<u>Final Report</u>
Name/Title: Carbon-water cycling in the critical zone: understanding ecosystem process variability across complex terrain
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Project Goals

Our project investigates the role of landscape structure and hydrologic redistribution of precipitation as first-order controls for soil respiration and aboveground carbon storage. In our assessment, we are focused on three main objectives:

(1) to test hypotheses about sources of variation in both aboveground and belowground stores for carbon and water and their fluxes with regard to landscape structure, with the eventual aim of inverting this understanding so that we can use terrain analysis to perform virtual experiments under climate change scenarios;
(2) to mechanistically assess how plot to landscape biogeophysical properties determine flow paths of water from the soil surface to the atmosphere via evapotranspiration or to stream channels, and in turn, how these flow paths affect carbon flux and storage; and
(3) to scale and model carbon storage and fluxes from the point and plot level to the landscape in complex terrain.

Study Site

Our primary study sites spanned elevations from 1480 to 3021 m within the Boulder Creek Watershed in the Front Range of Colorado with a climate gradient and forest types typical of the Rocky Mountains. We focused on three specific catchments with distinctly different landscape structures that were co-located with the DOE Niwot Ridge Ameriflux site, the Niwot Ridge LTER, and Boulder Creek Critical Zone Observatory (BC-CZO). We supplemented work at these BC-CZO sites with complementary observations and model development in the Jemez-Santa Catalina CZO sites in NM and Arizona.

Research Key Findings and Highlights

Aboveground biomass distribution and controls:

We found topography and climate play an integral role in the spatial variability and annual dynamics of aboveground carbon sequestration. Climate change predictions for the semi-arid, western United States include increased temperatures, more frequent and extreme drought events, and decreases in snowpack, all of which put forests at risk of drought induced mortality and enhanced susceptibility to disturbance events. We determined how species-specific tree growth patterns and water use efficiency responded to interannual climate variability and how this response varied with topographic position. We found that *Pinus contorta* and *Pinus ponderosa* both decreased in growth with water-limiting climate conditions, but complex terrain mediated this response by controlling moisture conditions in variable topoclimates. Foliar carbon isotope analyses showed increased water use efficiency during drought for *Pinus contorta*, but indicate no significant difference in water use efficiency of *Pinus ponderosa* between a drought year and a non-drought year. The responses of the two pine species to climate indicate that semi-arid forests are especially susceptible to changes and risks posed by climate change and that topographic variability will likely play a significant role in determining the future vegetation patterns of semi-arid systems.

Additionally, we found that topographically-driven water redistribution mediates climatic control over aboveground carbon storage in semi-arid forests. We quantified forest overstory aboveground carbon and topographic metrics related to water availability from aerial lidar across our three study catchments. The catchments range have mean annual precipitation and temperature ranging from 46 to 102 cm yr^{-1} and -1.2 to 9.8^oC. Carbon storage consistently increased from ridge to valley bottoms with the bottoms in each catchment having more than twice the carbon of ridges. Carbon storage was higher on N to NE aspects and lower on S to SW aspects across all catchments, a pattern most pronounced in the highest elevation, coldest, and wettest site. Our results suggest that lateral redistribution of plant available water and changes in energy related to the complex terrain are more important for carbon storage than an 11^oC range in temperature and doubling of local precipitation related to the elevation gradient. Specifically, toe-slopes tend to foster areas of disproportionately high net carbon uptake. Forecasts of forest vulnerability to drought and heat need to consider the critical role terrain plays in either mediating or exacerbating regional climate influences on total carbon uptake and water use in semi-arid forested ecosystems.

In a recent analysis of the continuous length of time of active transpiration and annual growth across our elevation gradient, we found that increases in the duration of transpiration (as a proxy for growing season length) had a strong positive correlation with basal area increment. The length of the growing season measured in this study decreased with elevation and was shorter on north-facing aspects versus south-facing aspects at similar elevations, confirming the importance of aspect and elevation effects on determining forest productivity in mountainous terrain. Moreover, the linkages among transpiration, air temperature, and growing season length indicated that future climate warming will extend the growing season length and increase mid-winter periods of productivity and potentially lead to asyncronicity between periods of water availability and forest transpiration.

Soil respiration versus temperature and moisture:

Forest soil respiration is a major carbon (C) flux that is characterized by significant variability in space and time. We found complex terrain alters temperature and moisture limitations of forest soil respiration across a semi-arid to subalpine gradient. We quantified growing season soil respiration during both a drought year and a non-drought year across a complex landscape to identify how landscape and climate interact to control soil respiration. Soil moisture superseded temperature in explaining watershed respiration patterns, with wetter yet cooler areas higher up and on north-facing slopes yielding greater soil respiration than lower and south-facing areas. Wetter subalpine forests had reduced moisture limitation in favor of greater seasonal temperature limitation, and the reverse was true for low-elevation semi-arid forests. Coincident climate poorly predicted soil respiration in the montane transition zone; however, antecedent precipitation from the prior ten days provided additional explanatory power. A seasonal trend in respiration remained after accounting for microclimate effects, suggesting that local climate alone may not adequately predict seasonal variability in soil respiration in montane forests. Soil respiration was more strongly related to seasonal patterns in soil moisture during the drought year highlighting the importance of landscape complexity in ecosystem response to drought.

Building on these findings that highlighted the surprisingly dominant role of moisture in controlling carbon flux at the three primary Boulder Creek CZO sites, we performed two years of soil CO2 flux measurements across a much broader range of lithology and soils in coniferous forests at the Santa Catalina Jemez CZO sites in NM and AZ. Across these broader lithological (granite, schist, and rhyolite) and climate (-3 to 26 ^{o}C) gradients, we employed a state factor approach to quantify how distal and proximal controls interact to influence both gaseous and dissolved C efflux. Multiple linear regression models explained 63% of the variability in summer and 98% of the variability in winter across all locations. Similar to results from BC-CZO, soil moisture was the strongest predictor of CO_2 flux in all models. Further, readily observable state factors related to liquid water availability (e.g. clay content, organic matter, snow cover) can be used to scale point observations to landscape scale fluxes.

Dissolved Organic Matter Transport:

In spring 2013, we completed nearly 50 continuous days of sampling of soil interstitial waters, groundwater, and surface water to examine the quantity and quality of dissolved organic matter (DOM) and dissolved organic carbon (DOC) being transported within and exported from our mid-elevation catchment. DOM transport is a key biogeochemical linkage across the terrestrial-aquatic interface in headwater catchments, and quantifying the biological and hydrological controls on DOM composition provides insight into DOM cycling at the catchment scale. We evaluated the mobility of DOM components during snowmelt in a montane, semi-arid catchment. DOM composition was evaluated on a near-daily basis within the soil and the stream during snowmelt, and was compared to groundwater samples using a site-specific parallel factor analysis (PARAFAC) model derived from soil extracts. The fluorescent component loadings in the interstitial soil water and in the groundwater were significantly different and did not temporally change during snowmelt. In the stream, a transition occurred during snowmelt from fluorescent DOM with higher contributions of amino acid-like components indicative of groundwater to higher humic-like contributions indicative of soil water. Furthermore, we identified a humic-like fluorescent component in the soil water and the stream that is typically only observed in extracted water soluble organic matter from soil which may suggest hillslope to stream connectivity over very short time scales. Qualitative interpretations of changes in stream fluorescent DOM were supported by two end-member mixing analyses of conservative tracers. After normalizing fluorescent DOM loadings for DOC concentration, we found that the peak in DOC concentration in the stream was driven by the non-fluorescent fraction of DOM.

Integrating Observations and Modeling to Identify Challenges in Ecohydrology of Complex Terrain

The results described above highlight how the interactions between climatological, hydrological, and ecological exhibit poorly recognized yet critical scale breaks in complex terrain. These transitions are associated with topography, lithology, soils, and vegetation demography that complicate efforts to extrapolate from point scale observations to the landscape. These observations and modeling results were major contributors to developing a grand challenges white paper for the 50th anniversary issue of Water Resources Research where we present four challenges for improving process understanding and developing operational models of ecohydrological coupling in complex terrain: (1) Identify the interactions among terrain, lithology, vegetation, water, and soil carbon cycling that control subsurface weathering and allow prediction of subsurface structure capable of supplying plant available water in excess of local soil moisture resources; (2) Quantify the amount, residence time, and movement of subsurface water to better predict partitioning of stored water between evapotranspiration and stream flow generation; (3) Evaluate the role of terrain complexity in modifying microclimatic influences on water demand; (4) Develop focused or targeted observations across a larger range of spatial scales to place site-specific work in regional context. These efforts will use the patterns associated with the rapidly increasing spatial and temporal data on critical zone structure to predict dominant processes and controls and thereby, sensitivity to change in the vast majority of locations that are not extensively instrumented and studied.

Dissemination of Results

<u>Published Publications</u>:

1. Burns, M.A., H.R. Barnard, R.S. Gabor, D.M. McKnight, P.D. Brooks. 2016. Dissolved organic matter transport reflects hillslope to stream connectivity during snowmelt in a semi-arid Catchment. *Water Resources Research*. doi: 10.1002/2015WR017878.
2. Mares R., H.R. Barnard, D. Mao, A. Revil, K. Singha. 2016. Determining the influence of transpiration on soil moisture movement using electrical resistivity imaging. *Journal of Hydrology*, 536: 327-338, doi: 10.1016/j.jhydrol.2016.03.003
3. Foster, L. Bearup, L., Molotch, N., Brooks, P.D., and Maxwell, R. 2016. Energy Budget Changes Impact Arid Mountain Hydrology More Than Snow-Rain Transitions, *Environ. Res. Lett*. doi:10.1088/1748-9326/11/4/044015
4. Field, J.P., D.D. Breshears, D.J. Law, L. López-Hoffman, P.D. Brooks, J. Chorover, J.D. Pelletier. 2016. Understanding ecosystem services from a geosciences perspective, Eos, 97, doi:10.1029/2016EO043591
5. Zapata-Rios X., P.D. Brooks, P.A. Troch, J. McIntosh., Q. Guo. 2015. Influence of terrain aspect on water partitioning, vegetation structure and vegetation greening in high elevation catchments in northern New Mexico. *Ecohydrology* DOI:10.1002/eco.1674
6. Brooks P.D., J. Chorover, Y.F. Reinfelder, S.E., Godsey, R.M. Maxwell, J.P. McNamara, N.C. Tague. 2015. Hydrological Partitioning in the Critical Zone: Recent Advances and Opportunities for Developing Transferrable Understanding of Water Cycle Dynamics, *Water Resources Research* 10.1002/2015WR017039
7. Knowles, J.F., A.A. Harpold, R. Cowie, M. Zeliff, H.R. Barnard, S.P. Burns, P.D. Blanken, J.F. Morse, M.W. Williams. 2015. The relative contributions of alpine and subalpine ecosystems to the water balance of a mountainous, headwater catchment*. Hydrological Processes, doi: 10.1002/hyp.10526.*
8. Berryman, E.M., H.R. Barnard, H.R. Adams, M.A. Burns, E. Gallo, P.D. Brooks. 2015. Complex terrain alters temperature and moisture limitations of forest soil respiration across a semi-arid to subalpine gradient. *Journal of Geophysical Research – Biogeosciences*, 120, *doi:10.1002/2014JG002802.*
9. Gabor, R.S., M.A. Burns, R.H. Lee, J.B. Elg, C.J. Kemper, H.R. Barnard, D.M. McKnight. 2015. Influence of leaching solution and catchment location on the fluorescence of water-soluble organic matter. *Environmental Science and Technology*, doi: 10.1021/es504881t.
10. Stielstra, C.M., K.A. Lohse, J. Chorover, J.C. McIntosh, G.A. Barron-Gafford, J.N. Perdrial, M. Litvak, H.R. Barnard, P.D. Brooks. 2015. Climatic and landscape influences on soil moisture are primary determinants of soil carbon fluxes in seasonally snow-covered forest ecosystems. *Biogeochemistry*, 123(3): 447-465, doi: 10.1007/s10533-015-0078-3.
11. Adams, H.R., H.R. Barnard, A.K. Loomis. 2014. Topography alters tree growth-climate relationships in a semi-arid forested catchment. *Ecosphere*, *5*(11), art148.
12. Barnard, H.R., Findley, M.C., J. Csavina. 2014. PARduino: a simple and inexpensive device for logging photosynthetically active radiation. *Tree Physiology*, 34, 640–645, doi: 10.1093/treephys/tpu044.

13. Field, J.P., D.D. Breshears, D.J. Law, L. López-Hoffman, P.D. Brooks, J. Chorover, G.A. Barron-Gafford, R.E. Gallery, M.E. Litvak, R. Lybrand, J. McIntosh, T. Meixner, G-Y. Niu, S.A. Papuga, J.D. Pelletier, C.R. Rasmussen, and P.A. Troch. 2014. A perspective on areas of emphasis for critical zone services, *Vadose Zone Journal* DOI: 10.2136/vzj2014.10.0142

Publications in Preparation (manuscripts exist in draft form):

1. Swetnam, T.L., P.D. Brooks, E.L. Gallo, H.R. Barnard, A.A. Harpold. 2016. Topographically-driven water availability constrains climatic control on carbon storage in mountain forests. Rejected from *PNAS* and now in prep for *Ecology*. Anticipated submission July 1, 2016.
2. Barnard, D.M., H.R. Barnard, N.P. Molotch. 2016. Topographic impacts on growing season length across an elevational gradient in montane coniferous forests. In prep for *Environmental Research Letters*. Anticipated submission August 1, 2016.
3. Barnard, H.R., B.A. Skeets, H.R. Adams, C.J. Crosby, W.B. Ouimet. 2016. Using xylem water to examine subsurface water storage and availability in berdock outcrops of a semi-arid catchment. In prep for *Journal of Arid Environments*. Anticipated submission July 2016.
4. Barnard, H.R., A.A. Harpold, A.B. Byers, D. Gochis, B.E. Ewers, P.D. Brooks. 2016. Resolving ecohydrologic flowpaths in a subalpine forest: a test of the two water worlds hypothesis. In prep for *Ecohydrology*. Anticipated submission August 2016.

Invited talks that featured project results (in addition 25 oral or poster presentations were made by project personnel at national meetings):

Talks by P.I. Barnard:

2016: University of Washington, School of Environmental and Forest Sciences, Seattle, WA.
2016: Colorado State University, Department of Forest and Range Stewardship, Ft. Collins, CO.
2015: University of Idaho, Department of Forest, Rangeland, and Fire Sciences, Moscow, ID.
2015: University of Vermont, School of Environment and Natural Resources, Burlington, VT.
2015: University of Wyoming, Graduate and Undergraduate Students in Hydrology Club, Laramie, WY.
2015: Society for Freshwater Science Annual Meeting, Milwaukee, WI.
2015: Panel speaker for 'Fort Collins: On the Front Lines of Climate Change', Fort Collins, CO
2014: CUASHI Biennial Colloquium 2014, Shepherdstown, WV.
2013: Colorado State University, Colorado Water Institute, Fort Collins, CO.
2012: 3rd International Conference on Forest and Water in Changing Climate, Fukuoka, Japan.

Talks by P.I. Brooks:

2016: Utah State University, Spring Runoff Conference, Logan, UT
2016: Healthy Headwater Convening, Salt Lake City, UT
2015: Global Change and Sustainability Center, University of Utah. Salt Lake City, UT
2015: Salt River Project, Phoenix, AZ
2014: Colorado Water Institute, Colorado State University, Fort Collins, CO
2014: Innovative Urban Transitions in Arid Region Hydrology, Salt Lake City, UT
2014: Sierra Nevada Research Institute, University of California, Merced, CA
2014: Arizona Hydrological Society, Flagstaff, AZ
2014: Salt River Project, Phoenix, AZ
2014: Northern Arizona University, Flagstaff, AZ
2014: Los Alamos National Lab, Los Alamos, NM
2013: Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ
2013: School of Natural Resources, University of Arizona, Tucson, AZ
2013: Chinese Academy of Science, Beijing, China
2013: Utah State University, Logan UT

Personnel

Name	**Role**	**Institution**
Holly Barnard	P.I.	University of Colorado
Paul Brooks	P.I.	University of Utah
Margaret Burns	M.A. Student	University of Colorado
Hallie Adams	M.A. Student	University of Colorado
Claire Stielstra	M.S. Student	University of Arizona
Erin Berryman	Post-doctoral researcher	University of Colorado
Rachel Gabor	Post-doctoral researcher	University of Utah
Tyson Swetnam	Post-doctoral researcher	University of Utah
Erika Gallo	Post-doctoral researcher	University of Arizona
Joel Biederman	Post-doctoral researcher	University of Arizona
David Barnard	Post-doctoral researcher	University of Colorado (salary supported by Boulder Creek CZO)
Xavier Zapata-Rios	Post-doctoral researcher	University of Arizona (externally supported)
Lyndsey Nesbitt	Research Associate	University of Utah
Daphne Szutu	Research Associate	University of Colorado
Alex Loomis	Undergraduate Honors student	University of Colorado
Anna Vinton	Undergraduate technician	University of Colorado
Mark Barckholtz	Undergraduate technician	University of Colorado
Ken Eggering	Undergraduate technician	University of Colorado
Traeger Meyer	Undergraduate technician	University of Colorado
Michelle Harrison	Undergraduate technician	University of Colorado
Breanna Skeets	Undergraduate intern and professional technician	Research Experience for Student in Solid Earth Science and University of Colorado
Zinnia Wilson	Undergraduate technician	University of Utah
Rebecca Smith	Undergraduate technician	University of Utah