saprock wells is plotted along with groundwater elevation from 2 associated meadow wells are presented in Figure 23. These data illustrate the connectivity between the meadow groundwater and the adjacent forested hillslopes. The saprock well and meadow wells show similar response times to forest ET (the meadow vegetation has senesced by this time) and precipitation events.

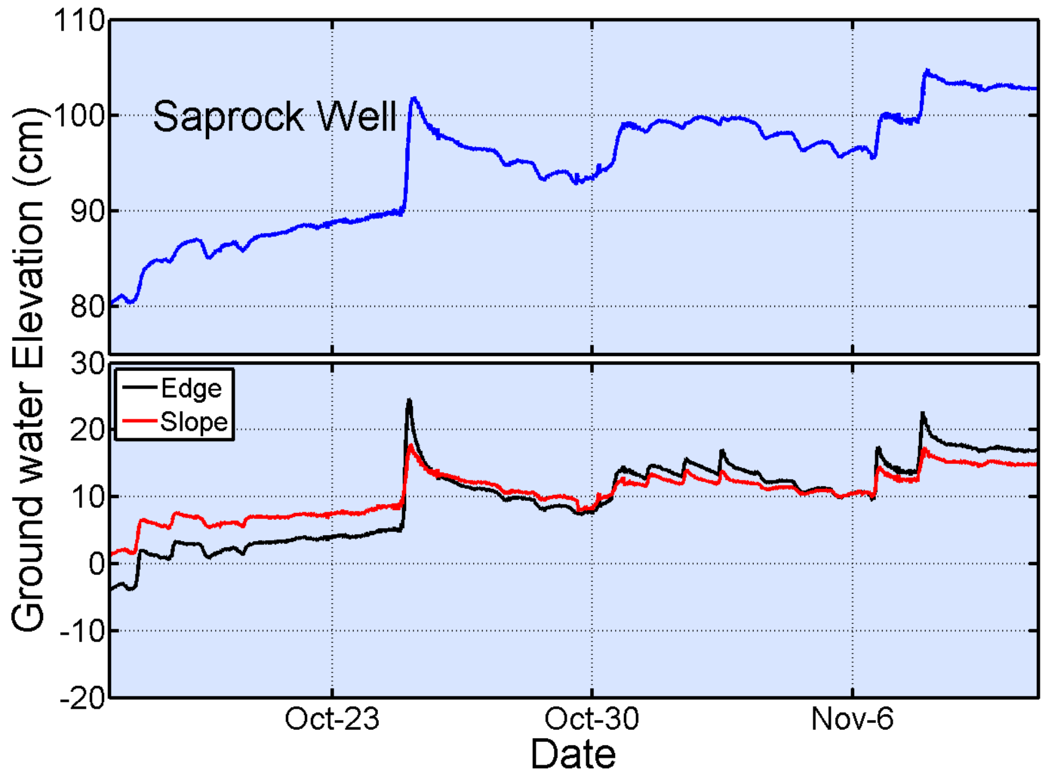

Figure 23. Relative Groundwater elevation for the monitoring well installed in the saprock (top) and two meadow monitoring wells (bottom), 2010.

Results for model simulations run with 0.01 m/s stream velocity, varying ground water input velocity, and light attenuation coefficients are presented after 4 hours of simulation (Figure 24) and 8 hours of Simulation (Figure 25). After 4 hours of run time, the simulations run with 0.9 m^{-1} light attenuation coefficient (K_d) exhibit better agreement with the measured vertical temperature profile of the pool than the simulations run with K_d = 0.3 or 0.6 m^{-1}. In addition, the simulations run with 10^{-7} and 10^{-6} m/s ground water input velocity demonstrate better agreement with the observed temperature data than the simulations run with no ground water input and with the relatively high ground water input velocity of 10^{-5} m/s. After 8 hours of model run time, the simulations run with K_d = 0.3 m^{-1} show the best agreement with the observed data. The light attenuation coefficients used for the model simulations are varied to represent attenuation coefficients determined by varied DOC concentrations; we used the power function for light attenuation developed by Bukaveckas and Robbins-Forbes (2000). A coefficient of 0.9 m^{-1} would result from approximately 5 mg/L DOC, which is the highest DOC concentration measured during the 2008 deployment. Lower light attenuation coefficients, 0.3 and 0.6 m^{-1}, are representative of lower DOC concentrations. Better model agreement with the higher K_d after four hours of simulation indicates that DOC is high at this time (~2 pm PST), whereas better model agreement with the lower attenuation coefficient after 8 hours of run time indicates that DOC concentrations have dropped off by this time (~ 6pm PST).

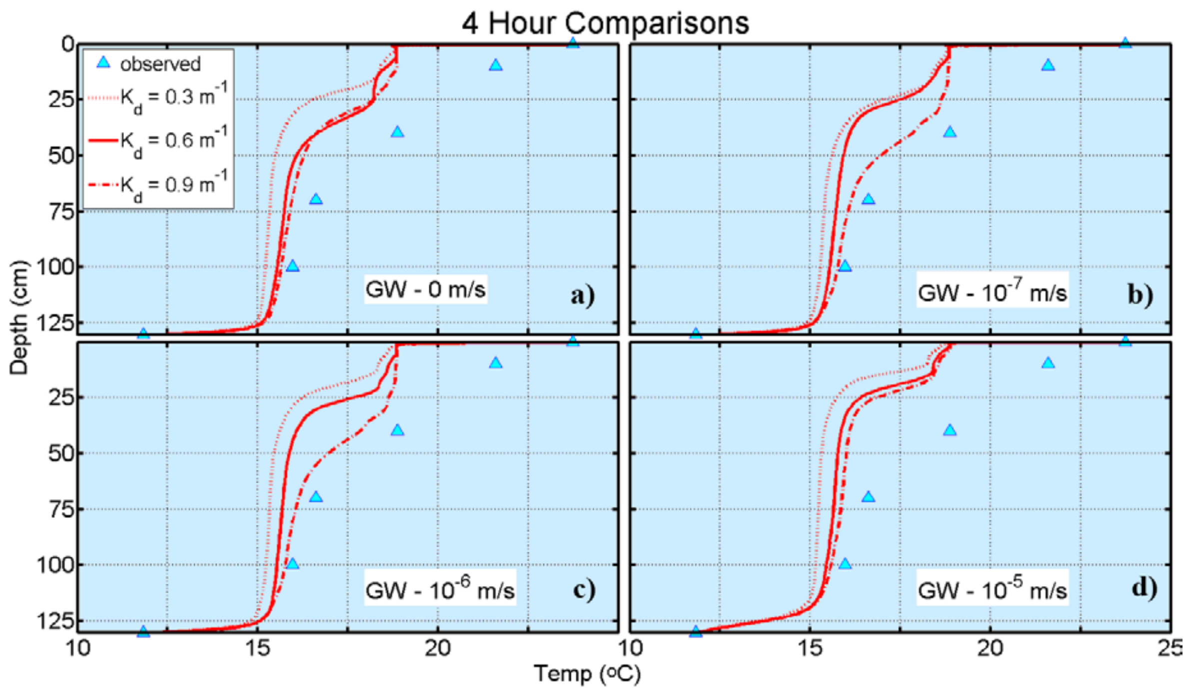

Figure 24. Fluent model simulations compared to measured pool temperatures after 4 hours run time for light attenuation coefficients (K_d) of 0.3, 0.6, and 0.9 m^{-1} and ground water input velocity of 0 (a), 10^{-7} (b), 10^{-6} (c), and 10^{-5} (d) m/s.

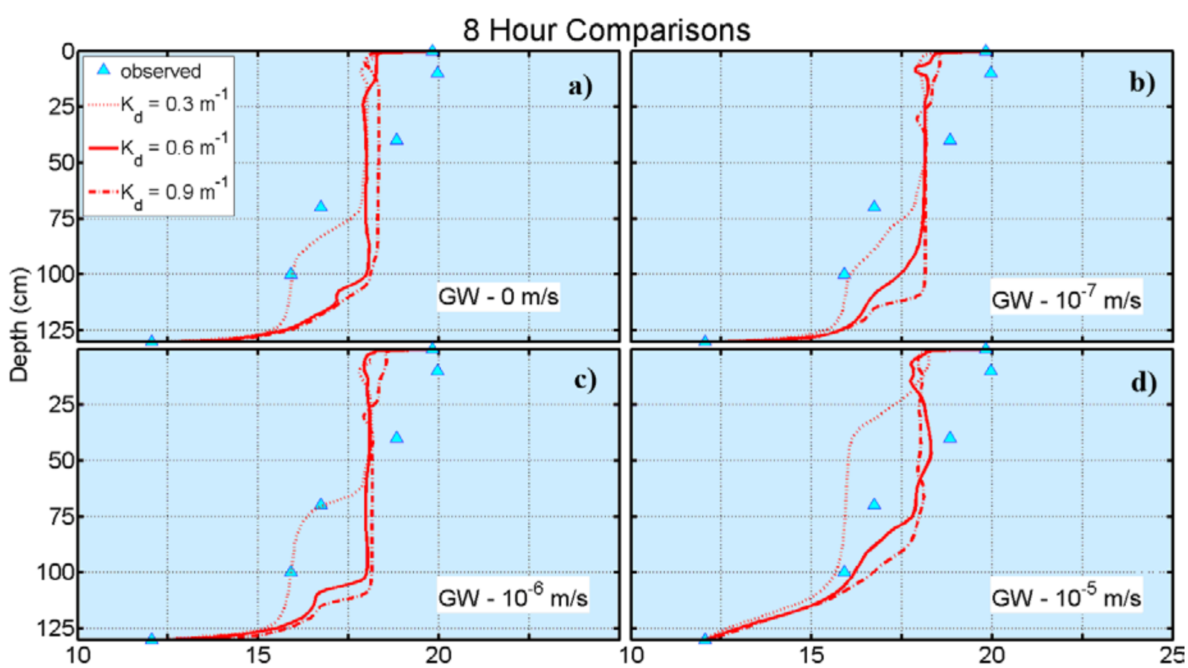

Figure 25. Fluent model simulations compared to measured pool temperatures after 8 hours run time for light attenuation coefficients (K_d) of 0.3, 0.6, and 0.9 m^{-1} and ground water input velocity of 0 (a), 10^{-7} (b), 10^{-6} (c), and 10^{-5} (d) m/s.

Results from the Fluent modeling efforts suggest that stream velocities over the top of the thermally stratified pools are on the low end of flows measured in the meadow. Model results with the greatest agreement with the observed data were obtained using groundwater inputs of 10^{-7} and 10^{-6} m/s which are in agreement with near stream piezometer data at the time the model simulates. The modeling results also indicate that DOC in the pool water column has an important role in determining light attenuation and, subsequently, thermal stratification in the pools. These results also indicate that DOC concentrations are dynamic over the course of the day, with high values in the early afternoon and lower values into the evening.

Physical controls on water and carbon exchange and plant production. The low elevation (380 m) tower shows peak photosynthesis in late winter and spring and reduced carbon uptake during summer drought (see Activities Figure 14). The 2020 m tower indicates forest photosynthesis is not markedly reduced by either midwinter cold (despite a very heavy snowpack) or late summer drought. Preliminary observations at the 1200 m site also show high rates of photosynthesis continuing in late summer and winter. The 2710 m tower indicates winter photosynthetic shutdown down at higher elevations. The trees at 2710 m are dormant during the winter, and active photosynthesis is not observed even on warmer days. There is a very sharp phenological threshold between 2020 and 2710 m that roughly coincides with the daytime freezing line and that results in a much shorter growing season up high.

Sap-flow data (Figure 26) show a similar seasonal pattern of canopy gas exchange. In late August, the ecosystem should be experiencing maximum summer drought stress. We find that cooler temperatures in late summer allow more CO_2 uptake, and upper canopy temperatures are cooler than surface temperatures. This confirms the trees at the P301 site do not cease active gas exchange in summer due to drought and suggests the cooler upper canopy mitigates the limitations on productivity of summer drought.

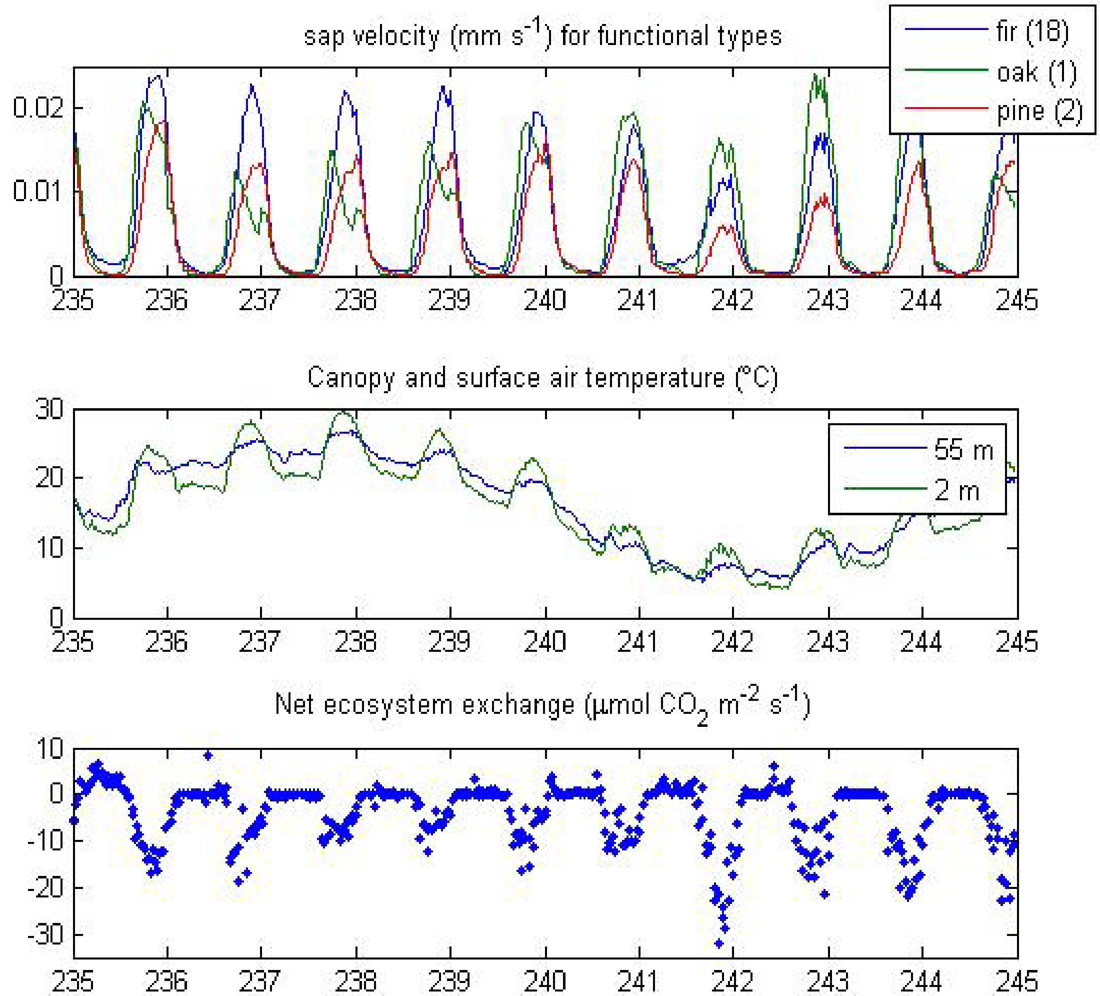

Figure 26. Sap flow compared to canopy top air temperature and carbon flux for late August 2010.

Ongoing measurements are revealing trends in biomass, net primary production (NPP), and carbon turnover rate along the climate gradient (see Activities Table 1). Biomass increases with elevation, peaking at 2020 m and diminishing somewhat above. Aboveground NPP (ANPP) broadly follows this trend, except at the highest site, where ANPP declines disproportionately. The difference between ANPP and biomass drives a shift in carbon turnover time; the biomass at 2710 m turns over at only one quarter the rate observed at the lower sites. This shift in carbon residence time has implications for the ability of these forests to sequester and hold large carbon stocks.

The very sharp reduction in ANPP from 2020 m to 2710 m coincides with the threshold where winter photosynthesis becomes impossible. The 2020 m site, and, to a lesser extent 1,200 m site, exist in a climatological “sweet spot” where photosynthesis continues year round (see Activities section Figure 14). This helps explain the large forest stature, high standing biomass, and high productivity of these ecosystems. We see significant summer drought limitation below this belt (at the 380 m elevation site) and significant cold limitation above the belt (2710 m site). With projected climate warming and drying, we expect a decrease in biomass and NPP at lower elevations, an increase at upper elevations, and unknown changes at the middle elevations.

Dynamic spatial-modeling of water and nutrient cycles. RHESSys (Tague and Band, 2004) was calibrated with existing CZO data, including snow depth, soil moisture, sapflux, ET from the flux tower and streamflow. Calibration was done separately for snowmelt parameters and soil-drainage parameters. For snow, snow-depth measurements at the 2 Providence climate stations were used to calibrate i) a temperature melt coefficient and ii) a linear threshold-temperature value for determining precipitation phase. The calibrated model captured the timing of snow accumulation and melt (Figure 27a). Soil parameters (saturated hydraulic conductivity (*K*) and decay of K with depth (m) were calibrated by comparing predicted streamflow with observed daily streamflow at outlet of two Providence Creek subwatersheds (P301 and P303, Figure 27b).

We used the GLUE approach (Beven and Freer, 2001) to assemble a set of functional model parameters and associated model predictions of streamflow, soil moisture and transpiration patterns. We then used the model estimates to develop a set of spatially explicit indicators of hydrologic similarity. Selected indicators focus on inter-annual variation in snow, soil moisture and transpiration; and in particular the post-snowmelt drying period – since this is likely to be the period most impacted by climate-driven changes in snow accumulation and melt. Clustering of model estimates identified six distinct clusters and show that eco-hydrologic behavior is a complex function of topography, drainage, micro-climate patterns (Table 2). We used the map of hydrologic similarity to identify additional strategic sampling points for summer 2010 (Figure 27). Initial results from monitoring at these strategic locations are shown in Figure 29. For all sites, in the summer, deep soil (90 cm) is wetter than shallow soil (30 cm). After October, shallow soil becomes wetter than deep soil. Cluster 5 has the highest soil moisture content, while cluster 2 has the lowest soil moisture content. Spatial variation of measured soil moisture is similar to that predicted by model clustering analysis (Figures 28 and 30). During the summer, sapflux declines at all sites (Figure 31) until October, when sapflux is maintained or increased except for Cluster 6. Sapflux recovery in October follows increased soil moisture. Vapor pressure deficit (VPD) also appears to influence the temporal trend of sapflux after moisture recovers (Figure 32). More detailed comparisons between model predictions and observed results will be conducted as additional data become available this coming summer.

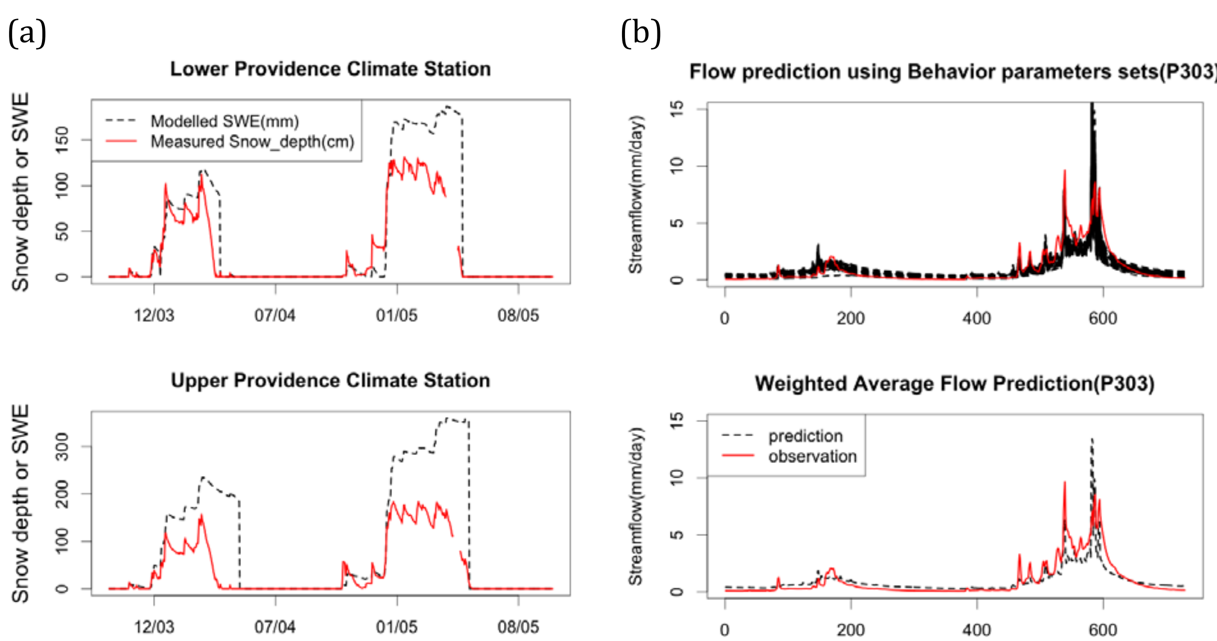

Figure 27. Model calibration: (a) snow predictions at lower and upper Providence climate stations; note that observed measurements are shown as depth and model predictions are in snow water equivalent; thus magnitudes cannot be directly compared but timing of accumulation and melt should be similar and (b) streamflow predictions and observations at the P303 gauging station.

Table 2: Physical properties of Mediods in six clusters

Cluster		1	2	3	4	5	6
Elevation		1967	1892	1921	1861	1876	1750
Slope		9.9	16.6	17.2	12.1	13.7	9.9
Aspect		NW	SE	WS	WS	S	NW
LAI		2.3	1.9	4.6	3.9	2.6	3.3
Ksat	30cm	22.73	3.44	13.05	5.38	7.73	5.60
	90cm	30.70	5.10	2.89	2.63	0.22	33.66

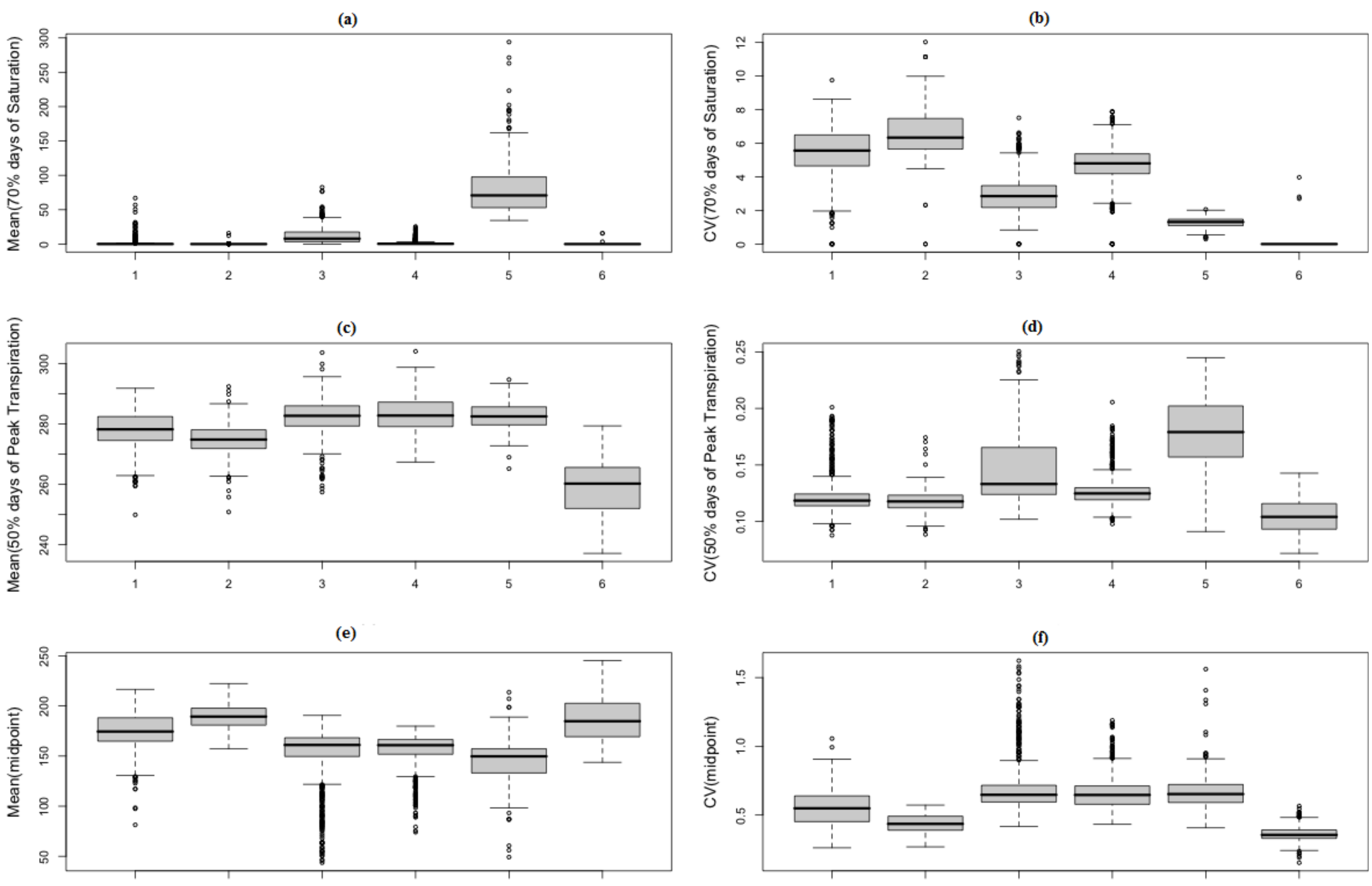

Figure 28. Model clustering results: (a, b) Mean and inter-annual variation of day following winter recharge (last day of winter rainfall for whole watershed) that root-zone soil moisture is fully saturation, (c, d) mean and inter-annual variation of day following winter recharge (last day of winter rain) that transpiration declines to 50% of its peak growing season value. (e, f) mean and inter-annual variation of day following winter recharge (last day of winter rain) that root-zone soil moisture declines to 50% of saturation.

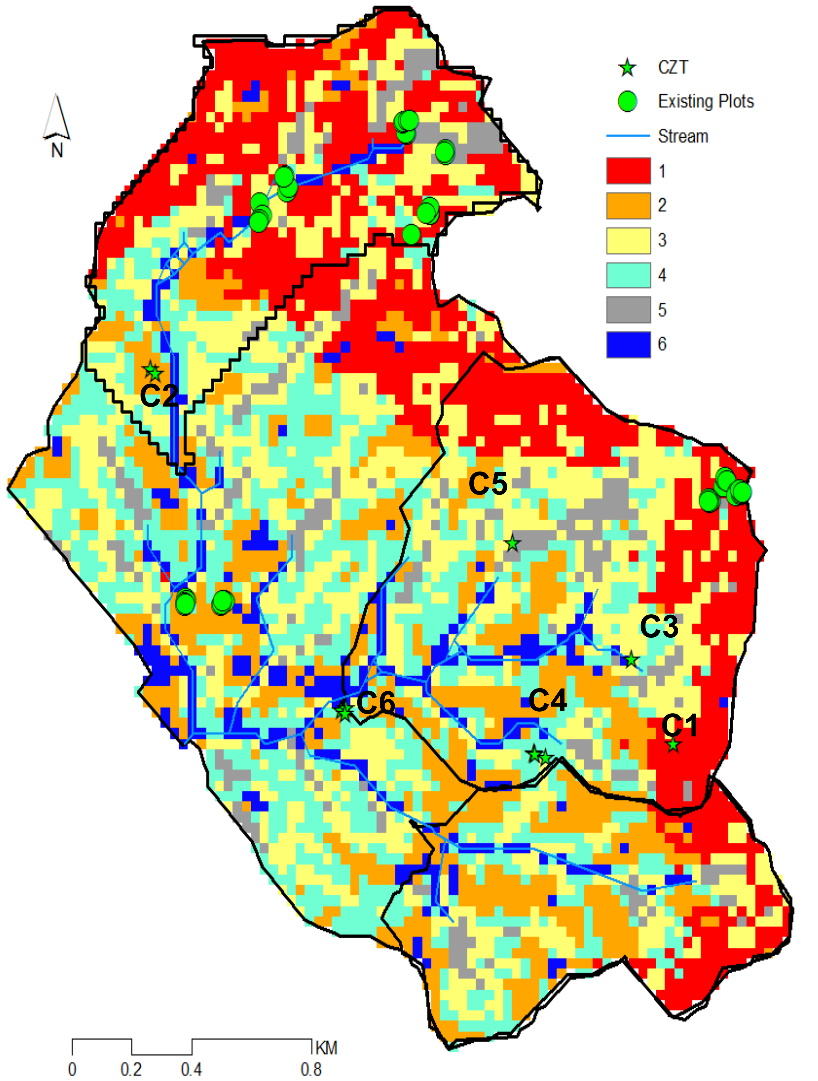

Figure 29. Soil moisture and Transpiration Clusters: circle mark is the existing sampling site in the CZO project. CZT (star mark) is additional sampling site, and for each of these points, we installed soil moisture sensors (5TE) at the two depths (30 and 90 m) and at the five soil pits within a 30 m plot (The location selection of soil pits within plot considers the vegetation cover and topographic difference); A sapflux sensor at the average-size white fir tree per plot was also installed.

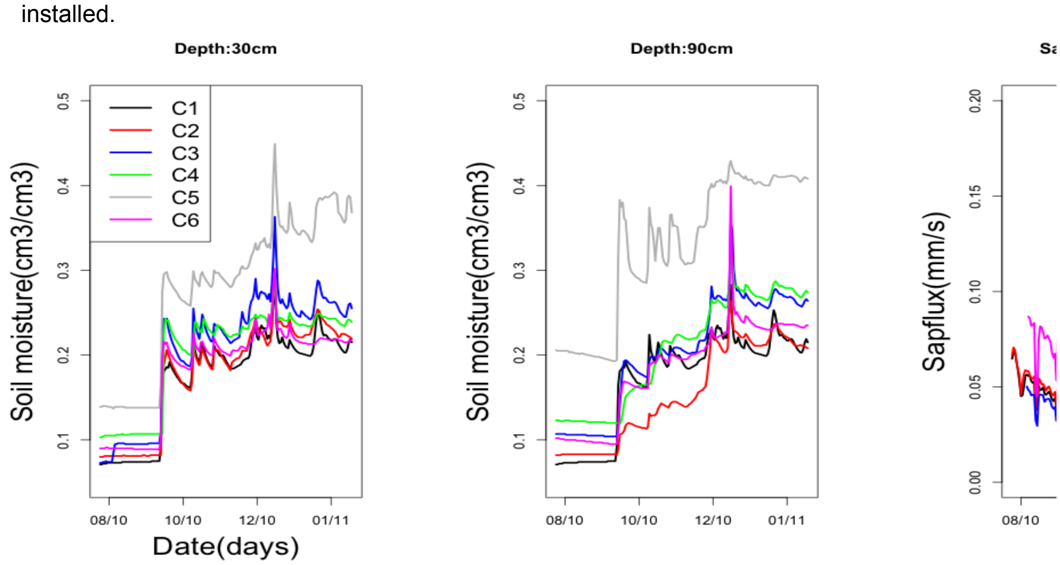

Figure 30. Collected soil moisture data and sapflux in the six mediods sites: (left) 30 cm and (middle) 90 cm and (right) sapflux.

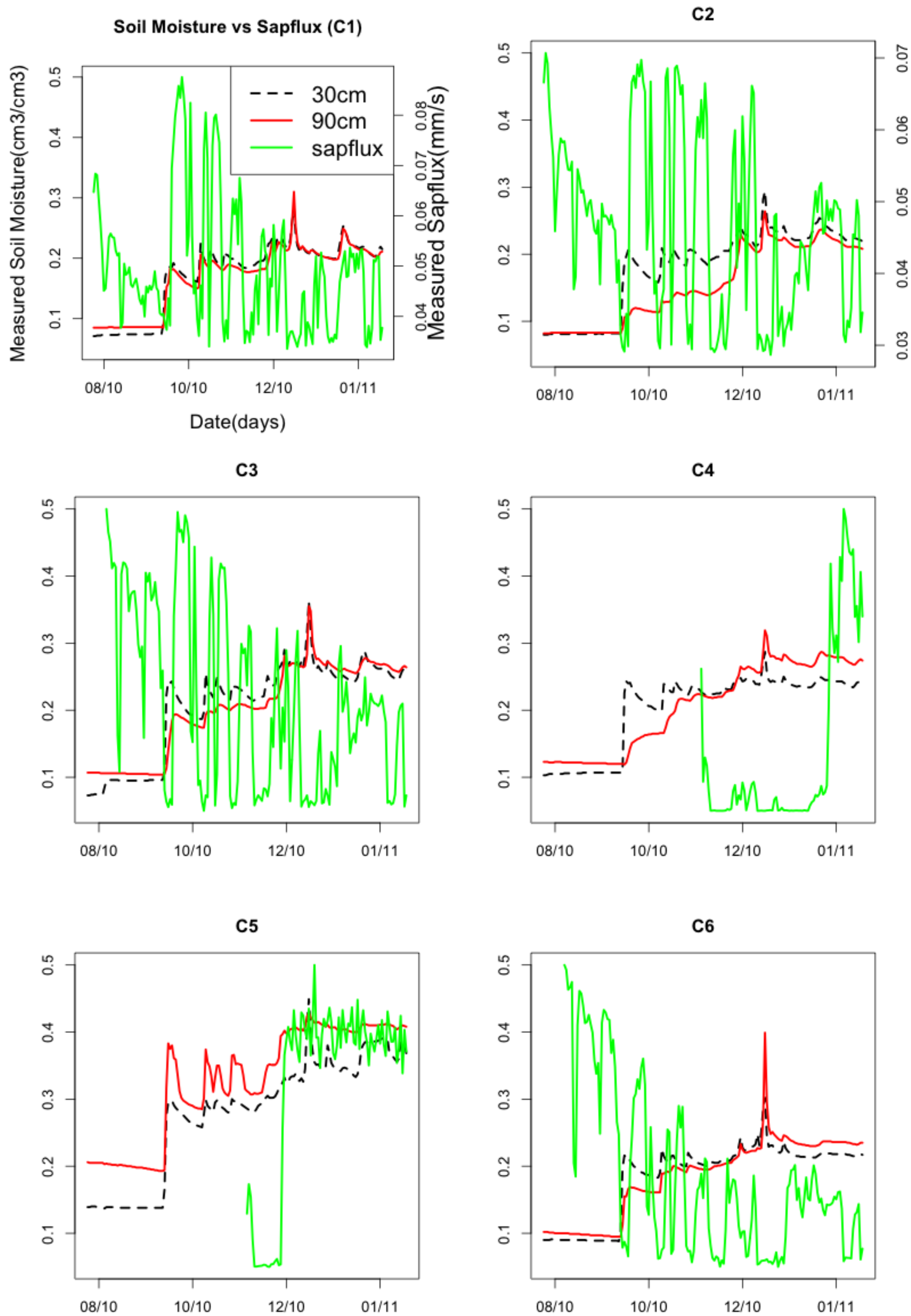

Figure 31. The relationship between soil moisture and sapflux in the mediod sites: Sapflux data is normalized by averaged value of each time series since the value is uncalibrated.

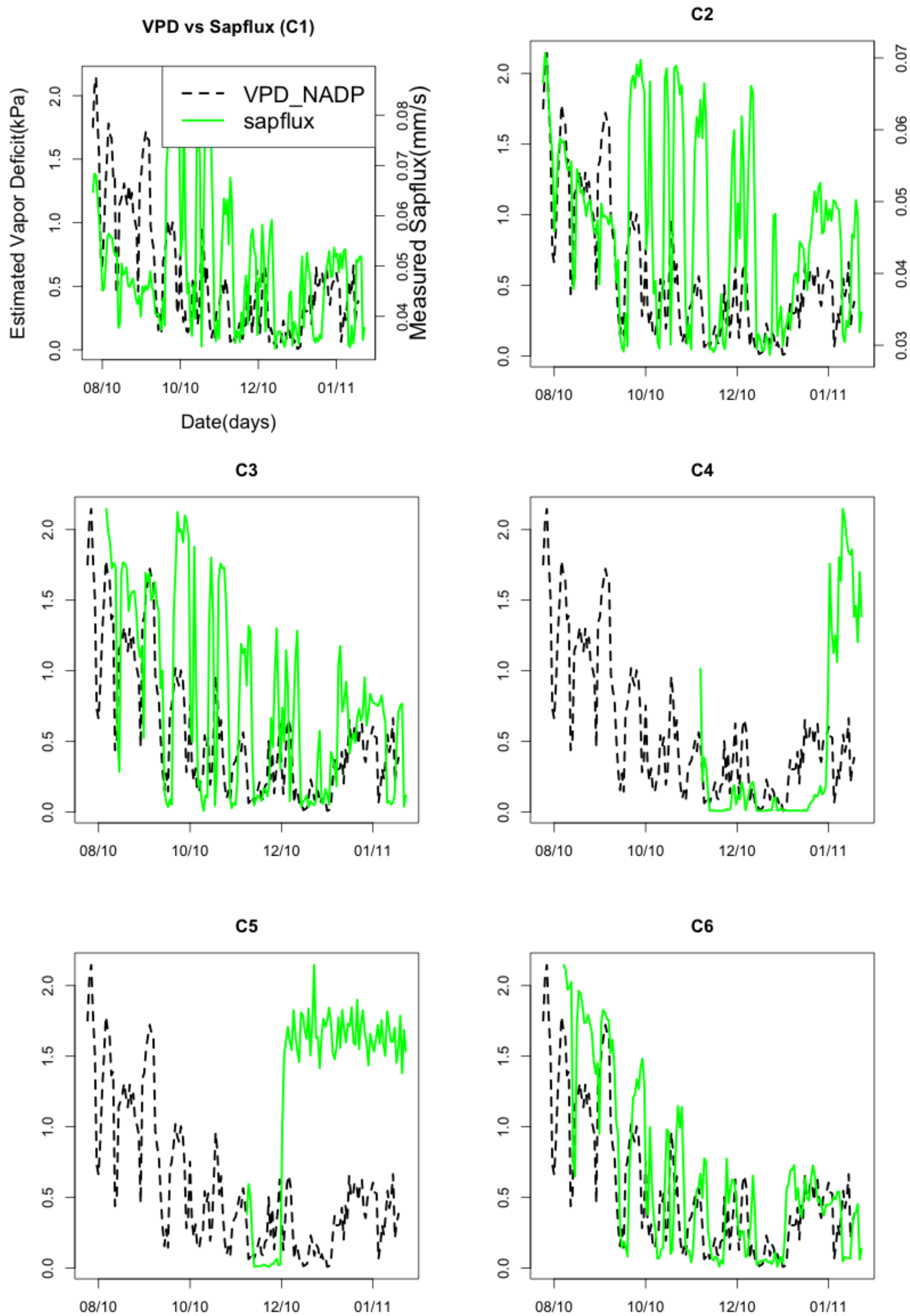

Figure 32. The relationship between vapor pressure deficit (VPD) and sapflux in the Mediod sites: VPD was calculated with measured daily minimum and maximum air temperature at upper Providence climate station.

The model generated clusters helped to isolate key spatial differences in eco-hydrologic responses that reflect the interaction among topography, drainage, and atmospheric forcing. Results from the first year of additional model-driven sampling show that transpiration and soil moisture patterns reflected by model clusters are similar to measured soil moisture patterns. These results are encouraging and suggest that model-based clusters provide a meaningful characterization of watershed patterns and are appropriate for characterizing the multiple-scale soil moisture variation in snow-dominated watersheds. Our additional data this year will be used to confirm this preliminary finding, refine the model structure and parameters and reduce model predictive uncertainty. Once we have are refined model we will used to investigate how a range of climate warming scenarios will alter soil-moisture dependent processes.

The plan for 2011 is to focus on 1) the importance of including the microclimate variation at fine spatial scale in ecohydrological modeling and 2) Investigation of patterns of eco-hydrologic response to warming for Sierra CZO watersheds using RHESSys.

Comparison between observations and model predictions based on preliminary data analysis identified the spatial interpolation of temperature and vapor pressure deficit as key sources of uncertainty and model error. To assist in the development of improved estimation of temperature/humidity patterns we are in the process of installing additional relative humidity/temperature sensors in strategic locations throughout the Providence watersheds (P301 and P303) (Figure 33). This additional monitoring will increase the density of the distributed microclimate network which, coupled with Regression Kriging techniques, will allow us to better estimate the spatial variability of microclimate and eventually improve the model predictions of snow, soil moisture, transpiration and streamflow.

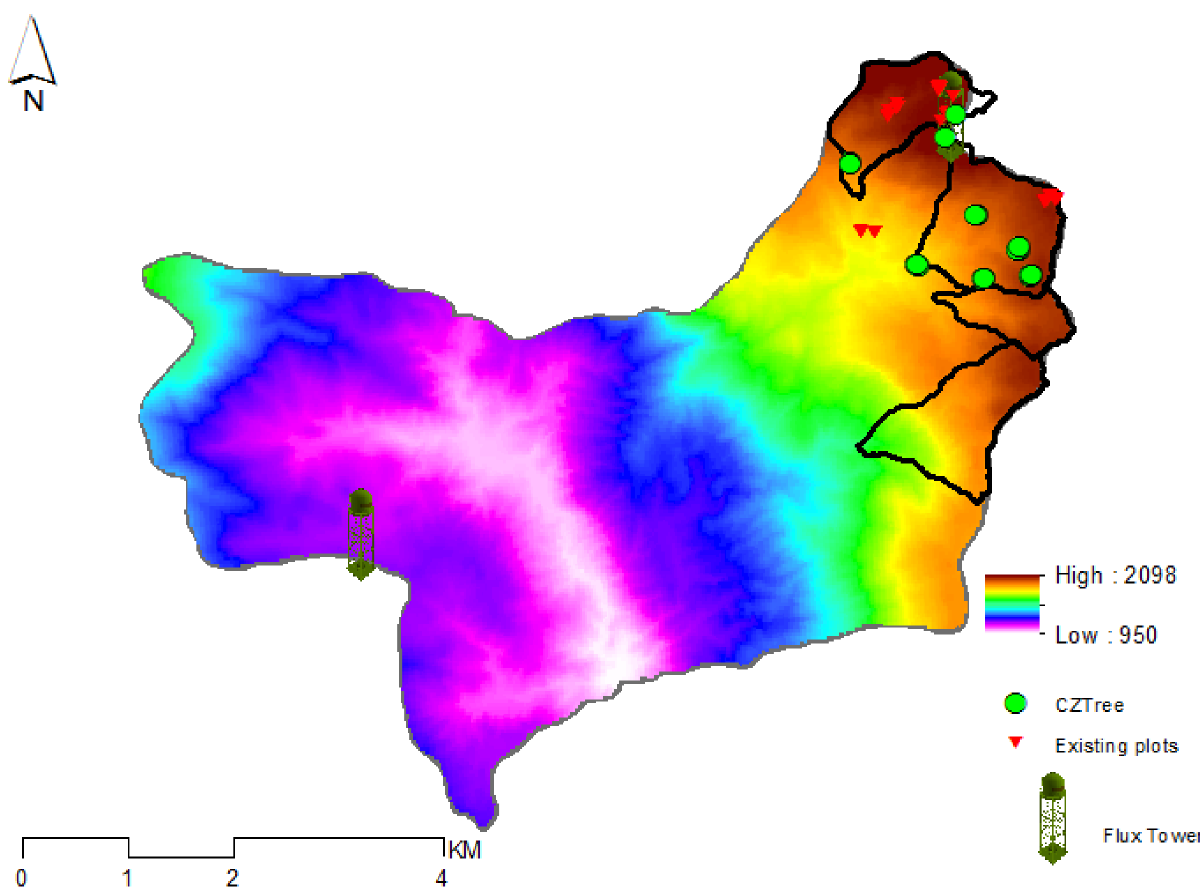

Figure 33. Elevation map and the locations of the CZTree sites, existing CZO air temperature/relative humidity measurements and flux towers.

We will test the improved accuracy of the RHESSys model ecohyrologic predictions (snow, soil moisture, transpiration and streamflow) using estimated spatial microclimate inputs. The model test will be conducted at plot, hillslope and watershed scales and for the different model variables. At the patch/plot scale, we evaluate improvements in model predictions of snow accumulation and melt, soil moisture and transpiration (sapflux) when using refined estimates of microclimate patterns. At the hillslope scale, ET from Eddy covariance flux tower in P303 watershed can be utilized to evaluate improvements in model estimates of ET. At the watershed scale, streamflow and spatial patterns reflected by strategically located soil moisture and sapflux measurements will be compared with model predictions of soil moisture, transpiration and streamflow, again using our improved interpolation of climate forcing.

Building on our prior work to parameterize and evaluate RHESSys eco-hydrologic estimates at the CZO site, we now use the model to investigate the sensitivity of eco-hydrologic variables to projected climate warming. We consider model estimates of snow, soil moisture, transpiration and streamflow across the 9 CZO watersheds that historically cross the transistion between rain-snow dominated sites under future warming scenarios. Watersheds include the Providence watersheds (P301, P303, P304 and D102), Bull watersheds (B201, B203, B204 and T003), and Wolverton watershed. We use model predictions to develop generalized relationships between the sensitivity to warming and a priori site characteristics (including topography, vegetation characteristics (biomass, species), geology and micro-climate patterns). To simulate climate warming, this study will apply simple 2 and 4 C° uniform temperature adding to the observed meteorological record based on recent GCM predictions for California Sierras over the next 50-100 years (2 to 5 C° predicted changed in Cayan et al., 2006). While actual warming scenarios are likely to be substantially more variable in time, we use this simple approach to focus on the direct impact of increasing temperature and avoid the complex and highly uncertain downscaling of climate model output.

Physical weathering rates. Topographic analysis was coupled with new data from cosmogenic nuclides in sediment in a test of Wahrhaftig's (1965) decades-old hypothesis that for the development of "stepped topography" in the southern Sierra Nevada by differential weathering of bare and soil-mantled granite. According to Wahrhaftig's hypothesis, bare granite weathers slower than soil-mantled granite; thus random erosional exposure of bare rock leads to an alternating sequence of steep, slowly weathering bedrock "steps" and gently sloped, but rapidly weathering, soil-mantled "treads." The hypothesis was tested with terrain analysis, to confirm the existence of the steps and treads, analysis of reflectance spectra, to identify bare versus soil-mantled terrain, and cosmogenic nuclides to determine whether (and by how much) bare rock erodes more slowly than soil-mantled rock. The terrain analysis confirms that the landscape is markedly stepped, but light spectrum analysis of the terrain shows that the steps are soil-mantled as often as the treads, inconsistent with Wahrhaftig's hypothesis. Moreover, cosmogenic nuclides show that treads are eroding slower than steps (Figure 34), undermining one of the fundamental underpinnings of the stepped topography hypothesis. Hence, although erosion rates are indeed faster where soil is present, the differential erosion thus produced does not produce topography in the way envisioned by Wahrhaftig (1965). Work on this topic was summarized in an extended abstract associated with the 9th International Conference on the Geochemistry of Earth's Surface, in Boulder CO., by Jessup et al. (2011); a full manuscript is forthcoming.

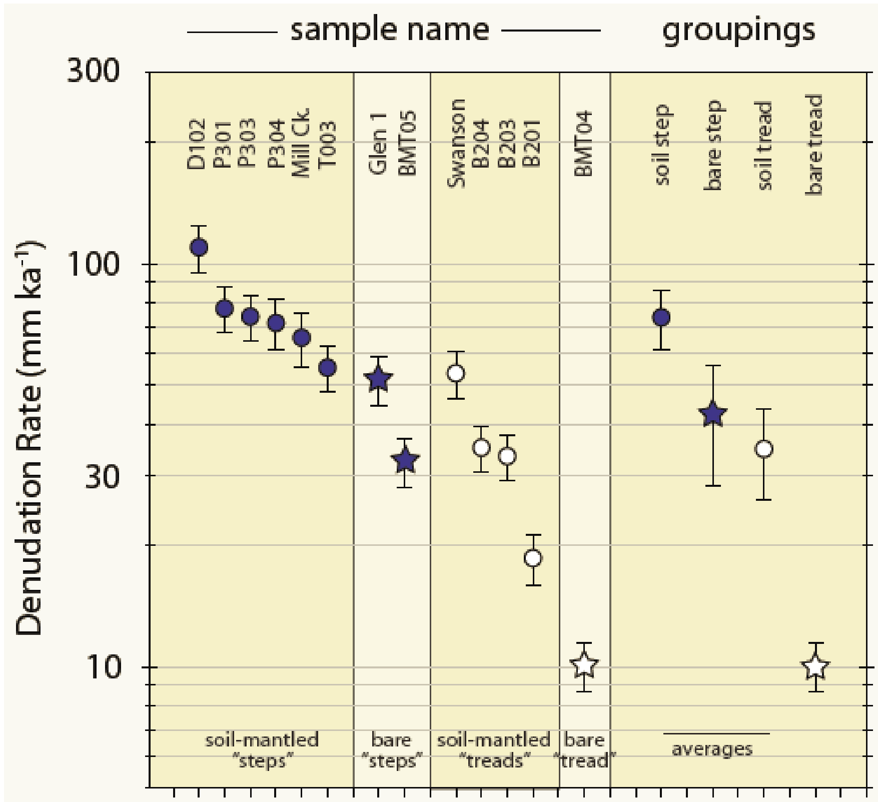

Figure 34. Cosmogenic nuclide-based erosion rates from the SSCZO and nearby watersheds.

New work on seismic velocity structure of the subsurface (to ~30 m depth) across 3 transects (like the one shown in Figure 35) tentatively shows that weathering extends 10-20 m into the underlying bedrock. The presence of material with P-wave velocities of <1 km/s to depths of 10 m or more suggests that the material (which is presumably saprolite) might serve as an as yet poorly understood but nevertheless important reservoir and/or conduit of water from the surface. Follow-up work in the fall of 2011 should help in determining whether such deeply weathered rock is pervasive throughout the CZO or restricted to areas like the one shown in Figure 35.

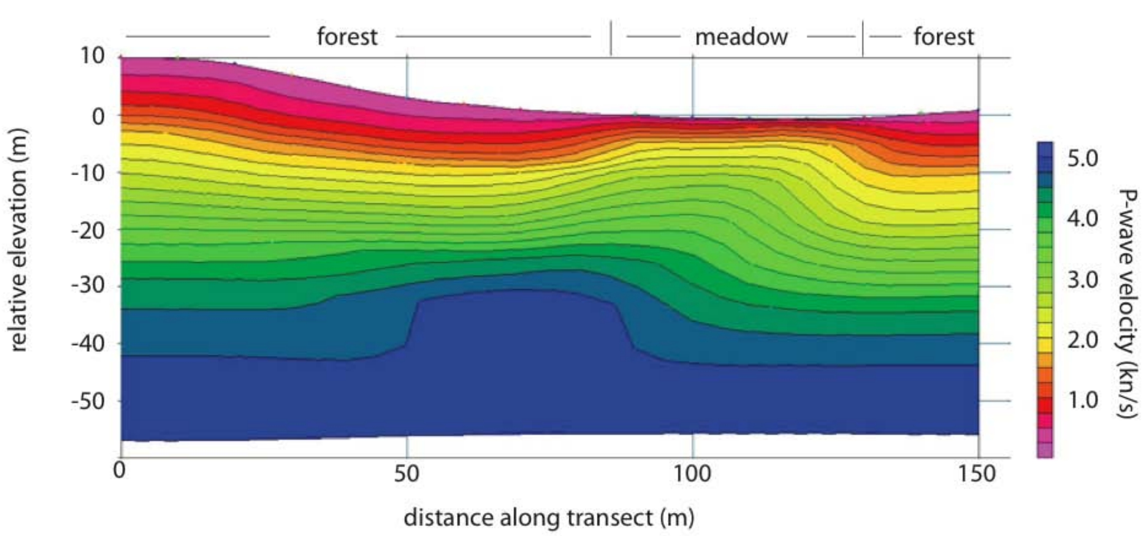

Figure 35. Preliminary travel time tomography image the shallow subsurface on slopes adjacent to the upper

New collaborations in project year 2010-2011 include Scott Miller (Associate Professor, Terrain Analysis, U. Wyoming), Steve Holbrook (Professor, Geophysics, U. Wyoming), Rohit Salve (Researcher, Hydrology, LBL), and Anthony Dosseto (Lecturer, Geochemistry, U. Wollongong). New students include Claire Lukens (PhD candidate, U. Wyoming) and Jesse Hahm (MS Student, U. Wyoming). This work has continuously supported 4-5 undergraduate students over the course of the project year.

Baseline hydrologic, sediment and geochemical characterization. Three end-members were determined using EMMA and conservative tracers; near surface runoff, rainstorm runoff, and baseflow (Figure 36). The mean fractional contribution of each end-member varied by site, and the results show that the contribution of near-surface runoff and baseflow were similar, ranging from 0.72 (B203 site) and 0.66 (T003) to 0.27 (P304) and 0.25 (B203), respectively. However, the fractional contribution of flow from rainstorms was much smaller, contributing between 0.063 (D102) and 0.019 (T003). Results displaying temporal variation in fractional contribution of each end-member from water year 2003-2007 are shown in Figure 37.

During periods of snowmelt (April of each year), near-surface runoff provided the greatest contribution to streamflow whereas the opposite occurred during periods of drought (October of each year), where baseflow contributed the most. The relative contribution of rainstorm runoff was lowest for most of the year with the exception of infrequent episodic peaks (Figure 37).

Contributions of near-surface runoff (or snowmelt runoff) and baseflow were highly correlated with streamflow discharge by a linear relationship at both Providence and Bull catchments (Figure 38). The R^2 values were 0.92-0.99 and 0.91-0.97 ($p < 0.001$) for near-surface runoff and baseflow, respectively. The slope varied from 0.53 to 0.83 for near-surface runoff and from 0.20 to 0.46 for baseflow.

All intercepts were negative for near-surface runoff, with a magnitude < 7, and all positive for baseflow, with a value also < 7. Those samples collected over four water years from 2004 to 2007 covered different climates and annual precipitation.

By performing a regression between mean end-member contribution and elevation, mean end-member contribution and slope (data not shown), it was determined that no statistically significant correlations were present amongst end-members. This data suggests the relative proportion of rain to snow did not control streamflow pathways across elevation or slope.

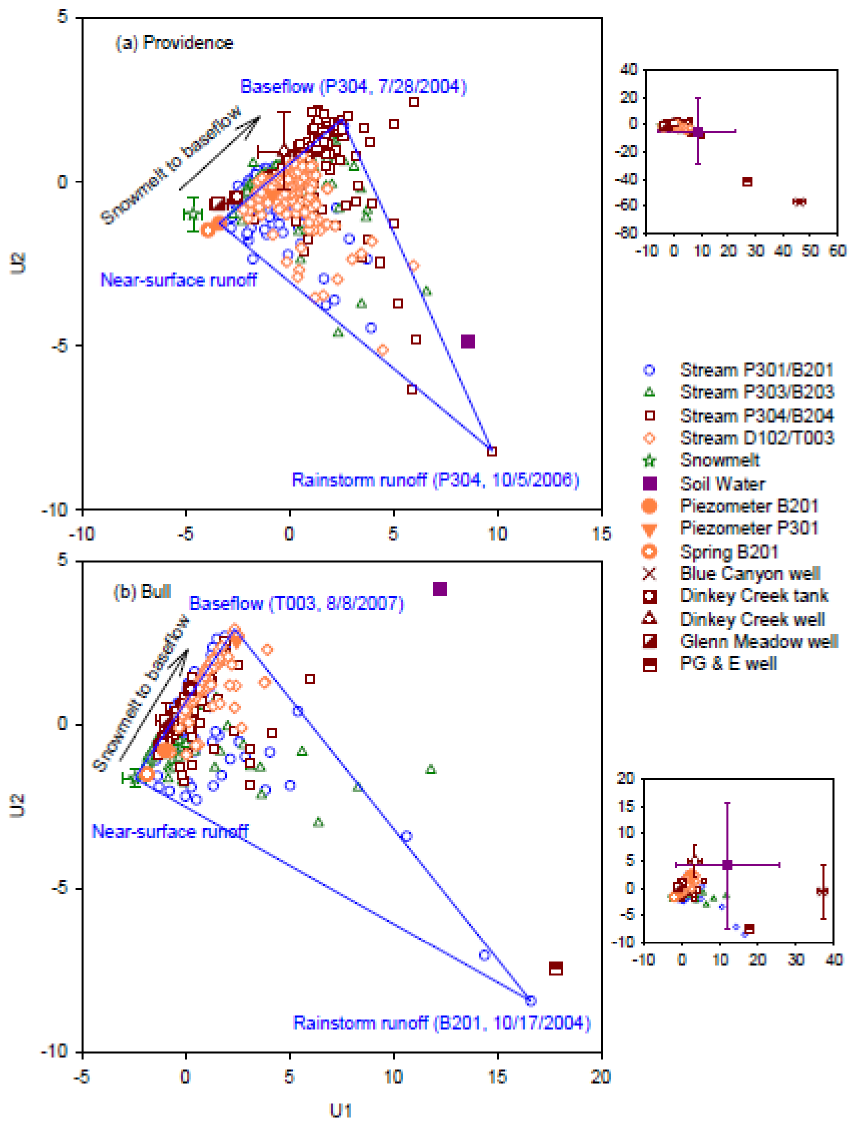

Figure 36. End-member mixing diagrams for Providence (a) and Bull (b) catchments. The majority of sample points lie within the triangles. Each corner of the triangle is a representative end-member (Near-surface runoff, Baseflow, and Rainstorm runoff). The arrow shows the change in distribution of samples from snowmelt to baseflow. Inset diagrams show all samples points including outliers.

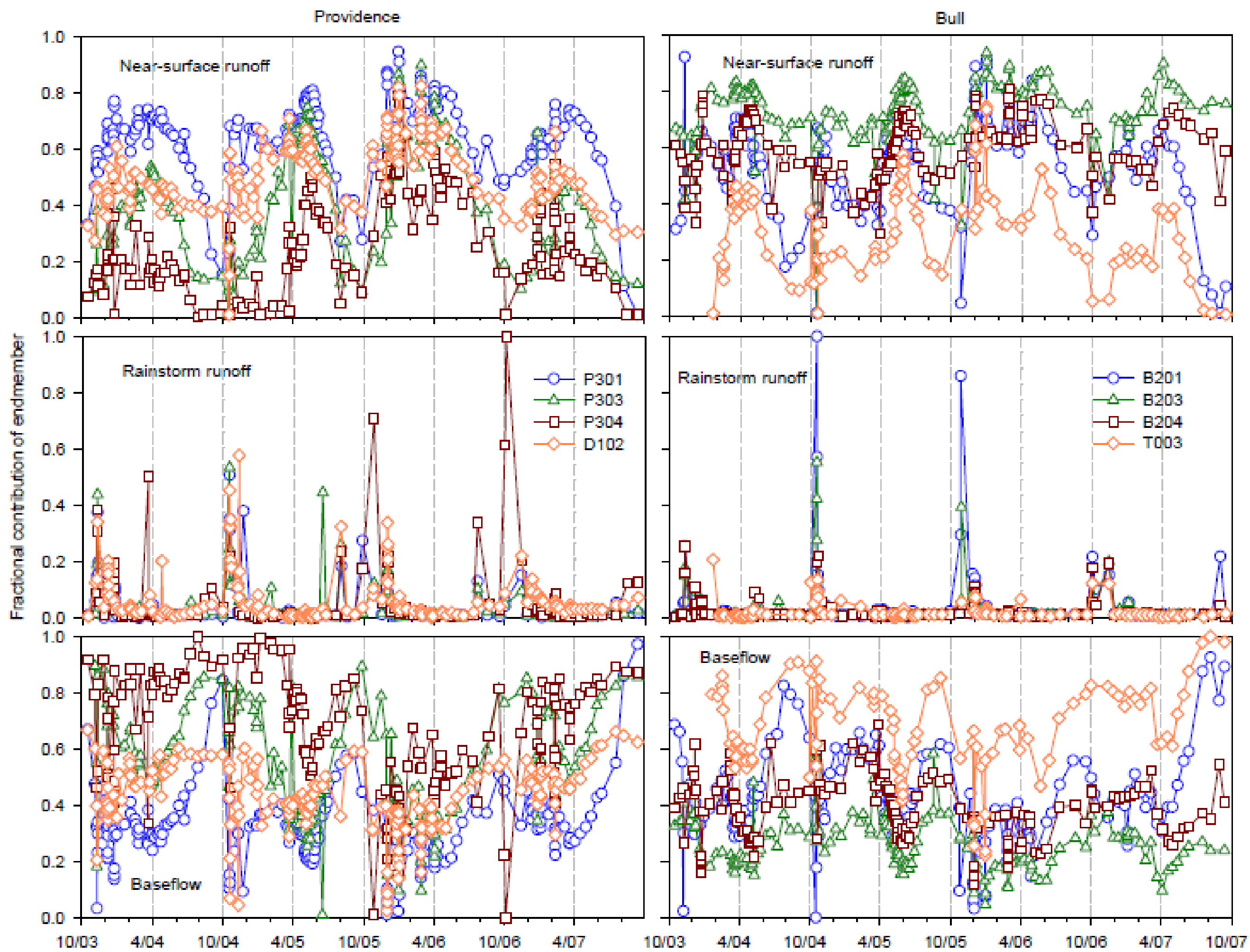

Figure 37. Temporal variation in fractional contribution of end-members for Providence and Bull sites. Data here shown here include water years 2003-2007.

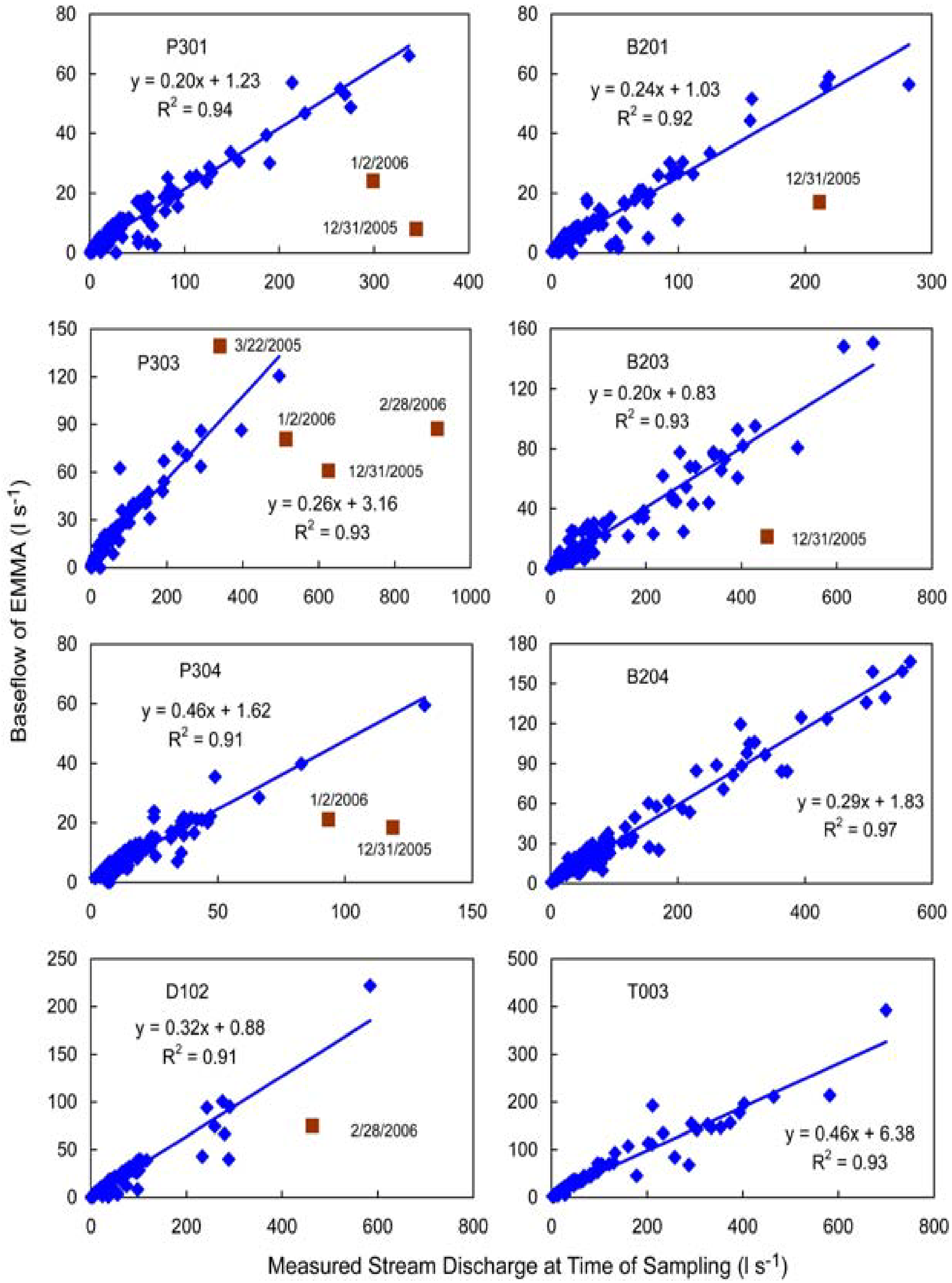

Figure 38. Correlation between the contribution of baseflow (by flow rate) determined by EMMA using geochemical tracers and stream flow discharge at each catchment.

Organic carbon in streams. Water samples for isotopic analysis are being analyzed at UC Merced. Water samples for organic carbon have been analyzed. The results from these samples are going through a rigorous QA/QC process, to ensure that data are correct.

Soil Nutrient Contents.

Resin lysimeter fluxes: Analysis of the resin lysimeter data shows that hotspots in resin-based nitrogen flux appear on a large scale just as they do on a small scale, and that inter-annual variation in soil fluxes is quite high whereas interannual variation in thorughfall fluxes is low. Interestingly, however, the average N fluxes among watersheds do not differ by much during any given year.

O horizon data: Analysis of the O horizon mass and nutrient content data showed hotspots but surprisingly little variation among watershed averages, as was the case for the resin lysimeters, except in the cases of Ca and Mg, which reflected differences previously reported in soils (lower in the Bull than in the Providence watersheds).

Intensive plot results: Major findings include**:** As expected, higher concentrations of macronutrients were apparent in ion exchange membranes that were pulled from the soil at the end of the snow season when compared to samples pulled after the first precipitation event in the preceding fall before snow. The nitrate hotspot cluster on gridpoint 3.5, 1.5 that appeared in the pre-snow samples was also the hotspot in the post-snow samples, indicating that the hotspot was not an ephemeral feature of the micro-landscape. At other grid points, it appears that hot spots can be very small and localized considering there were large differences in concentrations between samplers placed ~8 cm apart (Figure 39).

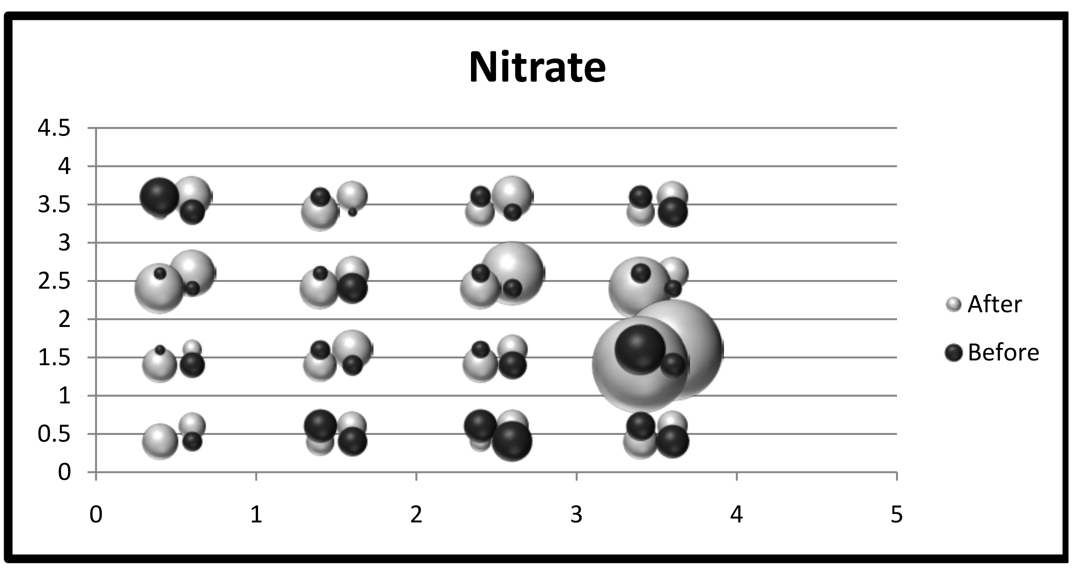

Figure 39. An example of nitrate data from year two. This graph represents the locations of all four samplers in a grid. The larger the circle, the higher concentrations of nitrate at that location. The black circles indicate nitrate concentrations for that location that was after the first fall rain event, but *before* the snow season. The black circles indicate the nitrate concentrations *after* the snow season.

Nitrogen fluxes from soil. Some data from the first three years of sampling are presented here for the Prenart soil vacuum lysimeters. NADP site CA28 data are available at their web site. No snowmelt or resin lysimeter data are reported here at this time. Analyses of N data are a priority for 2011.

Soil water concentrations at 13 cm and 26 cm mineral soil depths are taken using a Prenart vacuum lysimeter for the first three years of data collection. Average values are reported with one standard deviation in parenthesis. The minimum detection limit is 0.05 mg/L; however, if a value lower than this was measured it was reported and included in these summaries. Values at or above the minimum detection limit are in bold print.

Table 3 presents an annual average for all sample collection periods (approximately 12/year) by watershed. The majority of values is below the minimum detection limit and therefore can be assumed to have a concentration of zero. Usually (20 out of 24) the N concentrations reported have a higher value at the 13 cm depth than at the 26 cm depth indicating that N is depleted as it moves through the soil column. Only 29% (numbers in italics) of the average values reported here were at or above the 0.05 mg/L detection limit for all depths; the highest value reported is 0.14 mg/L. Nitrate has somewhat higher values (0.05 to 0.14 mg/L) than ammonium (0.05 to 0.10 mg/L) for all watersheds and all years. These soil water concentrations can be converted to flux values, and final results will address fluxes from the atmosphere to the top of the soil, the top of the soil to the 26 cm mineral soil depth, and the soils to the stream waters.

Table 3. Nitrogen concentrations

Watershed code	Nitrate soil water concentration, mg/L			Ammonium soil water concentration, mg/L		
	2003	2004	2005	2003	2004	2005
P301						
13 cm	0.06 (0.17)	0.01 (0.03)	0.04 (0.26)	0.03 (0.05)	0.02 (0.04)	0.10 (0.23)
26 cm	0.04 (0.01)	0.00 (0.00)	0.01 (0.02)	0.01 (0.02)	0.01 (0.02)	0.06 (0.17)
P303						
13 cm	0.02 (0.05)	0.05 (0.11)	*0.07 (0.21)*	0.02 (0.03)	*0.02 (0.04)*	0.03 (0.06)
26 cm	0.01 (0.03)	0.01 (0.01)	*0.10 (0.57)*	0.01 (0.03)	*0.07 (0.32)*	0.01 (0.05)
P304						
13 cm	0.12 (0.35)	0.07 (0.20)	0.05 (0.17)	0.05 (0.08)	0.02 (0.03)	*0.02 (0.02)*
26 cm	0.03 (0.06)	0.01 (0.03)	0.01 (0.02)	0.02 (0.03)	0.00 (0.00)	*0.06 (0.13)*
D102						
13 cm	0.14 (0.32)	*0.01 (0.01)*	0.10 (0.43)	0.05 (0.11)	0.01 (0.02)	0.03 (0.07)
26 cm	0.04 (0.08)	*0.02 (0.07)*	0.02 (0.05)	0.02 (0.04)	0.02 (0.03)	0.03 (0.05)

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