An Annotated Bibliography of Scientific Literature on Research and Management Activities Conducted in Tenderfoot Creek Experimental Forest

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Adams, Mary Beth; Loughry, Linda; Plaugher, Linda, comps. 2008. Tenderfoot Creek Experimental Forest (Montana). In: Experimental forests and ranges of the USDA Forest Service. Gen. Tech. Rep. NE-321, revised. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station: 137-138. **Abstract**: The USDA Forest Service has an outstanding scientific resource in the 77 Experimental Forests and Ranges that exist across the United States and its territories. These valuable scientific resources incorporate a broad range of climates, forest types, research emphases, and history. This publication, revised in March 2008, describes each of the research sites within the Experimental Forests and Ranges network, providing information about history, climate, vegetation, soils, long-term data bases, research history and research products, as well as identifying collaborative opportunities, and providing contact information.

Ahl, Robert Steven. 2007. Integrated modeling of long-term vegetation and hydrologic dynamics in Rocky Mountain watersheds. Missoula, MT: University of Montana. 244 p. Dissertation. **Abstract**: In natural landscapes forest structure is largely shaped by periodic disturbance processes. The spatial propagation of those processes can be enhanced or restricted by physical and vegetative landscape patterns. When long-term vegetation dynamics in watersheds are assessed, the landscape context may affect the magnitude and distribution of important disturbance processes occurring within individual analysis watersheds. To examine the effect of landscape context on watershed vegetation disturbance processes, SIMPPLLE was used to simulate vegetation change over one hundred years starting from current conditions, across 7.5 million ha of central Montana, USA. Out of 12 defined landscapes, 38 watersheds, bounded by exterior watersheds on all sides (i.e. the surrounding landscape), were selected for analysis, and vegetation dynamics within them were modeled in two distinct ways: 1) in isolation from other watersheds, and 2) in the context of the surrounding landscape. A clear pattern of how individual processes were affected was difficult to establish, but fire of various severities was more prevalent when watersheds were modeled in the landscape context compared to isolated scenarios. When total relative disturbance areas were compared, 84% of watersheds exhibited significantly different patterns due to context. Overall, vegetation simulations conducted in the landscape context resulted in more disturbed areas over time, in contrast with paired simulations conducted in isolation. The difference in mean decadal disturbed areas due to context, interpreted as a measure of landscape connectivity (LC), was modeled as a function of five variables that described the topography, landcover composition and configuration within watersheds, and in a 1 km buffer around their perimeter. Increasing values of LC indicated increasing influence of landscape processes on watershed processes. LC was

positively correlated with the proportion of forest cover within watersheds, and negatively associated with the amount of barren ground in the watershed perimeter. Watersheds with > 30% internal forest cover, and < 10% barren ground along the width of their perimeter were affected by landscape processes more strongly than those with larger proportions of barren land along their boundaries, and smaller proportion of forest cover within watersheds.

Ahl, R. S.; Woods, S. W. 2006. Simulating long-term landcover change and water yield dynamics in a forested, snow-dominated Rocky Mountain watershed. In: Junlander, Randall; McGurk, Bruce, eds. Western snow conference: Proceedings of the 74th annual western snow conference; 2006 April 17-20; Las Cruces, NM. [Soda Springs, CA]: [Omnipress]: 127-134. **Abstract**: Changes in the extent, composition, and configuration of forest cover over time due to succession or disturbance processes can result in measurable changes in streamflow and water yield. Removal of forest cover generally increases streamflow due to reduced canopy interception and evapotranspiration. In watersheds where snow is the dominant source of water, yield increases and advanced peak discharge are attributed to increased snow accumulation, and enhanced melt rates in forest openings. Because knowledge of long-term watershed-level streamflow responses to landcover dynamics is limited by relatively short-term gage data, we present a modeling approach that combines existing vegetation and hydrologic simulation systems to evaluate these interactions. Our findings suggest that both vegetation and hydrologic characteristics of the research watershed are at the limits of their estimated natural ranges. Although species composition remained fairly stable over time, the size and connectivity of current landcover patches are at the upper end of the estimated temporal distribution. The large proportion and continuous nature of forest cover associated with current conditions coincide with water yield, peak discharge rates, and flow variability that are at the low end of their modeled distributions. The integrated modeling approach we describe should be applicable in other ecosystems given knowledge of biophysical interactions and availability of appropriate data. By gaining an understanding of the possible range of variability due to natural conditions, management plans may be designed to maintain resources within estimated and desirable bounds.

Ahl, Robert S.; Woods, Scott W.; Zuuring, Hans R. 2008. Hydrologic calibration and validation of SWAT in a snow-dominated Rocky Mountain watershed, Montana, USA. Journal of the American Water Resources Association. 44(6): 1411-1430. **Abstract**: The Soil and Water Assessment Tool (SWAT) has been applied successfully in temperate environments but little is known about its performance in the snow-dominated, forested, mountainous watersheds that provide much of the water supply in western North America. To address this knowledge gap, we configured SWAT to simulate the streamflow of Tenderfoot Creek (TCSWAT). Located in central Montana, TCSWAT represents a high-elevation watershed with similar to 85% coniferous forest cover where more than 70% of the annual precipitation falls as snow, and runoff comes primarily from spring snowmelt. Model calibration using four years of measured daily streamflow, temperature, and precipitation data resulted in a relative error (RE) of 2% for annual water yield estimates, and mean paired deviations (Dv) of 36 and 31% and

Nash-Sutcliffe (NS) efficiencies of 0.90 and 0.86 for monthly and daily streamflow, respectively. Model validation was conducted using an additional four years of data and the performance was similar to the calibration period, with RE of 4% for annual water yields, Dv of 43% and 32%, and NS efficiencies of 0.90 and 0.76 for monthly and daily streamflow, respectively. An objective, regression-based model invalidation procedure also indicated that the model was validated for the overall simulation period. Seasonally, SWAT performed well during the spring and early summer snowmelt runoff period, but was a poor predictor of late summer and winter base flow. The calibrated model was most sensitive to snowmelt parameters, followed in decreasing order of influence by the surface runoff lag, ground water, soil, and SCS Curve Number parameter sets. Model sensitivity to the surface runoff lag parameter reflected the influence of frozen soils on runoff processes. Results indicated that SWAT can provide reasonable predictions of annual, monthly, and daily streamflow from forested montane watersheds, but further model refinements could improve representation of snowmelt runoff processes and performance during the base flow period in this environment.

Alaback, Paul B.; Lutes, Duncan C. [1997]. Methods for the quantification of coarse woody debris and an examination of its spatial patterning: a study from the Tenderfoot Creek Experimental Forest, MT. Completion Report INT-97083-RJVA. Missoula, MT: University of Montana, School of Forestry. 37 p. **Abstract**: Methods for the quantification of coarse woody debris volume and the description of spatial patterning were studied in the Tenderfoot Creek Experimental Forest, Montana. The line transect method was found to be an accurate, unbiased estimator of down debris volume (>10cm diameter) on ½ hectare fixed area plots, when perpendicular lines were used. The Fischer Photo Guide (1981) for woody fuels did not quantify large down debris as precisely as the line transect method on ¼ hectare plots. Chi-square tests found that down debris had a clumped spatial distribution in 23% of the tests. Pieces were found randomly distributed in the remaining 77% of the tests. Tests of log orientation showed evidence of clumping in 8 of 13 tests. The Paired Quadrat Variance method found no consistent scale of clumping in 24 plots of variance. Snags were found to have a clumped distribution in 37% of the tests, a random distribution in 62% of the tests and one test indicated a uniform distribution. The Variable Area Transect method accurately described snag density, however it was not successful at determining down piece density because the transect width was too narrow.

Arno, Stephen F.; Fiedler, Carl E. 2005. Lodgepole pine. In: Mimicking nature's fire: Restoring fire-prone forests in the west. Washington, DC: Island Press: 149-166. **Abstract**: This chapter reviews the ecology and management of lodgepole pine and provides examples of lodgepole pine restoration, management, and research in Gunnison National Forest, Bitterroot National Forest, Tenderfoot Creek Experimental Forest, and Banff National Park. In Tenderfoot Creek Experimental Forest, McCaughey and Hardy's research on management treatments (cutting with and without burning) is described.

Barrett, Stephen W. 1993. Fire history of Tenderfoot Creek Experimental Forest Lewis and Clark National Forest. Final Report INT-92679-RJVA. Missoula, MT: Systems for

Environmental Management. Unpublished report on file with: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT. 23 p. **Abstract**: The landscape and stand-level fire history of lodgepole pine dominated forest in Tenderfoot Creek Experimental Forest is assessed. Primary objective were to: 1) determine pre-1900 fire periodicities, severities, and burning patterns in the area's lodgepole pine dominated stands, and 2) document and map the forest age class mosaic, reflecting stand replacing fire history at the landscape level of analysis. Secondary objectives were to interpret the possible effects of long-term fire suppression on area forests, and to determine their relative position along the fire regimes continuum for northern Rockies lodgepole pine.

Bencala, Kenneth E.; Gooseff, Michael N.; Kimball, Briant A. 2006. Interpreting hyporheic exchange flows amidst a mosaic of stream-catchment connections. In: The Geological Society of America 2006 Philadelphia annual meeting--The pursuit of science: building on a foundation of discovery; 2006 October 22-25; Philadelphia, PA. Geological Society of America abstracts with programs 38(7). [Boulder, CO]: The Geological Society of America: 41. Abstract. **Abstract**: Interpretation of hyporheic exchange flows (HEFs) has progressed in the past 25 years from identifying individual HEFs to understanding the broader hydrologic context. Stream studies (with several colleagues) in Colorado (Mineral Creek, Silverton, Colo.) and Montana (Stringer Creek, Tenderfoot Experimental Forest, Montana) document stream-catchment connections of which hyporheic exchange flows are a component. These flows, typically studied at the 10-meter scale, occur amidst a mosaic of stream-catchment connections at both finer and coarser scales. In Mineral Creek, detailed tracer sampling shows that HEFs occur in a hydro-geochemical setting of significant meter-scale variation in the concentrations of acid mine drainage constituents. Transient Storage Model (TSM) simulations with the USGS code OTIS [http://co.water.usgs.gov/otis/] have been used in numerous streams to interpret in-stream responses of solute transport for streams influenced by HEFs [for examples, see http://smig.usgs.gov/SMIG/transtor_reader1.html]. In Stringer Creek, OTIS simulations are interpreted to suggest HEFs occur in a hydro-solute transport setting of continuing inflows and outflows within 100-200 m sub-reaches along the nominally gaining stream. Challenges for understanding hyporheic exchange flows, as addressed by several investigators, are further enhancing the usefulness of TSM simulations. In addition, a variety of process-based tools are simultaneously used, again by several investigators, to develop understanding of the hydrologic mechanisms by which streams are connected with their catchments.

Birdsall, Jennifer L.; McCaughey, Ward; Runyon, Justin B. 2011. Roads impact the distribution of noxious weeds more than restoration treatments in a lodgepole pine forest in Montana, USA. Restoration Ecology. doi: 10.1111/j.1526-100X.2011.00781.x: 7 p. [Published online 2011, April]. **Abstract**: A century of fire suppression has created unnaturally dense stands in many western North American forests, and silviculture treatments are being increasingly used to reduce fuels to mitigate wildfire hazards and manage insect infestations. Thinning prescriptions have the potential to restore forests to a more historically sustainable state, but land managers need to be aware of the potential impacts of such treatments on invasion by exotic plants. However, the effects

of these activities on the introduction and spread of invasive plants are not well understood. We evaluated noxious weed occurrence over a 9-year period (2001–2009) following thinning and burning treatments in a lodgepole pine forest in central Montana. Surveys were made in the treatment units and along roads for two shelterwood-with reserve prescriptions, each with and without prescribed burning, burned only, and untreated controls. Five species listed as noxious weeds in Montana were recorded: spotted knapweed (*Centaurea stoebe*), oxeye daisy (*Leucanthemum vulgare*), Canada thistle (*Cirsium arvense*), common tansy (*Tanacetum vulgare*), and houndstongue (*Cynoglossum officinale*). With the exception of Canada thistle, noxious weeds were confined to roadsides and did not colonize silvicultural treatment areas. Roadside habitats contributed more to the distribution of noxious plant species than did silvicultural treatments in this relatively uninvaded forest, indicating the importance of weed control tactics along roads and underscoring the need to mitigate exotic plant dispersal by motorized vehicles. In addition, these findings suggest that roadways should be considered when evaluating the potential for invasion and spread of exotic plants following forest restoration treatments.

Boice, Jeff. 1999. An analysis of stream channel cross section technique as a means to determine anthropogenic change in second order streams at the Tenderfoot Creek Experimental Forest, Meagher County, Montana--Locational information for reaches used in TCEF cross section study. RMRS RJVA-98541. [Bozeman, MT]: [Montana State University]. 34 p. **Abstract**: This report describes the locations of stream reaches and methodology used to establish stream cross sections for the “TCEF cross section study". Six second order tributaries to Tenderfoot Creek were used to assess the methodology of establishing cross sections. The author was concerned that several variables (i.e. bankfull width, bankfull depth, cross sectional area, Gini coefficient, and width to depth ratio) in adjacent cross sections would be spatially autrocorrelated. Of all of the variables tested, bankfull depth was the only variable that displayed spatial autocorrelation.

Bouchier, A.; Gooseff, M. N.; McGlynn, B.; Payn, R. A.; Briggs, M. A. 2006. Comparison of stream reach scale transport of rhodamine WT and NaCl in coupled mountain stream-hyporheic system. In: American Geophysical Union, fall meeting; 2006 December 11-15; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B23A-1055. Abstract. **Abstract**: The late-time behavior of breakthrough curves of rhodamine WT (RhWT) from tracer studies in streams have been interpreted as an indication of slow water paths, or hyporheic exchanges. Another interpretation of this behavior is that RhWT is being retarded during downstream transport, possibly by sorption and rate-limited desorption. In this study we assessed the transport of RhWT compared with NaCl during and after a 5 hour co-injection steady state drip experiment. The experimental stream reach was approximately 250 meters in length, ending at the Upper Stringer Creek stream gage in the Tenderfoot Creek Experimental Forest, MT. Electric conductivity (EC) and fluorescence concentrations were measured with data logging probes (every 10 seconds) located 1) at the end of a mixing length downstream of the injection point (input - approximately 16 meters downstream), and 2) at the Upper Stringer Creek stream gage (output - approximately

250 m downstream). We then converted EC time series to NaCl concentration time series for data analysis purposes. Analysis and comparison of the NaCl and RhWT breakthrough curves show that 1) the ratio of RhWT concentration to NaCl concentration is lower and decreasing at the reach output compared to the input, and 2) the NaCl concentration declines for approximately 6 hours after the drip is turned off, whereas the RhWT concentration declines for over 20 hours still at detectable concentrations. These findings indicate that RhWT is being retarded over the experimental stream reach.

Briggs, M.; Gooseff, M. N.; McGlynn, B. 2006. Scaling of transient storage parameter estimates with increasing reach length in a mountain headwater stream. In: American Geophysical Union, fall meeting; 2006 December 11-15; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B23A-1054. Abstract. **Abstract**: Numerous studies have used the methods of stream tracer experiments and subsequent solute transport modeling to determine transient storage characteristics of streams. Experimental reach length is often determined by site logistics, morphology, specific study goals, etc. Harvey et al. [1996] provided guidance for optimal study reach lengths, based on the Dahmkoler number, as a balance between timescales of advective transport and transient storage. In this study, we investigate the scaling of parameters in a solute transport model (OTIS) with increasing spatial scale of investigation. We conducted 2 6-hour constant rate injections of dissolved NaCl in Spring Park Creek, a headwater stream in the Tenderfoot Creek Experimental Forest, Montana. Below the first injection we sampled 4 reaches ~200m in length, we then moved upstream 640m for the second injection and sampled 3 more ~200 m reaches. Solute transport simulations were conducted for each of these sub-reaches and for combinations of these sub-reaches, from which we assessed estimates of solute velocity, dispersion, transient storage exchange, storage zone size, and Fmed (proportion of median transport time due to storage). Dahmkoler values calculated for each simulation (sub-reaches as well as longer combined reach) were within an order of magnitude of 1, suggesting that our study reach lengths were appropriate. Length-weighted average solute transport and transient storage parameters for the sub-reaches were found to be comparable to their counterparts in the longer reach simulation. In particular the average dispersion found for the sub-reaches (0.43 m^2/s) compared very favorably with the value for dispersion calculated for the larger reach (0.40 m^2/s). In contrast the weighted average of storage zone size for the sub-reaches was much greater (1.17 m^2) than those calculated for the injection reach as a whole (0.09 m^2) by a factor of ~13. Weighted average values for transient storage exchange and size for the sub-reaches were both found to be higher than that of the reach as a whole, but only by factors of ~2.5 and 3 respectively. This study indicates that some values of solute transport and transient storage for a particular reach can be reasonably extrapolated from its corresponding component reach values.

Dickmann, D. I.; Rollinger, J. L. 1998. Fire for restoration of communities and ecosystems. Bulletin of the Ecological Society of America. 79(2): 157-160. **Abstract**: A review of the meeting: Fire for restoration of communities and ecosystems; ESA annual

meeting, 1997. This article highlights Colin Hardy's description of research on Tenderfoot Creek Experimental Forest that tested various combinations of silvicultural treatments and prescribed mixed-severity and low-intensity fires.

Downs, Christopher C.; White, Robert G.; Shepard, Bradley B. 1997. Age at sexual maturity, sex ratio, fecundity, and longevity of isolated headwater populations of westslope cutthroat trout. North American Journal of Fisheries Management. 17(1): 85-92. **Abstract**: We sampled 19 isolated headwater populations of westslope cutthroat trout *Oncorhynchus clarki lewisi* in Montana to provide estimates of fecundity, longevity, sex ratio, and age at sexual maturity. Fecundity was estimated for 31 fish collected from two streams in the upper Missouri River drainage. Females smaller than 149 mm fork length (FL) were generally immature and their fecundities could not be estimated. Mean fecundities (SD) were 227 eggs (41.1) for 150–174-mm fish, 346 eggs (85.6) for 175–199-mm fish, and 459 eggs (150.8) for 200-mm and larger fish. A linear regression model (two stream samples combined) to predict fecundity (E) from fork length was developed ($E = –494.9 + 4.4sFL$; $r^2 = 0.51$, $P < 0.001$) for westslope cutthroat trout in the upper Missouri River drainage. Regression slopes of fecundity against fish length differed significantly ($P < 0.01$) between these and some of the previously studied populations. Steeper slopes were associated with lacustrine-adfluvial populations. The average sex ratio was 1.3 males per female across all sampled streams. Males began to mature sexually at age 2 and all were mature by age 4. Some females (27%) were sexually mature at age 3 and most of them (93%) were mature by age 5. Length was a better predictor of sexual maturity than age. Males matured at 110–160 mm and females at 150–180 mm FL. The maximum estimated age was 8 years based on otoliths from 475 fish collected from our 19 study streams and 14 additional streams.

Emanuel, R. E.; D'Odorico, P.; Epstein, H. E.; Muth, D. J. 2006. Data assimilation for a watershed-scale model of transpiration and vegetation water-stress. In: American Geophysical Union, joint assembly; 2006 May 23-26; Baltimore, MD. Washington, DC: Eos Transactions, American Geophysical Union: H43B-05. Abstract. **Abstract**: A recent effort has combined photosynthesis-limited and soil water-limited models of stomatal conductance to simulate control of conductance by different environmental variables at different times. This new framework also defines the threshold at which soil water content becomes limiting to transpiration as a function local environmental conditions (light, temperature and atmospheric vapor pressure), parameters representing different vegetation types, and nutrient status. Such a dynamic water-stress threshold may play an important role in estimating evapotranspiration, particularly over heterogeneous land surfaces. Until now, the modeling framework has only been applied for simple crop canopies. We assimilate datasets necessary to apply this model of transpiration and dynamic water-stress to a small watershed (500 ha) in the northern Rocky Mountains (Tenderfoot Creek Experimental Forest, USFS, Montana). In 2005, two flux towers were installed within the watershed, and LIDAR data were collected for the entire watershed. A synthesis of remote sensing (IKONOS and LIDAR), distributed watershed modeling (TOPMODEL), and surface hydrometeorology (eddy covariance, ancillary micrometeorology, SNOTEL and stream discharge) is used

to evaluate the effects of spatially heterogeneous water-stress on watershed-scale transpiration at time scales ranging from a single day to an entire year.

Emanuel, Ryan E.; Epstein, Howard E.; McGlynn, Brian L.; Welsch, Daniel L.; Muth, Daniel J.; D'Odorico, Paulo. 2010. Spatial and temporal controls on watershed ecohydrology in the northern Rocky Mountains. Water Resources Research. 46, W11553, doi:10.1029/2009WR008890: 14 p. **Abstract**: Vegetation water stress plays an important role in the movement of water through the soil-plant-atmosphere continuum. However, the effects of water stress on evapotranspiration (ET) and other hydrological processes at the watershed scale remain poorly understood due in part to spatially and temporally heterogeneous conditions within the watershed, especially in areas of mountainous terrain. We used a spatially distributed model to understand and evaluate the relationship between water stress and ET in a forested mountain watershed during the snow free growing season. Vegetation water stress increased as the growing season progressed, due to continued drying of soils, and persisted late into the growing season, even as vapor pressure deficit decreased with lower temperatures. As a result, ET became decoupled from vapor pressure deficit and became increasingly dependent on soil moisture later in the growing season, shifting from demand limitation to supply limitation. We found water stress and total growing season ET to be distributed nonuniformly across the watershed due to interactions between topography and vegetation. Areas having tall vegetation and low topographic index experienced the greatest water stress, yet they had some of the highest evapotranspiration rates in the watershed.

Emanuel, R. E.; Riveros-Iregui, D.; McGlynn, B. L.; Epstein, H. E.; Welsch, D. L. 2010. A watershed context for interpreting the landscape-scale spatial heterogeneity of biosphere-atmosphere carbon exchange in complex terrain. In: American Geophysical Union, fall meeting 2010; 2010 December 13-17; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B11D-0404. Abstract. **Abstract**: Topography plays an important role in determining landscape complexity, especially in mountain regions, where ridges, peaks, valleys and other features impose gradients in climate and other environmental variables that are capable of influencing biosphere-atmosphere carbon exchange. Understanding the spatial distribution of land-atmosphere carbon fluxes is important in mountain regions, particularly in the western US where forested mountainous areas are important sinks for atmospheric carbon dioxide. Watersheds naturally provide a process-based context for understanding this topography-induced landscape complexity, including the spatial variability of resources such as water and nutrients, because the internal structures and boundaries of watersheds are themselves defined by the mechanisms that redistribute these variables across the landscape. We exploit the dependence of biosphere-atmosphere carbon exchange on resource availability and the underlying control of these resources by landscape structure to investigate links between the spatial heterogeneity of biological activity and watershed characteristics. We synthesize research using high-resolution remote sensing imagery, spatially distributed measurements of soil respiration, shallow groundwater dynamics, leaf-level ecophysiology and a variety of other ground-based measurements collected over the

course of five years from a highly instrumented watershed in the Tenderfoot Creek experimental Forest (Montana, USA), to propose and test a watershed-based framework for interpreting spatially averaged observations of carbon fluxes (i.e., tower-based measurements). Our approach provides a mechanistic framework to help understand how and why carbon fluxes from different watershed positions respond differently to landscape-scale environmental controls. This watershed context provides new insight into the coupling of carbon and water fluxes at the landscape scale in complex terrain.

Emanuel, Ryan E.; Riveros-Iregui, Diego A.; McGlynn, Brian L.; Epstein, Howard E. 2011. On the spatial heterogeneity of net ecosystem productivity in complex landscapes. Ecosphere. 2(7): 1-13. **Abstract**: Micrometeorological flux towers provide spatially integrated estimates of net ecosystem production (NEP) of carbon over areas ranging from several hectares to several square kilometers, but they do so at the expense of spatially explicit information within the footprint of the tower. This finer-scale information is crucial for understanding how physical and biological factors interact and give rise to tower measured fluxes in complex landscapes. We present a simple approach for quantifying and evaluating the spatial heterogeneity of cumulative growing season NEP for complex landscapes. Our method is based on spatially distributed information about physical and biological landscape variables and knowledge of functional relationships between constituent fluxes and these variables. We present a case study from a complex landscape in the Rocky Mountains of Montana (US) to demonstrate that the spatial distribution of cumulative growing season NEP is rather large and bears the imprint of the topographic and vegetation variables that characterize this complex landscape. Net carbon sources and net carbon sinks were distributed across the landscape in manner predictable by the intersection of these landscape variables. We simulated year-to-year climate variability and found that some portions of the landscape were consistently either carbon sinks or carbon sources, but other portions transitioned between sink and source. Our findings reveal that this emergent behavior is a unique characteristic of complex landscapes derived from the interaction of topography and vegetation. These findings offer new insight for interpreting spatially integrated carbon fluxes measured over complex landscapes.

Farnes, Phillip E.; Hansen, Katherine J.; McCaughey, Ward W. 2002. Evaluation of climatic data, post-treatment water yield and snowpack differences between closed and open stands of lodgepole pine on Tenderfoot Creek Experimental Forest. Final Report Joint Venture Agreement No. 01-JV-11222022-115. [Bozeman, MT]: [Montana State University, Department of Earth Sciences]. 50 p. **Abstract**: Objectives of this Joint Venture Agreement included: 1) input all snow and related climate data from Tenderfoot Creek Experimental Forest into computer files; 2) produce an updated 30-year average annual precipitation map based on the 1971-2000 period; 3) summarize, analyze, and publish a report/manuscript on comparison of snowpack between open and closed stands of lodgepole pine; 4) estimate change in water yield due to research silvicultural cutting treatments. Included in this report (appendix 6) is the study, "Snowpack comparison between an opening and a lodgepole pine stand" written by Ward W. McCaughey and Phillip E. Farnes. This study found, that the annual maximum snow

water equivalent on the canopy pillow averaged 77% of the open pillow over the winters from 1993 to 2000. Melt rates under the canopy averaged 46% of that in the open. On average, final melt-out of the canopy pillow is 9 days ager the open pillow.

Farnes, Phillip E.; McCaughey, Ward W.; Hansen, Katherine J. 1994. Hydrologic and geologic characterization of Tenderfoot Creek Experimental Forest, Montana. Final Report RJVA-INT-92734. Bozeman, MT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, Bozeman, Montana. 212 p. **Abstract**: The hydrology and geology of Tenderfoot Creek Experimental Forest is described in the included report, "Geology of Tenderfoot Creek Experimental Forest, Little Belt Mountains, Meagher County, Montana" written by Mitchell W. Reynolds. Baseline hydrologic and climatic data from 1961-1990 are included.

Farnes, Phillip E.; McCaughey, Ward W.; Hansen, Katherine J. 1999. Flumes, historic water yield and climatological data for Tenderfoot Creek Experimental Forest, Montana. Final Report RJVA-INT-96071. Bozeman, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 37 p. **Abstract**: The objectives of this Research Joint Venture Agreement were to install and calibrate three flumes on the Tenderfoot Creek Experimental Forest (TCEF) in central Montana; check calibration of the existing seven flumes on TCEF; estimate the influence of fire on water yields over the 400-year fire history period; and estimate back records of monthly temperature, monthly snow water equivalent, monthly precipitation for TCEF, and monthly streamflow for the lower Tenderfoot Creek flume.
The technical paper, "Historic role of fire in determining the natural variability of annual water yield in mountain watersheds" (McCaughey et al. 1997) is included in this report.

Farnes, P. E.; McCaughey, W. W.; Hansen, K. J. 2004. Role of fire in determining annual water yield in mountain watersheds. In: Wallace, L. L., ed. After the fires: the ecology of change in Yellowstone National Park. New Haven, CT: Yale University Press: 200-231. **Abstract**: This paper presents the computation procedures for estimating average annual water yields based on annual precipitation and vegetation cover types. These procedures allows for an estimation of water yields under current conditions, under various levels of vegetation management, or under historic water yield based on fire history. Two examples of evaluating fire's role in determining annual water yield in mountain watersheds in the USA are presented. Annual water yield was estimated using developed procedures for the Tenderfoot Creek Experimental Forest in central Montana for the past 400+ years based on fire history records. Additionally, the increase in runoff for 11 years after the 1988 fires in Yellowstone National Park, Wyoming, was estimated using runoff-forecasting equations developed with prefire data, and this was compared with the analytical procedures similar to Tenderfoot Creek.

Farnes, Phillip E.; Shearer, Raymond C.; McCaughey, Ward W.; Hansen, Katherine J. 1995. Comparisons of hydrology, geology, and physical characteristics between Tenderfoot Creek Experimental Forest (east side) Montana, and Coram Experimental Forest (west side) Montana. Final Report RJVA-INT-92734. Bozeman, MT: Montana

State University, College of Letters and Sciences, Department of Earth Sciences. 19 p. **Abstract**: Physical features, precipitation rates and patterns, temperature, streamflow patterns, and runoff are compared between Tenderfoot Creek Experimental Forest and Coram Experimental Forest.

Flora, Gloria E.; McCaughey, Ward. 1998. Environmental assessment: Tenderfoot Creek Experimental Forest--Vegetative treatment research project, Kings Hill Ranger District, Lewis and Clark National Forest, Meagher County, Montana. [Great Falls, MT]: [U. S. Department of Agriculture, Forest Service, Lewis and Clark National Forest]. 5 chapters (+ appendices). **Abstract**: Environmental assessment of the Tenderfoot Research Project. This research project proposes to harvest timber in two treatment subwatersheds, Spring Park Creek and Sun Creek. The silvicultural system proposed is a two-aged system termed “shelterwood with reserves,” that uses even distribution of single or small groups and uneven distribution and shape of large residual groups. Additionally, two kinds of prescribed fire treatments will be applied; low-intensity underburn and mixed severity broadcast burn.

Fultz, Jessica E. 2005. Effects of shelterwood management on flower-visiting insects and their floral resources. Bozeman, MT: Montana State University. 163 p. Thesis. **Abstract**: Habitat alteration can affect pollinating-insect community structure, decreasing the efficiency of pollinators on which many agricultural and natural ecosystems rely. Within the Tenderfoot Creek Experimental Forest (TCEF), located in the Little Belt Mountains of Central Montana, two different types of silvicultural techniques, even and group shelterwood, were applied to alter the natural habitats within the lodgepole pine (*Pinus contorta*) forests. Following logging, surveys of the flower-visiting insects and their floral resources were conducted within four treatments, even and group shelterwood, unlogged and meadow. In addition, individual insects were collected and the pollen removed from their bodies was counted and identified. The density of floral resources and the abundance of flower-visiting insects, as well as several diversity measures of both, were calculated, to examine the response of insects and plants to logging. Spearman rank correlations were used to examine changes over the sample years. Non-metric multi-dimensional scaling (NMS) was used to create ordinations of the treatments while multiple response permutation procedure (MRPP) tested the hypothesis of no difference between treatments with respect to either floral resources or flower-visiting insects. Correlations between the abundances of floral resources and flower-visiting insect taxa were also conducted using Mantel tests. Kruskal-Wallis tests were used to test the hypothesis of no difference between insect taxa with respect to pollen quantity and richness. NMS was used to create ordinations of species within families with respect to types of pollen and quantity carried. Changes in density, abundance, and diversity between years were detected as were differences among treatments. Associations between floral resources and flower-visiting insects were detected. Differences among insect species with respect to pollen type and quantity were detected. Overall, the alteration of the original forest habitats changed the community structure of not only the flower-visiting insects but also their floral resources in the two shelterwood treatments.

Godtel, Donald. 1998. Appendix A--Biological assessment, TCEF research project for Lewis and Clark National Forest. Great Falls, MT: U.S. Department of Agriculture, Forest Service, Lewis and Clark National Forest. 7 p. **Abstract**: An environmental analysis has been prepared which describes and evaluates the management alternatives for the timber harvest and burning within the Tenderfoot Creek Experimental Forest (TCEF) project area. The project area lies within the headwaters of the Tenderfoot drainage of the Lewis and Clark National Forest. The purpose of this biological assessment is to review the possible effects of the preferred alternative on endangered, threatened, proposed and candidate species and their habitats in order to determine whether or not a "may adversely affect" situation exists. This assessment, which was first written in 1997 was updated in 1998 to reflect the status of lynx.

Gooseff, Michael; Payn, Robert; McGlynn, Brian; Bencala, Ken; Wondzell Steve, B. 2007. Multiple spatial scales of surface water-groundwater exchange in a headwater stream in Montana, USA. In: Geological Society of America, Denver annual meeting; 2001 October 28-30; Denver, CO. Geological Society of America abstracts with programs 39(6). Geological Society of America: 480. Abstract. **Abstract**: Reach-scale solute transport studies are often used to characterize transient storage of solutes or groundwater-surface water exchanges, yet the results characterize only a small component of a longer stream. We examined the spatial distribution of streamflow exchanges in a headwater stream at the US Forest Service's Tenderfoot Creek Experimental Forest in central Montana, USA. In early August 2005, we conducted a long-term (approx. 8 days) Rhodamine WT (RWT) tracer injection in a 2.8 km stream reach. When steady-state RWT concentrations were achieved, we then conducted a series of chloride slug (approx. instantaneous) releases in 28 100-m and 14 200-m long subreaches along the 2.8-km study reach. Stream discharge increased from 0.8 L s^{-1} (at the head) to 27 L s^{-1} (at the base) along the 2.8-km study reach. Thus, although the stream gains water at the scale of the 2.8-km study reach, results of these tracer experiments demonstrated simultaneous hydrologic gains and losses in the individual subreaches on multiple spatial scales. Subreaches with some of the larger losses of water were also the subreaches with larger gains of water. Simultaneous gains and losses measured within a given subreach are consistent with longer subsurface, hyporheic, hydrologic retention times not measurable through interpretation of recovered tracer alone. In all 100 m and 200 m subreaches, mass loss of RWT from the long-term injection was less than that of chloride from the slug releases, indicating the influence of long hyporheic flowpaths along the 2.8 km reach.

Grabs, Thomas. 2010. Water quality modeling based on landscape analysis: importance of riparian hydrology. Stockholm, Sweden: Stockholm University. 39 p. Dissertation. **Abstract**: Several studies in high-latitude catchments have demonstrated the importance of near-stream riparian zones as hydrogeochemical hotspots with a substantial influence on stream chemistry. An adequate representation of the spatial variability of riparian-zone processes and characteristics is the key for modeling spatiotemporal variations of stream-water quality. This thesis contributes to current knowledge by refining landscape-analysis techniques to describe riparian zones and by introducing a conceptual framework to quantify solute exports from riparian zones. The

utility of the suggested concepts is evaluated based on an extensive set of hydrometric and chemical data comprising measurements of streamflow, groundwater levels, soil-water chemistry and stream chemistry.
Standard routines to analyze digital elevation models that are offered by current geographical information systems have been of very limited use for deriving hydrologically meaningful terrain indices for riparian zones. A model-based approach for hydrological landscape analysis is outlined, which, by explicitly simulating groundwater levels, allows better predictions of saturated areas compared to standard routines. Moreover, a novel algorithm is presented for distinguishing between left and right stream sides, which is a fundamental prerequisite for characterizing riparian zones through landscape analysis. The new algorithm was used to derive terrain indices from a high-resolution LiDAR digital elevation model. By combining these terrain indices with detailed hydrogeochemical measurements from a riparian observatory, it was possible to upscale the measured attributes and to subsequently characterize the variation of total organic-carbon exports from riparian zones in a boreal catchment in Northern Sweden. Riparian zones were recognized as highly heterogeneous landscape elements. Organic-rich riparian zones were found to be hotspots influencing temporal trends in stream-water organic carbon while spatial variations of organic carbon in streams were attributed to the arrangement of organic-poor and organic-rich riparian zones along the streams. These insights were integrated into a parsimonious modeling approach. An analytical solution of the model equations is presented, which provides a physical basis for commonly used powerlaw streamflow-load relations.

Grabs, T.; Seibert, Jan; Jencso, Kelsey; McGlynn, Brian. 2009. Calculation of side-separated contributions to stream networks– a new tool to characterize riparian zones. In: Purves, Ross; Gruber, Stephan; Straumann, Ralph; Hengl, Tomislav, eds. Proceedings of Geomorphometry; 2009 August 31-September 2; Zurich, Switzerland. [Place of publication unknown]: [Publisher unknown]: 38-43. **Abstract**: Streams play a key role in many environmental studies and research areas. From a hydrological perspective, streams and other flow pathways carry the spatio-temporally convoluted signal of all upstream, hydrologically-connected processes. Modern tools for GIS-based hydrological landscape analysis (HLA) embrace this concept for calculating values of upslope area or for aggregating upslope terrain indices. Recent studies, however, suggest that not all upslope processes contribute equally to the observed stream signal and that particularly riparian zones hold the key for a better understanding of stream responses. Riparian zones are, by nature, elongated strips of land directly adjacent to a stream network and located on both of its sides. Being the last stage before a drop of water enters a stream network, the potential imprint left by riparian zones is likely to be considerably larger than indicated by their actual extend. However, traditional HLA methods used to characterize these zones are mostly inapplicable because most methods fail to account for small extend of riparian zones and for the fact that they are located on opposite sides in a stream network. To overcome limitations of traditional HLA methods, we developed a novel method to calculate side-separated contributions from adjacent hillslopes. Water table and elevation data from the 22 km^2 Tenderfoot Creek catchment, Montana, demonstrated clearly the importance of the new method. Separating contributions from the two sides produced significantly different results than

produced by standard HLA methods. More importantly, only upslope area calculated by the new method was able to predict the hydrological connection between hillslope and riparian water tables as observed in 24 transects along the stream network.

Grabs, T. J.; Jencso, K. G.; McGlynn, B. L.; Seibert, J. 2010. Calculating terrain indices along streams: a new method for separating stream sides. Water Resources Research. 46: 1-10. **Abstract**: There is increasing interest in assessing riparian zones and their hydrological and biogeochemical buffering capacity with indices derived from hydrologic landscape analysis of digital elevation data. Upslope contributing area is a common surrogate for lateral water flows and can be used to assess the variability of local water inflows to riparian zones and streams. However, current geographic information system algorithms do not provide a method for easily separating riparian zone and adjacent upland lateral contributions on each side of the stream. Here we propose a new algorithm to compute side-separated contributions along stream networks. We describe the new algorithm and illustrate the importance of distinguishing between lateral inflows on each side of streams with hillslope-riparian zone-stream hydrologic connectivity results from high-frequency water table data collected in the 22 km^2 Tenderfoot Creek catchment, Montana.

Gray, Katharine L.; Reinhardt, Elizabeth. 2003. Analysis of algorithms for predicting canopy fuel. In: Second international wildland fire ecology and fire management congress and fifth symposium on fire and forest meteorology; 2003 November 16-20; Orlando, FL. Boston, MA: American Meteorological Society: 11 p. **Abstract**: We compared observed canopy fuel characteristics with those predicted by existing biomass algorithms. We specifically examined the accuracy of the biomass equations developed by Brown (1978). We used destructively sampled data obtained at 5 different study areas. We compared predicted and observed quantities of foliage and crown biomass for individual trees in our study sites for ponderosa pine, Douglas fir, and lodgepole pine. In addition, we observed the appropriateness of using similar species to predict canopy fuel characteristics when the actual species is not accounted for using Brown's equations. For example, we used western red cedar in place of incense cedar and grand fir instead of white fir. We also evaluated the importance of tree dominance as a predictor of crown biomass. Adjustments were made to Brown's equations in order to improve the predictability of the equations for future use. We also compared plot totals to assess the usefulness of the method for predicting stand level canopy fuel characteristics.

Hardy, Colin C. 1999. On the move: recent happenings in vegetation research. In: Eco-Report: Bitterroot Ecosystem Management Research Project. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 12. **Abstract**: This article summarizes the current (1999) research associated with the Bitterroot Ecosystem Research Management Project (BEMRP). Research includes: whitebark pine regeneration, silviculture and prescribed fire treatments in Tenderfoot Creek Experimental Forest, restoration of old-growth ponderosa pine, and riparian area restoration.

Hardy, Colin C.; Keane, Robert E.; Stewart, Catherine A. 2000. Ecosystem-based management in the lodgepole pine zone. In: Smith, Helen Y., ed. The Bitterroot Ecosystem Management Research Project: what we have learned: symposium proceedings; 1999 May 18-20; Missoula, MT. Proc. RMRS-P-17. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 31-35. **Abstract**: The significant geographic extent of lodgepole pine (*Pinus contorta*) in the interior West and the large proportion within the mixed-severity fire regime has led to efforts for more ecologically based management of lodgepole pine. New research and demonstration activities are presented that may provide knowledge and techniques to manage lodgepole pine forests in the interior West. First, at the stand and watershed levels, a current application of a suite of restoration treatments to lodgepole pine stands within a watershed in central Montana is discussed. Second, a Bitterroot Ecosystem Management Research Project (BEMRP) study is presented that characterized landscape and patch dynamics in lodgepole pine forests at a coarser spatial resolution. Various landscape metrics for quantification of the range of variation in aerial extent of cover type and structural stage categories were used, and the implications for ecosystem management are discussed.

Hardy, Colin C.; McCaughey, Ward W. 1997. Restoring fire in lodgepole pine forests of the intermountain west. In: Ecological Society of America, 1997 annual meeting: Changing ecosystems: natural and human influences; 1997 August 10-14; Albuquerque, NM. In: Supplement to Bulletin of the Ecological Society of America. 78(4): 15. Abstract. **Abstract**: We are developing new management treatments for regenerating and sustaining lodgepole pine (*Pinus contorta*) forests through emulation of natural disturbance processes. Lodgepole pine is the principal forest cover on over 26 million hectares in western North America. While infrequent, stand replacing fires following mountain pine beetle outbreaks are common to the inland form (var. *latifolia*), more frequent nonlethal and mixed severity fires also significantly affected stand development and landscape patterns. This diversity of fire regimes resulted in spatially complex forests with a mosaic of one-and multi-aged stands. Our demonstration treatments are being tested on the Tenderfoot Creek Experimental Forest (TCEF) in central Montana, where other companion studies as well as extensive water quality and quantity studies are being performed. Our challenge is to design economical silvicultural and prescribed fire treatments which maintain spatial and biological diversity. Two paired sub-watersheds within TCEF will be used for treatment activities; two others will serve as untreated controls. Research will evaluate replicated two-aged silvicultural treatments with and without prescribed fire. A fifth treatment will be prescribed fire alone. Results of these research demonstration studies will be assessed for potential application to lodgepole pine forests on other areas, including the Bitterroot National Forest in western Montana.

Hardy, Colin C.; Reinhardt, Elizabeth D. 1998. Modeling effects of prescribed fire on wildlife habitat: stand structure, snag recruitment and coarse woody debris. In: Fire and wildlife in the Pacific Northwest: research, policy, and management; 1998 April 6-8; Spokane, WA. [Bethesda, MD]: The Wildlife Society, Northwest Section, Oregon and Washington Chapters: 67-74. **Abstract**: Tenderfoot Creek Experimental Forest is used

as case study to model the effects of prescribed fire and silvicultural treatments on stand structure, snag recruitment, and coarse woody debris. The Forest Vegetation Simulator (FVS) and the Fire and Fuels Extension simulate the effects of the following treatment prescriptions: shelterwood with reserves, prescribed fire, shelterwood plus prescribed fire, and no treatment.

Hardy, Colin C.; Smith, Helen Y.; McCaughey, Ward. 2006. The use of silviculture and prescribed fire to manage stand structure and fuel profiles in a multi-aged lodgepole pine forest. In: Andrews, Patricia L.; Butler, Bret W., comps. Fuels management-- How to measure success: conference proceedings; 2006 March 28-30; Portland, OR. RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 451-464. **Abstract**: This paper presents several components of a multi-disciplinary project designed to evaluate the ecological and biological effects of two innovative silvicultural treatments coupled with prescribed fire in an attempt to both manage fuel profiles and create two-aged stand structures in lodgepole pine. Two shelterwood silvicultural treatments were designed to replicate as well as enhance the existing multi-aged stand structure on the Tenderfoot Creek Experimental Forest in central Montana: the first, with reserve trees evenly distributed; the second, with reserves contained within small (1/10-1/4 acre) groups. Retention of reserve trees was targeted at 50%, without regard to diameter or species. Eight even distribution and eight group-retention treatments were applied on 16 units totaling 649 acres. Half of the units were broadcast burned following harvest using a common burn prescription on all units. Allowable overstory mortality specified in the prescribed fire plan was 50%. Plot-based fuel inventories and fire effects observations were performed at permanent plot locations prior to and following harvest, and after burning. Fuel moisture samples were acquired immediately prior to ignition. Data from four prescribed-burned treatment units were evaluated for this paper: two even-retention units and two grouped retention units. Harvest activities resulted in significant increases in fine-fuel loading (1-, 10-, and 100-hour fuel), which was subsequently reduced by prescribed fire to near pre-harvest levels. Consumption of large woody fuel was similar for both treatment types. The fire-induced mortality of overstory trees was greater in the even distribution than in the grouped distribution. Despite careful execution of a relatively conservative burn plan, mortality in the even treatments exceeded the prescription threshold of 50% by an additional 28%. Additional data collected at the plots include trees per acre, residual tree mortality, residual tree growth, regeneration, windthrow, hydrologic responses, soil impacts, and beetle activity. A comprehensive summary of the treatments will follow subsequent monitoring scheduled to occur five and ten years after burning.

Hazen, George A. R.; Emanuel, R. E.; Jencso, K. G.; McGlynn, B. L. 2010. Vegetation influences on hillslope-stream connectivity in a forested northern Rocky Mountain watershed. In: American Geophysical Union, fall meeting 2010; 2010 December 13-17; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H53B-1011. Abstract. **Abstract**: Little is known about the combined effects of vegetation and topography on hillslope water table dynamics. These interactions are especially important in forested headwater catchments, where complex terrain and

occasionally dense vegetation can result in large spatial and temporal variability in fluxes of water from hillslopes to streams. We use empirical evidence from a forested, subalpine watershed in the northern Rocky Mountains (Stringer Creek, MT, part of Tenderfoot Creek Experimental Forest) to understand how vegetation interacts with topography to influence patterns of hydrologic connectivity between hillslopes and streams. We combined field measurements, including time series of shallow groundwater levels, with remotely sensed terrain and vegetation variables to identify vegetation-related patterns in hillslope-riparian-stream (HRS) connectivity during a growing season for thirteen hillslopes within the Stringer Creek watershed covering a range of upslope accumulated areas (UAAs) and vegetation densities. Two regimes were observed where some transects were connected more often than predicted by UAA alone whereas other transects were connected less often than predicted by UAA. We discuss the emergence of these two regimes from the perspective of the hillslope water balance, and we identify the roles of groundwater and ET in generating these patterns.

Hood, Sharon M.; Cluck, Danny R.; Smith, Sheri L.; Ryan, Kevin C. 2008. Using bark char codes to predict post-fire cambium mortality. Fire Ecology. 4(1): 57-73. **Abstract**: Cambium injury is an important factor in post-fire tree survival. Measurements that quantify the degree of bark charring on tree stems after fire are often used as surrogates for direct cambium injury because they are relatively easy to assign and are non-destructive. However, bark char codes based on these measurements have been inadequately tested to determine how well they relate to live or dead cambium. Methods for assessing cambium injury through direct sampling have also been questioned as a potential factor for increasing tree mortality. In this study we used data collected from 11 wildfires and 6 prescribed fires in California, Idaho, Montana, and Wyoming to develop a relationship between bark char codes and cambium status for 14 coniferous species. Burned trees were assessed at groundline for bark char severity on each bole quadrant and then sampled at the center of each quadrant to determine cambium status (live or dead). We found that the moderate and deep bark char codes were strongly associated with dead cambium for thin-bark species: lodgepole pine (*Pinus contorta*), whitebark pine (*P. albicaulis*), western white pine (*P. monticola*), western redcedar (*Thuja plicata*), Engelmann spruce (*Picea engelmannii*), western hemlock (*Tsuga heterophylla*), and subalpine fir (*Abies lasiocarpa*). However, bark char codes were somewhat inaccurate in predicting cambium status of the thicker-bark species of white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*P. jeffreyi*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and sugar pine (*P. lambertiana*). We also evaluated the effect of direct cambium sampling on ponderosa pine tree mortality in eastern Montana. Mortality rates were equivalent for eastern Montana ponderosa pines with and without cambium sampling. Our results support using bark char codes as surrogates for cambium sampling in tree species with thin bark, but bark char codes for thick-bark species, especially the moderate char code, are often not accurate fire-injury variables, as they do not correlate well with cambium status.

Jencso, K.; McGlynn, B. L.; Gooseff, M.; Wondzell, S.; Bencala, K. 2006. Landscape

controls on hillslope-riparian-stream hydrologic connections in a set of nested catchments, northern Rocky Mountains. In: American Geophysical Union, fall meeting; Washington, DC: Eos Transactions, American Geophysical Union: H31E-1473. Abstract. **Abstract**: Understanding how local hillslope-riparian connections and source water dynamics translate to catchment scale hydrologic and solute response remains a challenge. We examined hydrologic connections between hillslope, riparian, and stream zones across catchments ranging in size from 3 to 30 km2, within the Tenderfoot Creek Experimental Forest (U.S. Forest Service) in the northern Rocky Mountains of Montana, USA. We quantified hillslope and riparian lateral contributing area and estimated the volume of riparian reservoirs through landscape analysis of Airborne Laser Swath Mapping (ALSM) derived digital elevation models. Based on this landscape analysis, 12 transects of topographic end-members were selected with a range of hillslope and riparian extents. Wells and nested piezometers were installed across the stream, riparian, and hillslope zone along each transect, and were monitored for solutes, specific conductance, and water table dynamics. Patterns in water level fluctuations and solute/conductivity measurements through the year and during runoff events indicate hydrologic connections and source water dynamics unique to each landscape setting. Our approach provides a framework for quantification of the spatial distribution of runoff source areas and first steps toward spatially explicit links between localized hillslope/riparian controls on runoff source areas and whole catchment hydrologic and solute response.

Jencso, Kelsey G.; McGlynn, Brian L.; Gooseff, Michael N.; Bencala, Kenneth E.; Wondzell, Steven M. 2010. Hillslope hydrologic connectivity controls riparian groundwater turnover: implications of catchment structure for riparian buffering and stream water sources. Water Resources Research. 46: 1-18. **Abstract**: Hydrologic connectivity between catchment upland and near stream areas is essential for the transmission of water, solutes, and nutrients to streams. However, our current understanding of the role of riparian zones in mediating landscape hydrologic connectivity and the catchment scale export of water and solutes is limited. We tested the relationship between the duration of hillslope-riparian-stream (HRS) hydrologic connectivity and the rate and degree of riparian shallow groundwater turnover along four HRS well transects within a set of nested mountain catchments (Tenderfoot Creek Experimental Forest, MT). Transect HRS water table connectivity ranged from 9 to 123 days during the annual snowmelt hydrograph. Hillslope water was always characterized by low specific conductance (similar to 27 mu S cm^{-1}). In transects with transient hillslope water tables, riparian groundwater specific conductance was elevated during base flow conditions (similar to 127 mu S cm^{-1}) but shifted toward hillslope signatures once a HRS groundwater connection was established. The degree of riparian groundwater turnover was proportional to the duration of HRS connectivity and inversely related to the riparian: hillslope area ratios (buffer ratio; $r^2 = 0.95$). We applied this relationship to the stream network in seven subcatchments within the Tenderfoot Creek Experimental Forest and compared their turnover distributions to source water contributions measured at each catchment outlet. The amount of riparian groundwater exiting each of the seven catchments was linearly related ($r^2 = 0.92$) to their median riparian turnover time. Our observations suggest that the size and spatial arrangement

of hillslope and riparian zones along a stream network and the timing and duration of groundwater connectivity between them is a first-order control on the magnitude and timing of water and solutes observed at the catchment outlet.

Jencso, Kelsey G.; McGlynn, Brian L.; Gooseff, Michael N.; Wondzell, Steven M.; Bencala, Kenneth E.; Marshall, Lucy A. 2009. Hydrologic connectivity between landscapes and streams: transferring reach-and plot-scale understanding to the catchment scale. Water Resources Research. 45: 1-16. **Abstract**: The relationship between catchment structure and runoff characteristics is poorly understood. In steep headwater catchments with shallow soils the accumulation of hillslope area (upslope accumulated area (UAA)) is a hypothesized first-order control on the distribution of soil water and groundwater. Hillslope-riparian water table connectivity represents the linkage between the dominant catchment landscape elements (hillslopes and riparian zones) and the channel network. Hydrologic connectivity between hillslope-riparian-stream (HRS) landscape elements is heterogeneous in space and often temporally transient. We sought to test the relationship between UAA and the existence and longevity of HRS shallow groundwater connectivity. We quantified water table connectivity based on 84 recording wells distributed across 24 HRS transects within the Tenderfoot Creek Experimental Forest (U. S. Forest Service), northern Rocky Mountains, Montana. Correlations were observed between the longevity of HRS water table connectivity and the size of each transect's UAA (r^2 = 0.91). We applied this relationship to the entire stream network to quantify landscape-scale connectivity through time and ascertain its relationship to catchment-scale runoff dynamics. We found that the shape of the estimated annual landscape connectivity duration curve was highly related to the catchment flow duration curve (r^2 = 0.95). This research suggests internal catchment landscape structure (topography and topology) as a first-order control on runoff source area and whole catchment response characteristics.

Jencso, K. G.; McGlynn, B. L.; Gooseff, M. N.; Wondzell, S. M.; Bencala, K. E.; Payn, R. A. 2007. Topographic controls on hillslope-riparian water table continuity in a set of nested catchments, northern Rocky Mountains, Montana. In: American Geophysical Union, fall meeting; 2007 December 10-14; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H21A-0168. Abstract. **Abstract**: Understanding how hillslope and riparian water table dynamics influence catchment scale hydrologic response remains a challenge. In steep headwater catchments with shallow soils, topographic convergence and divergence (upslope accumulated area-UAA) is a hypothesized first-order control on the distribution of soil water and groundwater. To test the relationship between UAA and the longevity of hillslope-riparian-stream shallow groundwater connectivity, we quantified water table continuity based on 80+ recording wells distributed across 24 hillslope-riparian-stream cross-sections. Cross-section upstream catchment areas ranged in size from 0.41 to 17.2 km^2, within the Tenderfoot Creek Experimental Forest (U.S. Forest Service), northern Rocky Mountains, Montana, USA. We quantified toe-slope UAA and the topographic index (TI = ln a/tanβ) with a Multiple-D- Infinity (area routing in multiple infinite downslope directions) flow accumulation algorithm analysis of 1, 3, 10, and 30m ALSM derived DEMs. Indices derived from the 10m DEM best characterized subsurface

flow accumulation, highlighting the balance between the process of interest, topographic complexity, and optimal grid scale representation. Across the 24 transects, toe-slope UAA ranged from 600-40,000 m^2, the TI ranged from 5-16, and riparian widths were between 0-60m. Patterns in shallow groundwater table fluctuations suggest hydrologic dynamics reflective of hillslope-riparian landscape setting. Specifically, correlations were observed between longevity of hillslope-riparian water table continuity and the size of the UAA (r^2=0.84) and its topographic index (r^2=.86). These observations highlight the temporal component of topographic-hydrologic relationships important for understanding threshold mediated hydrologic variables. We are working to quantify the characteristics and spatial distribution of hillslope-riparian sequences and their water table dynamics to temporally link runoff source areas to whole catchment hydrologic response.

Jencso, K. G.; McGlynn, B. L.; Marshall, L. A. 2010. Linking catchment structure to hydrologic function: implications of catchment topography for patterns of landscape hydrologic connectivity and stream flow dynamics. In: American Geophysical Union, fall meeting; 2010 December 13-17; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H14B-05. Abstract. **Abstract**: The relationship between catchment structure (topography and topology), stream network hydrologic connectivity, and runoff response remains poorly understood. Hillslope-riparian-stream (HRS) water table connectivity serves as the hydrologic linkage between a catchment's uplands and the channel network and facilitates the transmission of water and solutes to streams. While there has been tremendous interest in the concept of hydrological connectivity to characterize catchments, there are relatively few studies that have quantified hydrologic connectivity at the stream network and catchment scales. Here, we examine how catchment topography influenced patterns of stream network HRS connectivity and resultant runoff dynamics across 11 nested headwater catchments in the Tenderfoot Creek Experimental Forest (TCEF), MT. This study extends the empirical findings of Jencso et al. (2009) who found a strong linear relationship (r^2 = 0.92) between the upslope accumulated area (UAA) and annual duration of shallow ground water table connectivity observed across 24 HRS transects (146 groundwater recording wells) within the TCEF. We applied this relationship to the entire stream network to quantify the frequency distribution of stream network connectivity through time (as a function of UAA) and ascertain its relationship to catchment-scale runoff dynamics. Each catchment's estimated connectivity duration curve (CDC) was highly related to its flow duration curve (FDC); albeit the rate of change of runoff with respect to stream network connectedness varied significantly across catchments. To ascertain potential reasons for these differences we compared the slope of each catchment's CDC-FDC relationship (annual, peak, transition and baseflow periods) in multiple linear models against median values of common terrain indices and land cover-vegetation characteristics. Significant predictors ($p<0.05$) included the flow path distance to the creek (DFC), the flow path gradient to the creek (GTC), and their ratios DFC/GTC. Our results suggest that spatio-temporal distributions of upland-riparian-stream hydrologic connectivity can provide insight into runoff source area dynamics, runoff implications of catchment morphology and topology, and a direct and quantifiable link between catchment structure and hydrologic dynamics.

Jencso, K. G.; McGlynn, B. L.; Pacific, V. J. 2009. Variable flushing mechanisms and landscape structure control stream DOC export during snowmelt in a set of nested catchments. In: American Geophysical Union, fall meeting; 2009 December 14-18; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B43A-0344. Abstract. **Abstract**: Stream DOC dynamics during snowmelt have been the focus of much research, and both one-dimensional (1D) and two-dimensional (2D) DOC export mechanisms have been proposed. However, landscape structure control on the spatial and temporal variability of these DOC mobilization and delivery mechanisms from the soil to the stream remains poorly understood. We investigated stream, soil, surface and groundwater DOC dynamics across 6 transects and 7 watersheds with a wide range of landscape settings during snowmelt (April 15 - July 15) in the U.S. Forest Service Tenderfoot Creek Experimental Forest in the northern Rocky Mountains, Montana. We found that the relative importance of 1D and 2D DOC flushing mechanisms was strongly controlled by landscape position and the degree of hydrologic connectivity between the stream, riparian, and hillslope zones. 1D flushing required a hydrologic connection across the riparian-stream interface, and likely occurred at landscape positions with a wide range of upslope accumulated area (UAA - the amount of land area draining to a particular location) and wetness status (such as at baseflow). In contrast, 2D flushing appeared restricted to areas with a hydrologic connection across the entire hillslope-riparian-stream continuum, which generally occurred only at areas with high UAA, and/or at times of high wetness (such as at peak snowmelt). Further, the relative amount of DOC-rich riparian and wetland zones strongly influenced stream DOC export. Cumulative stream DOC export was highest from catchments with a large proportion of riparian:upland area, and ranged from 7.8 to 13.3 kg ha^{-1} across the study period. This research suggests that the greatest stream DOC export during snowmelt in complex subalpine catchments occurs at the intersection of high hydrologic connectivity and large DOC source areas.

Jimenez, D. M.; Butler, B. W.; Reardon, J. 2003. Stem mortality in surface fires. Part II, experimental methods for characterizing the thermal response of tree stems to heating by fires. In: Proceedings of the 2nd international wildland fire ecology and fire management congress and the 5th symposium on fire and forest Meteorology; 2003 November 16-20; Orlando, FL. Boston, MA: American Meteorological Society: 2B.2. **Abstract**: Current methods for predicting fire-induced plant mortality in shrubs and trees are largely empirical. These methods do not exhibit a wide range of applicability and are not readily linked to duff burning, soil heating, and surface fire behavior models. A detailed model predicting the temperature distribution through a tree stem as a function of time for a time varying heat pulse has been developed. Evaluation of model accuracy has required the development of new techniques for quantifying the heat flux at the bark surface and change in temperatures within plant stems. The techniques must work for a range of heating regimes, stem diameters, and tree species. Here, we describe the experimental methodology used for this effort. Data were collected in field and laboratory studies, the methodology used for each varied. Representative cambial temperatures and surface heat fluxes from four species are presented for a range of stem diameters. Typical surface heating fluxes measured in the field studies ranged

from 15 to 80 kW-m^{-2}, magnitude and duration depended on fuel type and loading. Fluxes measured in laboratory studies ranged from 15 to 40 kW-m^{-2}. It is anticipated that the methods developed in this study will be used to obtain data for additional species.

Keane, Robert E. 2008. Surface fuel litterfall and decomposition in the northern Rocky Mountains, U.S.A. Res. Pap. RMRS-RP-70. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 22 p. **Abstract**: Surface fuel deposition and decomposition rates are important to fire management and research because they can define the longevity of fuel treatments in time and space and they can be used to design, build, test, and validate complex fire and ecosystem models useful in evaluating management alternatives. We determined rates of surface fuel litterfall and decomposition for a number of major forest types that span a wide range of biophysical conditions in the northern Rocky Mountains, USA. We measured fuel deposition for more than 10 years with semi-annual collections of fallen biomass sorted into six fuel components (fallen foliage, twigs, branches, large branches, logs, and all other canopy material). We gathered this material using a network of seven to nine, 1-m^2 litter traps installed at 28 plots that were established on seven sites with four plots per site. We measured decomposition for only fine fuels using litter bags installed on five of the seven sites and monitored for biomass loss from the bags each year for 3 years. Deposition and decomposition rates are summarized by plot, cover type, and habitat type series. We also present various temporal and spatial properties of litterfall and decomposition fluxes across the six fuel components.

Keane, Robert E. 2008. Biophysical controls on surface fuel litterfall and decomposition in the northern Rocky Mountains, USA. Canadian Journal of Forest Research. 38(6): 1431-1445. **Abstract**: Litterfall and decomposition rates of the organic matter that comprise forest fuels are important to fire management, because they define fuel treatment longevity and provide parameters to design, test, and validate ecosystem models. This study explores the environmental factors that control litterfall and decomposition in the context of fuel management for several major forest types in the northern Rocky Mountains (Idaho and Montana), USA. Litterfall was measured for more than 10 years using semiannual collections of six fine fuel components (fallen foliage, twigs, branches, large branches, logs, and all other canopy material) collected from a network of 1 m^2 litterfall traps installed at 28 plots across seven sites. Decomposition of foliage, twigs, branches, and large branches were measured using litter bags installed on five of the seven sites. Measured litterfall and decomposition rates were correlated with major environmental and vegetation variables using regression analysis. Annual foliage litterfall rates ranged from 0.057 kg.m^{-2}.$year^{-1}$ for dry *Pinus ponderosa* Dougl. ex Laws. stands to 0.144 kg.m^{-2}.$year^{-1}$ on mesic *Thuja plicata* Donn ex D. Don stands and were correlated with the vegetation characteristics of leaf area index, basal area, and tree height ($r > 0.5$), whereas decomposition rates were correlated with the environmental gradients of temperature and relative humidity ($r > 0.4$).

Keane, Robert E.; Reinhardt, Elizabeth D.; Scott, Joe; Gray, Kathy; Reardon, James. 2005. Estimating forest canopy bulk density using six indirect methods. Canadian

Journal of Forest Research. 35(3): 724-739. **Abstract**: Canopy bulk density (CBD) is an important crown characteristic needed to predict crown fire spread, yet it is difficult to measure in the field. Presented here is a comprehensive research effort to evaluate six indirect sampling techniques for estimating CBD. As reference data, detailed crown fuel biomass measurements were taken on each tree within fixed-area plots located in five important conifers types in the western United States, using destructive sampling following a series of four sampling stages to measure the vertical and horizontal distribution of canopy biomass. The six ground-based indirect measurement techniques used these instruments: LI-COR LAI-2000, AccuPAR ceptometer, CID digital plant canopy imager, hemispherical photography, spherical densiometer, and point sampling. These techniques were compared with four aggregations of crown biomass to compute CBD: foliage only, foliage and small branchwood, foliage and all branchwood (no stems), and all canopy biomass components. Most techniques had the best performance when all canopy biomass components except stems were used. Performance dropped only slightly when the foliage and small branchwood canopy biomass aggregation (best approximates fuels available for crown fires) was employed. The LAI-2000, hemispherical photography, and CID plant canopy imager performed best. Regression equations that predict CBD from gap fraction are presented for all six techniques.

Klade, Richard J. 2006. Building a research legacy -- The Intermountain Station 1911-1997. Gen. Tech. Rep. RMRS-GTR-184. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 259 p. **Abstract**: Includes highlights of the history of organizations that preceded formation of the Intermountain Forest and Range Experiment Station in 1954. Provides detailed accounts of Intermountain Station research and administrative accomplishments, some of the people who led activities, and changes in the organization from 1954 through 1997 when the Intermountain and Rocky Mountain Stations merged to become the Rocky Mountain Research Station. Many significant Station publications are indicated by title in the text, and the references list includes other publications that provide additional historic background on research programs and results.

Kollenberg, Cassandra L.; O'Hara, Kevin L. 1999. Leaf area and tree increment dynamics of even-aged and multiaged lodgepole pine stands in Montana. Canadian Journal of Forest Research. 29(6): 687-695. **Abstract**: Age structure and distribution of leaf area index (LAI) of even and multiaged lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) stands were examined on three study areas in western and central Montana. Projected leaf area was determined based on a relationship with sapwood cross-sectional area at breast height. Stand structure and LAI varied considerably between individual plots. LAI and stand stem volume increment were significantly higher in multiaged than even-aged stands with the exception of one study area, which had higher volume increment in even-aged stands. Older cohorts and higher canopy strata generally had greater LAI than younger cohorts and lower strata. Ratios of stem volume increment to leaf area were used to assess stand, cohort, and individual tree vigor or growing space efficiency (GSE). Even-aged stands had significantly higher GSEs in individual study areas and overall than multiaged stands. Cohort GSE generally

increased with increasing age of the cohort. Stand increment was weakly associated with stand LAI. Individual tree volume increment was strongly related to projected leaf area when stands were divided by age-classes or canopy strata. These results suggest separating these stands into components, such as age classes or canopy strata, and summing predicted increment for each component may provide more accurate prediction of stand increment than using whole-stand LAI.

Lisle, Thomas E.; Adams, Mary Beth; Reid, Leslie M.; Elder, Kelly. 2010. Hydrologic influences of forest vegetation in a changing world: learning from Forest Service Experimental Forests, Ranges, and Watersheds. In: Adams, Mary Beth; NcNeel, Joe; Rodriguez-Franco, Carlos, eds. Meeting current and future conservation challenges through the synthesis of long-term silviculture and range management research. Gen Tech. Rep. WO-84. Washington, DC: U.S. Department of Agriculture, Forest Service: 37-49. **Abstract**: The importance of forests in providing reliable sources of clean water cannot be underestimated. Therefore, there is a pressing need to understand how hydrologic systems function in forested ecosystems, in response to a variety of traditional and novel stressors and environments. Long-term watershed research on Experimental Forests and Ranges (EFRs) of the Forest Service has provided many examples of how vegetation management affects streamflows. New challenges and new stressors will require a deeper understanding and novel research and synthetic activities to help ensure sound forest management for a variety of end uses, included reliable supplies of clean water. In this paper, we discuss the potential role of EFRs for addressing new and challenging issues in forest hydrology.

Lutes, Duncan C. 2002. Assessment of the line transect method: an examination of the spatial patterns of down and standing dead wood. In: Laudenslayer, William F., Jr.; Shea, Patrick J.; Valentine, Bradley E.; Weatherspoon, C. Phillip; Lisle, Thomas E., tech. coords. Proceedings of the symposium on the ecology and management of dead wood in western forests; 1999 November 2-4; Reno, NV. Gen. Tech. Rep. PSW-GTR-181. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 665-675. **Abstract**: The line transect method, its underlying assumptions, and the spatial patterning of down and standing pieces of dead wood were examined at the Tenderfoot Creek Experimental Forest in central Montana. The accuracy of the line transect method was not determined due to conflicting results of t-tests and ordinary least squares regression. In most instances down pieces were randomly distributed along transect segments. Down pieces generally had a clumped distribution of their directional orientation. Standing pieces were usually found to be randomly distributed within belt transects. Consistent clumping scale of down or standing pieces was not found when studied using the paired quadrat variance method.

Marshall, Lucy; Smith, Tyler. 2008. A study of recently developed MCMC techniques for efficiently characterizing the uncertainty of hydrologic models. In: American Geophysical Union, fall meeting; 2008 December 15-19; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H51B-0794. Abstract. **Abstract**: The implementation of Bayesian methods, and specifically Markov chain Monte Carlo (MCMC) methods, are becoming much more widespread due to their usefulness in

uncertainty assessment of hydrologic models. These methods have the ability to explicitly account for non-stationarities in model errors (via the likelihood), complex parameter interdependence and uncertainty, and multiple sources of data for model conditioning. These properties hold particular importance for hydrologic models where we need to characterize complex model errors (including heteroscedasticity and correlation) and where a full assessment of the uncertainty associated with the modeled results is desirable. Traditional MCMC algorithms can be difficult to implement due to computational constraints for high-dimensional models with complex parameter spaces and expensive model functions. Failure to effectively explore the parameter space can lead to false convergence to a local optimum and a misunderstanding of the model's ability to characterize the system. While past studies have shown adaptive MCMC techniques to be more desirable than traditional MCMC approaches, few hydrologic studies have taken advantage of these new advances, given their varying difficulty in implementation. We investigated three recently developed MCMC algorithms, the Adaptive Metropolis (AM), the Delayed Rejection Adaptive Metropolis (DRAM) and the Differential Evolution Markov Chain (DE-MC). These algorithms are newly devised and intended to better handle issues common to hydrologic modeling including multi-modality of parameter spaces, complex parameter interactions, and the computational cost associated with potentially expensive hydrologic functions. We evaluated each algorithm through application to two case studies; (1) a synthetic Gaussian mixture with five parameters and two modes and (2) a nine-dimensional snowmelt-hydrologic modeling study applied to an experimental watershed. Each of the three algorithms was compared in terms of its efficiency in converging to the posterior density, its effectiveness in searching the posterior parameter space (including the sampling of the tails of the posterior parameter distributions), its computational burden, and the ease of implementation of the algorithm for hydrologic settings. While the more complicated algorithms are shown to be more effective in simulating a model's posterior distribution, they suffer from increased computational and logistical costs.

McCaughey, Ward. 2003. Research on stand management options for reducing fuels and restoring two-aged lodgepole pine communities on the Tenderfoot Creek Experimental Forest. In: Omi, Philip N.; Joyce, Linda A., tech. eds. Fire, fuel treatments, and ecological restoration: Conference proceedings; 2002 April 16-18; Fort Collins, CO. RMRS-P-29 Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 457. Abstract. **Abstract**: Fire-dependent lodgepole pine stands comprise significant acreages of mid and upper-elevation forests in the Northern Rockies, providing wood products, wildlife habitat, livestock forage, water, recreational opportunities, and expansive viewsheds. Many lodgepole pine stands are in late-successional stages and at risk to pests and catastrophic-scale fires. Tenderfoot Creek Experimental Forest is located on the Lewis and Clark National Forest in the Little Belt Mountains of Central Montana. Twenty percent of the lodgepole pine stands on the experimental forest were found to be two-aged and another 30 percent were in an indistinct mosaic of a duel-fire complex. This paper describes preliminary results of the Tenderfoot Research Project designed to evaluate two-aged harvest methods in lodgepole pine stands by integrating silviculture and prescribed fire. Research studies evaluate the effects of harvesting and prescribed fire on several resources such as

water quality and quantity, wildlife, forest fuels, and vegetation response.

McCaughey, Ward; Stewart, Cathy; Hardy, Colin. 1996. Restoring the subalpine mosaic. In: Eco-Report: Bitterroot Ecosystem Management Research Project. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 7. **Abstract**: This article highlights the restoration effort in the Tenderfoot Creek Experimental Forest. The project will evaluate the effects of alternative harvesting methods in lodgepole pine stands on water, wildlife, forest health, fuels, and vegetation.

McCaughey, Ward W. 1996. Tenderfoot Creek Experimental Forest. In: Schmidt, Wyman C.; Friede, Judy L., comps. Experimental forests, ranges, and watersheds in the Northern Rocky Mountains: a compendium of outdoor laboratories in Utah, Idaho, and Montana. Gen. Tech. Rep. INT-GTR-334. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 101-108. **Abstract**: This is a compendium of experimental forests, ranges, watersheds, and other outdoor laboratories, formally established by the Forest Service and Agricultural Research Service of the U.S. Department of Agriculture, and the universities in Utah, Idaho, and Montana. The purposes, histories, natural resource bases, data bases, past and current studies, locations, and who to contact for information are given for these areas that represent ecosystems ranging from deserts to cold subalpine forests.

McCaughey, Ward W.; Farnes, Phillip E.; Hansen, Katherine J. 1997. Historic role of fire in determining annual water yield from Tenderfoot Creek Experimental Forest, Montana, USA. In: 65th annual meeting, western snow conference: joint meeting with the 54th annual eastern snow conference and Canadian Geophysical Union.; 1997 May 4-8; Banff, AB. [Place of publication unknown]: [Publisher unknown]: 52-60. Abstract.
Abstract: Water production from mountain watersheds depends on total precipitation input, the type and distribution of precipitation, the amount intercepted in tree canopies, and losses to evaporation, transpiration and groundwater. A systematic process was developed to estimate historic average annual runoff based on fire patterns, habitat cover types and precipitation patterns on the Tenderfoot Creek Experimental Forest.
A fire history study in the Little Belt Mountains of central Montana indicates much of the experimental forest watershed burned in the 1700's and 1800's. Fire scars and existing timber stands on the 3,709 ha experimental forest show that two fires occurred in the 1700's and six in the 1800's covering more than 1,660 ha (45 percent) and 2,415 ha (65 percent), respectively. One small 32 ha stand on the experimental forest has not burned since 1580. The last major fire (206 ha) occurred in 1902 and three other small fires (covering only 19 ha) have been observed since the implementation of active fire suppression in the early 1900's. There has been no logging on this 3,709 ha forest of which 9 percent of the total area is composed of non-timbered meadows or rock outcrops.
Annual water yield was estimated for Tenderfoot Creek Experimental Forest for the past 400+ years utilizing fire history, habitat cover types, current average annual precipitation and water yield/precipitation/cover type relationships. The maximum average annual runoff was estimated at 12,480 cubic dekameters (dams3) in the late 1500's based on 30 years of average annual precipitation (1961-1991). The 1581 to 1997 average water

yield was estimated to be 11,680 dams3. The maximum water yield estimated for Tenderfoot Creek Experimental Forest, if all timber were removed, would be around 13,240 dams3. The minimum runoff if the entire forest was composed of mature lodgepole pine would be 11,230 dams3. The present yield of 11,360 dams3 is near the lowest yield of 11,250 dams3 estimated for 1873 and near the minimum possible for this experimental forest. During a wet year with all of the timber removed, runoff could be as high as 21,190, or in a dry year with most of the watershed covered with a mature forest as low as 5,620 dams3. On TCEF, fire suppression and succession appear to be creating conditions for a major fire event unless portions of the forest are removed by management actions that mimic historic vegetation patterns.

McCaughey, Ward W.; Glasgow, Lance S.; Wright, David K. 2010. Tenderfoot Creek Experimental Forest sediment collection data: 1994-2009, [Online]. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station (Producer).
Available:http://www.fs.fed.us/rm/data_archive/dataaccess/contents_expforests.shtml [2011, December 15]. **Abstract**: This data product contains daily average sediment flow data for several creeks in the Tenderfoot Creek Experimental Forest watershed from 1994 to 2009. Sediment data were collected at eight sites in the upper Tenderfoot Creek watershed. Four samplers were placed at the bottom of four sub-watersheds flowing into Tenderfoot Creek. These sub watersheds (and respective collection site names) are Spring Park (SPPA), Sun (LOSU), Stringer (LOST) and Bubbling Creek (BUBB). Two additional samplers were placed on Sun Creek above (UPSU) and below (MISU) a logging road constructed in 2000. An additional collection sampler was on the west fork of Stringer Creek (UPST). Tenderfoot Creek also contains two collection samplers (UPTE and LOTE). UPTE is located above and LOTE is below the sub watersheds SPPA, LOSU, BUBB, and LOST (see map included in this archive).
Two sub watersheds: Sun Creek and Spring Park Creek had experimental shelterwood harvests in 1999 and 2000. Portions of these units were prescribed burned between 2001 and 2003. Two adjacent subwatersheds: Bubbling Creek and Stringer Creek serve as control units for the silviculture treatments (see McCaughey et. al. 2006 in the Cross-Reference section).
Sediment collection correlates with hydrologic flow data and stream nutrient data collected at a series of hydrologic flumes on the experimental forest. See the Cross-Reference section for access to these data.

McCaughey, Ward W.; Glasgow, Lance S.; Wright, David K. 2010. Tenderfoot Creek Experimental Forest 15 minute streamflow data: 2000-2009, [Online]. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station (Producer).
Available:http://www.fs.fed.us/rm/data_archive/dataaccess/contents_expforests.shtml [2011, December 15]. **Abstract**: This data product contains 15 minute stream flow rates (cubic feet per second) for 11 flumes in the upper Tenderfoot Creek watershed from 2000 to 2009. Two sub watersheds: Sun Creek and Spring Park Creek had experimental shelterwood harvests in 1999 and 2000. Portions of these units were prescribed burned between 2001 and 2003. Two adjacent subwatersheds: Bubbling

Creek and Stringer Creek serve as controls. Additional flumes were placed on the Pack Creek and Passionate Creek subwatersheds and the upper and lower sections of Tenderfoot Creek.

McCaughey, Ward W.; Glasgow, Lance S.; Wright, David K. 2010. Tenderfoot Creek Experimental Forest water quality data: 1992-2009, [Online]. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station (Producer). Available:http://www.fs.fed.us/rm/data_archive/dataaccess/contents_expforests.shtml [2011, December 15]. **Abstract**: This data product contains water quality data analyzed from water samples taken at 11 hydrologic flumes on the Tenderfoot Creek Experimental Forests from 1992 to 2009. Water quality parameters measured include specific conductance, calcium, ammonia, phosphorus , pH , alkalinity, sulfate, sodium, potassium, chloride, suspended solids, total Kjeldahl nitrogen (TKN), nitrate plus nitrite, nitrite, magnesium, hardness, bicarbonate, and carbonate.

McCaughey, Ward W.; Martin, Steven J.; Blomquist, Dean A. 2006. Two-aged silvicultural treatments in lodgepole pine stands can be economically viable. Research Note RMRS-RN-29. Fort Collins, CO: United States Department of Agriculture, Forest Service, Rocky Mountain Research Station. 6 p. **Abstract**: Economically viable silvicultural options are critical for management activities that provide wood products, reduce forest fuels, improve forest health, and enhance wildlife habitat. The Tenderfoot Research Project was developed in the late 1990s to evaluate and quantify ecological and biological effects of two-aged silvicultural treatments including prescribed fire in lodgepole pine forests. Research treatments were designed and installed on the Tenderfoot Creek Experimental Forest to create reserve stand structures that emulate stands created by natural fires, and to evaluate hydrologic and vegetative response. Timber products extracted through this research project included sawlogs, stud logs, posts, rails, firewood, and pulpwood. There was a net profit from the sale of products removed from the 649 acres treated.

McGlynn, B. L.; Epstein, H.; Welsch, D.; Gooseff, M.; Riveros, D.; Pacific, V.; Muth, D.; Emanuel, R.; Payn, R.; Jencso, K. 2006. Tenderfoot Creek Experimental Forest, Montana: measuring and modeling carbon and water fluxes from point to watershed scales. In: American Geophysical Union, fall meeting; 2006 December 11-15; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B53A-0337. Abstract. **Abstract**: We seek to link distributed point and flux tower measurements with watershed scale modeling approaches to bridge traditional gaps in research and understanding in C generation and flux. Our research site is the US Forest Service's Tenderfoot Creek Experimental Forest (TCEF), located in the Little Belt Mountains of central MT. We have built extensive distributed infrastructure including 168 soil gas wells, 62 temperature-moisture- CO_2 flux plots, 75 groundwater wells and piezometers, 4 real-time moisture-temperature- CO_2 gradient flux plots, and 2 CO_2 and H_2O eddy-covariance flux towers. This new (2005) instrumentation is concentrated in the 550 ha Stringer Creek watershed, one of 7 sub-watersheds nested within the greater TCEF, that contains 2 SNOTEL sites and 7 stream gauges and more than 12

years of historical data. In addition we have recently acquired airborne laser swath mapping (ALSM) topography data at ~1m resolution that also contains significant information on vegetation structure and density. This level of infrastructure, existing data, and data acquisition potential is available in few, if any, locations throughout the world. We seek to use this infrastructure to understand the dynamics of carbon exchange and processing between aquatic, terrestrial, and atmospheric systems at the plot, patch, and catchment scale. Specifically, we are1) quantifying soil air CO_2 concentration and surface efflux heterogeneity across space and time, and determining associated temperature, moisture, substrate, and biological controls on CO_2 regimes. 2) We are refining and applying a distributed simulation model of catchment respiration. 3) We are determining the strength of the communication between terrestrial C reservoirs and aquatic systems by characterizing C cycling and fate during stream transport at the stream network scale, as a function of channel-atmosphere interactions, groundwater-surface water interactions (hyporheic interactions and discharge gains), and aquatic ecosystem respiration. 4) We are using eddy covariance systems to examine the controls of both vegetation type and climate on net ecosystem exchange of carbon and water. 5) Lastly, we seek to couple the recently acquired topographic data at fine spatial scales to the simulation model for extrapolating carbon and water fluxes and transformations across the entire watershed; validating with existing flux tower data and other ground measurements. We believe that this scaling approach is unprecedented in carbon cycle research, yet necessary for continued progress as we seek to understand the relationships between process dynamics and landscape level response.

Mincemoyer, Scott A.; Birdsall, Jennifer L. 2006. Vascular flora of the Tenderfoot Creek Experimental Forest, Little Belt Mountains, Montana. Madrono. 53(3): 211-222. **Abstract**: Tenderfoot Creek Experimental Forest (TCEF) is situated in the Little Belt Mountains of Montana, 120 km east of the Continental Divide. TCEF is composed of 3693 ha at elevations between 1840 and 2420 m and is dominated by lodgepole pine forest, which covers about 3366 ha, with interspersed floristically rich meadows. Our floristic inventory is based on collections and field observations made by Scott Mincemoyer during 1996-1999 and collections by Jennifer Birdsall during 2003-2005. We also include collections made by Earle Layser in 1992 and Jessica Fultz in 2002-2003. The vascular flora of TCEF consists of 312 species, representing 162 genera and 44 families. Twenty-seven exotic species occur in TCEF including *Centaurea maculosa*, *Chrysanthemum leucanthemum* [*Leucanthemum vulgare*], *Cirsium arvense*, and *Tanacetum vulgare* which are listed as noxious weeds in Montana. *Phlox kelseyi* var. *missoulensis* is found in the experimental forest and is listed as sensitive by the USDA Forest Service Northern Region.

Moore, Chadwick A.; McCaughey, Ward W. 1997. Snow accumulation under various forest stand densities at Tenderfoot Creek Experimental Forest, Montana, USA. In: 65th annual meeting, western snow conference: joint meeting with the 54th annual eastern snow conference and Canadian Geophysical Union.; 1997 May 4-8; Banff, Alberta, Canada. [Place of publication unknown]: [Publisher unknown]: 42-51. Abstract. **Abstract**: Snow accumulation in forested watersheds is controlled by climate, elevation,

topographic factors and vegetation structure. Conifers affect snow accumulation principally by intercepting snow with the canopy which may later be sublimated. Various tree, stand, species and canopy densities of a subalpine fir habitat (ALBA/VASC) in central Montana were studied to determine if there was a response of snow accumulation to vegetation. Tree canopy cover, basal area, age since stand initiation, and species composition were measured at several sites with minimal topographic differences. Peak snow water equivalent was measured at 270 sample points within 8 stands divided between 3 study areas and at three corresponding open meadows. The study took place during the winter of 1995-1996 on the Tenderfoot Creek Experimental Forest in the Little Belt Mountains near Great Falls, Montana. It is administered by the USDA Rocky Mountain Research Station.
Variation in peak accumulation (SWE) on the forest floor was impacted the greatest by the percent of canopy cover measured by the 30^{o} view angle of a photocanopyometer. Half of the variation in snow accumulation can be attributed to variation in canopy cover. A 6.4 percent decrease in peak snow water equivalent was observed per 10 percent increase in canopy density. Snow samples under subalpine fir and Engelmann spruce canopies showed a closer correlation between canopy and peak snow water equivalent than did lodgepole pine canopies. Basal area was found to be a poor predictor of snow accumulation.

Mulica, Stephanie K.; Potts, Donald F.; Pfister, Robert D. 2002. Instream flow and water regime of selected riparian habitats in west-central Montana. Final contract report for: Riparian vegetation flow requirements in the Tenderfoot Watershed, west-central Montana. Challenge cost share agreement #RMRS-99198-CCS. Missoula, MT: University of Montana, School of Forestry, Montana Forest and Conservation Experiment Station. 59 p. (+appendices). **Abstract**: The purpose of this study was to help define the characteristics of the riparian water regime with both quantitative in-stream flow and groundwater information. The objectives were to: 1) determine the interaction of in-stream flow in reference reaches with groundwater in surrounding riparian areas; 2) gain an understanding of flow and inundation duration on reference reaches and how they influence riparian vegetation distribution in surrounding riparian areas; and 3) define the dynamics of water table change in riparian habitats examined in this study. Results suggested that, groundwater had less of a connection with surface water as one increased through the elevation zones. The gradient of the elevation of surface water and the water table became more pronounced in moderate and high elevation transect sites. Further investigation of the relationship between elevation and habitats that experienced inundated conditions revealed moderate evidence that elevation played a large part in where inundated conditions; and thus plants tolerant of those conditions; would occur.

Muth, D. J.; Epstein, H.; Emanuel, R.; McGlynn, B.; Welsch, D. 2007. Net ecosystem exchange in a forested montane watershed: trends and trials in complex terrain. In: American Geophysical Union, fall meeting; 2007 December 10-14; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B21D-06. Abstract. **Abstract**: Recent years have seen increased study of the land-atmosphere exchange of mass and energy as measured by the eddy covariance technique. Because these

results have yielded significant promise, offering the opportunity to integrate small-scale heterogeneities at the ecosystem level, an increasing number of researchers have begun employing the method in montane areas typical of the Rocky Mountains. Problematically, these areas can exhibit complex terrain and tall canopies, introducing the need for a more complete treatment of the mass balance equation to account for advective flows and storage terms brought on by atmospheric stability. Promisingly, a variety of data filtering, modeling, and measurement techniques have shown potential in alleviating some these concerns. Because high altitude forests have shown considerable carbon sequestration potential and may be particularly susceptible to climate change scenarios affecting temperature, moisture, and snowpack accumulation, it is important that eddy covariance measurements continue in these non-ideal settings so that methodologies can be refined, and ecosystem-level mass and energy cycling dynamics can be evaluated. To this end, a 40-meter tower outfitted to FLUXNET specifications was erected over a lodgepole pine-dominated system in the Tenderfoot Creek Experimental Forest, Montana. Initial results indicate that on particularly stable nights ($u\times<0.1$), subcanopy concentrations of CO_2 became elevated to ~100ppm above levels measured on sufficiently turbulent nights ($u\times>0.4$). Resultant turbulent flux, as shown by the unfiltered eddy covariance system, exhibit nocturnal carbon emissions that are much larger in times of high turbulence, and much smaller in times of low turbulence. The difference can be an order of magnitude. Presumably, this is due to understory-atmosphere decoupling in times of stability. In order to account for underestimation of nocturnal ecosystem respiration, data were conservatively filtered, excluding measurements under a friction velocity ($u\times$) of 0.4 m/s. Resultant data gaps were filled with nocturnal respiration measurements obtained from soil and leaf chambers, and compared to nighttime eddy flux measurements obtained in sufficiently turbulent conditions. The results show that this forest is a substantial carbon sink at a rate of 350 g C/m^2/yr, and indicate the promise of continuing these studies in complex terrain.

Muth, D. J.; Epstein, H.; McGlynn, B.; Welsch, D. 2006. Estimating net ecosystem exchange in complex terrain: a case study from a subalpine, montane forest system. In: American Geophysical Union, fall meeting; 2006 December 11-15; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B52B-05. Abstract.
Abstract: Through ecosystem measurement networks such as Ameriflux and FLUXNET, carbon cycling studies are becoming increasingly linked. However, important gaps in this carbon flux data set occur in the vast montane forests typical of the Rocky Mountains and similar areas throughout the world. Problematically, these areas can exhibit complex terrain and tall canopies, which often invalidate assumptions of turbulent transport theory used in eddy covariance techniques. This is particularly true when the atmosphere is stably stratified, which is often the case at night. Though direct investigations into the resulting advection phenomena are underway, they are costly, involving the erection of multiple towers to obtain a three-dimensional control volume capable of including horizontal fluxes in the mass balance equation. It is therefore of great interest to investigate methods of data treatment that can effectively circumvent problematic conditions, while providing reliable results. A 40-meter tower outfitted to FLUXNET specifications was erected over a lodgepole pine-dominated system in the

Tenderfoot Creek Experimental Forest, Montana. In order to account for surmised underestimation of nocturnal ecosystem respiration, data were conservatively filtered, excluding measurements under a friction velocity (u*) of 0.4 m/s. Resultant data gaps were filled with nocturnal respiration measurements obtained from soil and leaf chambers, and compared to nighttime eddy flux measurements obtained in sufficiently turbulent conditions. Initial results indicate that on particularly stable nights (u* <0.1), subcanopy concentrations of CO_2 became elevated to ~100ppm above levels measured on sufficiently turbulent nights (u*>0.4). Resultant turbulent flux, as shown by the unfiltered eddy covariance system, exhibit nocturnal carbon emissions that are much larger in times of high turbulence, and much smaller in times of low turbulence. The difference can be an order of magnitude. Presumably, this is due to understory-atmosphere decoupling in times of stability. Since, this storage term is not recovered in the morning hours, we assume that an unmeasured advection component is at work. Encouragingly, estimates of net ecosystem exchange derived from chamber measurements compare very favorably with eddy covariance measurements from turbulent conditions indicating the potential for reliable gap-filing for a single tower system on complex terrain.

O'Neill, Kevin M.; Fultz, Jessica E.; Ivie, Michael A. 2008. Distribution of adult Cerambycidae and Buprestidae (Coleoptera) in a subalpine forest under shelterwood management. Coleopterists Bulletin. 62(1): 27-36. **Abstract**: We examined the distribution of adult Buprestidae and Cerambycidae in the Tenderfoot Creek Experimental Forest in the Little Belt Mountains of central Montana, U.S.A., using pan traps and sweep samples on different species of flowering plants. Using several methods during multi-year (2001-2004), summer-long surveys, we documented the presence of adults of three species of Buprestidae and ten Cerambycidae. Pan traps were placed along transects within meadows, unlogged lodgepole pine forests, and in differentially-logged plots initially logged in 1999-2000 and managed by the U.S. Forest Service. Results from pan trap samples support the conclusion that, compared to unlogged plots and meadows, adult buprestids and cerambycids were more abundant in the shelterwood areas after 2001, perhaps because of the greater abundance of decaying wood in the logged areas. Cerambycids, particularly Cosmosalia chrysocoma (Kirby) and Gnathacmaeops pratensis (Laicharting), were also commonly collected on flowers, and were most likely to be found on those with white blossoms and readily accessible nectar and pollen.

Pacific, Vincent Jerald. 2007. Variability in soil CO2 production and surface CO2 efflux across riparian-hillslope transitions. Bozeman, MT: Montana State University. 103 p. Thesis. **Abstract**: The spatial and temporal controls on soil CO_2 production and surface CO_2 efflux have been identified as an outstanding gap in our understanding of carbon cycling. I investigated both the spatial and temporal variability of soil CO_2 concentrations and surface CO_2 efflux across eight topographically distinct riparian-hillslope transitions in the ~300 ha subalpine upper-Stringer Creek Watershed in the Little Belt Mountains, Montana. Riparian-hillslope transitions provide ideal locations for investigating the spatial and temporal controls on soil CO_2 concentrations and surface CO_2 efflux due to strong gradients in respiration driving factors, including

soil water content, soil temperature, and soil organic matter. I collected high frequency measurements of soil temperature, soil water content, soil air CO_2 concentrations (20 cm and 50 cm), surface CO_2 efflux, and soil C and N concentrations (once) at 32 locations along four transects. Soil CO_2 concentrations were more variable in riparian landscape positions, as compared to hillslope positions, as well as along transects with greater upslope accumulated area. This can be attributed to a greater range of soil water content and higher soil organic matter availability. Soil gas diffusion also differed between riparian and hillslope positions. Soil gas transport limited surface CO_2 efflux in riparian landscape positions due to high soil water content (despite strong concentration gradients), while efflux was gradient (production) limited in hillslope positions. This led to spring-fall reversal of maximum riparian and hillslope soil CO_2 concentrations, with highest hillslope concentrations near peak snowmelt and highest riparian concentrations during the late summer and early fall. Soil temperature was a dominant control on the overall temporal variability of soil CO_2. However, soil water content controlled differences in the timing of soil CO_2 concentration peaks within and between riparian and hillslope positions, as exemplified by those locations closest to Stringer Creek (wetter landscape positions) peaking up to three months later than those riparian locations near the riparian-hillslope transition. This work suggests that one control on the spatial and temporal variability of watershed soil CO_2 concentrations and surface CO_2 efflux is a soil water content mediated tradeoff between CO_2 production and transport.

Pacific, Vincent Jerald. 2009. Hydrology and landscape structure control subalpine catchment carbon export. Bozeman, MT: Montana State University. 149 p. Dissertation.
Abstract: Carbon export from high elevation ecosystems is a critical component of the global carbon cycle. Ecosystems in northern latitudes have become the focus of much research due to their potential as large sinks of carbon in the atmosphere. However, there exists limited understanding of the controls of carbon export from complex mountain catchments due to strong spatial and temporal hydrologic variability, and large heterogeneity in landscape structure. The research presented in this dissertation investigates the control of hydrology and landscape structure and position on two major avenues of carbon loss from mountain watersheds: soil respiration and stream dissolved organic carbon (DOC) export. Measurements of soil respiration and its biophysical controls (soil water content, soil temperature, vegetation, soil organic matter, and soil physical properties) and stream and groundwater DOC dynamics are presented across three years and multiple riparian-hillslope transitions within a complex subalpine catchment in the northern Rocky Mountains, Montana. Variability in soil respiration was related to hydrologic dynamics through space and time and was strongly influenced by topography and landscape structure. Cumulative soil CO_2 efflux was significantly higher from wet riparian landscape positions compared to drier hillslope locations. Changes in hydrologic regimes (e.g. snowmelt and precipitation timing and magnitude) also impacted soil respiration. From a wet to a dry growing season, there were contrasting and disproportionate changes in cumulative growing season surface CO_2 efflux at wet and dry landscape positions. Stream DOC export was also influenced by landscape structure and hydrologic variability. The mobilization and delivery mechanisms of DOC from the soil to the stream were dependent upon the size

of DOC source areas and the degree of hydrologic connectivity between the stream and the riparian and hillslope zones, which varied strongly across the landscape. This dissertation provides fundamental insight into the controls of hydrology and landscape structure on carbon export from complex mountain watersheds. The results of this research have large implications for the carbon source/sink status of high elevation mountain ecosystems, the influence of changing hydrologic regimes on soil respiration, and the use of landscape analysis to determine the locations of large source areas for carbon export.

Pacific, Vincent J.; Jencso, Kelsey G.; McGlynn, Brian L. 2010. Variable flushing mechanisms and landscape structure control stream DOC export during snowmelt in a set of nested catchments. Biogeochemistry. 99(1-3): 193-211. **Abstract**: Stream DOC dynamics during snowmelt have been the focus of much research, and numerous DOC mobilization and delivery mechanisms from riparian and upland areas have been proposed. However, landscape structure controls on DOC export from riparian and upland landscape elements remains poorly understood. We investigated stream and groundwater DOC dynamics across three transects and seven adjacent but diverse catchments with a range of landscape characteristics during snowmelt (April 15–July 15) in the northern Rocky Mountains, Montana. We observed a range of DOC export dynamics across riparian and upland landscape settings and varying degrees of hydrologic connectivity between the stream, riparian, and upland zones. DOC export from riparian zones required a hydrologic connection across the riparian–stream interface, and occurred at landscape positions with a wide range of upslope accumulated area (UAA) and wetness status. In contrast, mobilization of DOC from the uplands appeared restricted to areas with a hydrologic connection across the entire upland–riparian–stream continuum, which generally occurred only at areas with high UAA, and/or at times of high wetness. Further, the relative extent of DOC-rich riparian and wetland zones strongly influenced catchment DOC export. Cumulative stream DOC export was highest from catchments with a large proportion of riparian to upland area, and ranged from 6.3 to 12.4 kg ha^{-1} across the study period. This research suggests that the spatial/temporal intersection of hydrologic connectivity and DOC source areas drives stream DOC export.

Pacific, Vincent J.; McGlynn, Brian L.; Riveros-Iregui, Diego A.; Epstein, Howard E.; Welsch, Daniel L. 2009. Differential soil respiration responses to changing hydrologic regimes. Water Resources Research. 45: 1-6. **Abstract**: Soil respiration is tightly coupled to the hydrologic cycle (i.e., snowmelt and precipitation timing and magnitude). We examined riparian and hillslope soil respiration across a wet (2005) and a dry (2006) growing season in a subalpine catchment. When comparing the riparian zones, cumulative CO_2 efflux was 33% higher, and peak efflux occurred 17 days earlier during the dry growing season. In contrast, cumulative efflux in the hillslopes was 8% lower, and peak efflux occurred 10 days earlier during the drier growing season. Our results demonstrate that soil respiration was more sensitive to drier growing season conditions in wet (riparian) landscape positions.

Pacific, Vincent J.; McGlynn, Brian L.; Riveros-Iregui, Diego A.; Welsch, Daniel L.;

Epstein, Howard E. 2011. Landscape structure, groundwater dynamics, and soil water content influence soil respiration across riparian-hillslope transitions in the Tenderfoot Creek Experimental Forest, Montana. Hydrological Processes. 25(5): 811-827.
Abstract: Variability in soil respiration at various spatial and temporal scales has been the focus of much research over the last decade aimed to improve our understanding and parameterization of physical and environmental controls on this flux. However, few studies have assessed the control of landscape position and groundwater table dynamics on the spatiotemporal variability of soil respiration. We investigated growing season soil respiration in a similar to 393 ha subalpine watershed in Montana across eight riparian-hillslope transitions that differed in slope, upslope accumulated area (UAA), aspect, and groundwater table dynamics. We collected daily-to-weekly measurements of soil water content (SWC), soil temperature, soil CO_2 concentrations, surface CO_2 efflux, and groundwater table depth, as well as soil C and N concentrations at 32 locations from June to August 2005. Instantaneous soil surface CO_2 efflux was not significantly different within or among riparian and hillslope zones at monthly timescales. However, cumulative integration of CO_2 efflux during the 83-day growing season showed that efflux in the wetter riparian zones was similar to 25% greater than in the adjacent drier hillslopes. Furthermore, greater cumulative growing season efflux occurred in areas with high UAA and gentle slopes, where groundwater tables were higher and more persistent. Our findings reveal the influence of landscape position and groundwater table dynamics on riparian versus hillslope soil CO_2 efflux and the importance of time integration for assessment of soil CO_2 dynamics, which is critical for landscape-scale simulation and modelling of soil CO_2 efflux in complex landscapes.

Pacific, V. J.; Riveros, D. A.; McGlynn, B. L.; Welsch, D.; Epstein, H. 2005. CO2 production and efflux across riparian/hillslope transitions in the Tenderfoot Creek Experimental Forest, Montana. In: American Geophysical Union, fall meeting; 2005 December 5-9; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B43A-0255. Abstract.
Abstract: The spatial and temporal controls on soil CO_2 production and efflux have been identified as an outstanding gap in our understanding of carbon cycling. We investigated the primary driving factors and their variability over space and time of soil CO_2 concentration and efflux across environmental gradients in the 550 ha Stringer Creek watershed, Little Belt Mountains, Montana. We collected measurements of soil temperature, soil moisture, C:N ratios, CO_2 efflux, and soil air CO_2 concentrations at two depths (20 cm and 50 cm) at 32 locations across riparian/hillslope transitions in a high elevation mountain watershed in the northern Rocky Mountains. We found that aspect exerted a large control on soil CO_2 concentration and efflux as western aspects had larger CO_2 concentrations and efflux than eastern aspects. We also found that riparian landscape positions showed greater variability in soil CO_2 concentrations and efflux than hillslope landscape positions. In addition, we installed and collected hourly data from groundwater monitoring wells at over half of the sampling locations in order to determine the effect of groundwater fluctuations on soil CO_2 concentration and efflux. We found a large increase in soil CO_2 concentration and efflux as riparian landscape positions changed from saturated to unsaturated conditions. We also examined the diurnal variation in soil CO_2 concentrations and efflux and found that both CO_2 concentrations and efflux reached

their maximum during the late afternoon. We conclude that environmental gradients related to catchment topography in soil moisture and soil temperature led to CO_2 concentration and efflux heterogeneity through space and time. We suggest that controlling variables such as riparian versus hillslope landscape position, aspect, differences in C:N ratios, and groundwater fluctuations are the primary controls on heterogeneity in CO_2 concentration and efflux across riparian/hillslope transitions.

Parks, Noreen. 2009. Exploring connections between landscapes and streams. PNW Science Findings 119. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 5 p. **Abstract**: New technology has given scientists the means to probe the hidden world of belowground hydrology. Steve Wondzell with the Pacific Northwest Research Station and his colleagues conducted several experiments in Montana's Tenderfoot Creek Experimental Forest and Oregon's H.J. Andrews Experimental Forest to determine which factors control the timing and location of water inputs from hillslopes to streams, the movement of water down the stream channel, and the consequences of these processes on watershed outputs. They found that the configuration of uplands draining into a watershed strongly affects the quantities of water delivered to a stream. In general, water from upper hillslopes reached the stream only during abundant precipitation and snow melting, except in places where the landscape was deeply incised and consistently hydrologically linked to the channel. These patterns of connectivity explain the seasonal patterns of runoff observed in individual watersheds.

Patil, S.; Covino, T. P.; Drummond, J. D.; Packman, A. I.; Schumer, R.; Payn, R. A.; McGlynn, B. L. 2010. Intra-stream variability in tracer breakthrough curves: geomorphic controls on tailing behaviors. In: American Geophysical Union, fall meeting; 2010 December 13-17; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H51E-0947. Abstract. **Abstract**: Tracer breakthrough curve (BTC) tails reflect the retention of solute mass within stream reaches. However, controls on the spatial variability of mass retention across stream networks are not fully understood. As part of a synthesis of tracer injection studies in many different streams, we analyzed the tailing behavior of salt injection BTCs measured at different locations along Stringer Creek, located in a 5.5 sq. km watershed of the Tenderfoot Creek Experimental Forest, Montana. Payn et al. (2009) obtained BTC measurements at 27 equally spaced locations along a 2600 m length of the stream. BTCs in upstream reaches (first 1400 m) had heavy power-law receding tails, whereas the BTCs in downstream reaches (1400 to 2600 m) were much more symmetric and had sharply tempered tails. Mass recovery was more variable at the upstream reaches than at the downstream reaches. Changes in solute injection behavior coincided with a pronounced change in stream geology and morphology. The underlying bedrock changes from sandstone in the upstream reaches to granite-gneiss in the downstream reaches. Channel slopes vary from 5 - 6% in the upper reaches to approximately 9% in the downstream reaches, and the channel sinuosity varies from 1.3 in the uppermost reach to 1.05 near the catchment outlet. These changes in channel morphology result in a gradually increasing streamflow velocity in the downstream direction. We hypothesize that the tempering of recession tails in downstream reaches occurs due to physical constraints on the extent of the

hyporheic zone underneath the channel. Channel geomorphology can control not only the stream flow conditions, but also the extent of hyporheic exchange and the tailing of in-stream solute BTCs.

Payn, R. A.; Gooseff, M. N.; Jencso, K.; McGlynn, B. L. 2008. Variability in stream flow and specific discharge along three headwater streams in central Montana, USA. In: American Geophysical Union, fall meeting; 2007 December 15-19; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H11B-0755. Abstract. **Abstract**: Specific discharge is commonly used to quantify the runoff at a watershed outlet with respect to the watershed area. However, little is known about how specific discharge is distributed along stream valleys within watersheds. Analyses of stream flow and specific discharge distributions may provide insight into the interactions of runoff generating processes and stream-subsurface exchange. We compare longitudinal distributions of stream channel flow and specific discharge in 3 mountain headwater streams of the Tenderfoot Creek Experimental Forest in central Montana, comprising 2.6-, 1.4-, and 2.3-km valley lengths with 5.5, 4.0, and 4.5 km^2 of total contributing area, respectively. We performed an instantaneous tracer release every 100 m along each valley, and used dilution gauging to estimate stream channel flow from each release. Multiple series of tracer tests were performed during the summer baseflow recession following snowmelt. We used topographic analysis of digital elevation models to quantify sub-basin contributing areas to each location where flow was measured. We then calculated specific discharges by normalizing each estimate of stream channel flow by its corresponding sub-basin contributing area. The study streams demonstrated substantial variability in specific discharge in both space and time. For example, a 1300-m upstream segment showed consistently lower specific discharges than an 800-m downstream segment in the same stream, where the ratio of specific discharges in the upstream segment to specific discharges in the downstream segment generally ranged from 0.7 at higher baseflows to 0.3 at lower baseflows. The differences in specific discharges over the segments were likely driven by both the variability in source water input from contributing areas and the variability in the importance of segment-scale stream-subsurface exchange relative to stream channel flow. We compare the stream flow and specific discharge distributions across space and time in the context of multi-scaled structural characteristics of the stream valleys. These comparisons reveal the influence of interactive, hierarchical controls on the distribution of stream channel flow characteristics, which are important to applying watershed-scale hydrologic principles to stream system understanding across networks.

Payn, R. A.; Gooseff, M. N.; McGlynn, B. L.; Bencala, K. E.; Wondzell, S. M. 2006. Tracer observations of spatial and temporal variations in water exchange across the stream-catchment interface. In: American Geophysical Union, fall meeting; 2006 December 11-15; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B22C-06. Abstract. **Abstract**: The location of runoff source areas and distribution of stream-reach travel times along a stream network influence solute dynamics observed at the watershed outlet. We examined the spatial distribution of streamflow source areas and the temporal and spatial pattern of stream reach travel time distributions in a headwater stream at the US Forest Service's Tenderfoot Creek

Experimental Forest in central Montana, USA. We used conservative tracer additions to examine stream reach water balances in 28 100-m and 14 200-m reaches along a 2.8-km valley length draining a ~550 ha catchment. Mass recovery analyses of long-term Rhodamine WT constant-rate addition and short-term chloride addition experiments demonstrated simultaneous hydrologic gains and losses over individual reaches on multiple time scales. In early August 2005, discharge increased from 0.8 to 27 L sec-1 from the head to the base of the 2.8-km stream segment. The 100-m reach with the largest net gain (6 L sec-1) also reflected one of the largest losses of chloride slug tracer mass (25%), corresponding to a gross hydrologic loss of at least 1.5 L sec-1. We interpret these concurrent gains and losses to indicate connection with long-term catchment flow paths not measurable through interpretation of recovered tracer alone. We are currently analyzing repeated tracer experiments throughout the summer to examine changes in streamflow source areas and stream travel time distributions throughout snowmelt discharge recession.

Payn, R. A.; Gooseff, M. N.; McGlynn, B. L.; Bencala, K. E.; Wondzell, S. M. 2009. Channel water balance and exchange with subsurface flow along a mountain headwater stream in Montana, United States. Water Resources Research. 45: 1-14. **Abstract**: Channel water balances of contiguous reaches along streams represent a poorly understood scale of stream-subsurface interaction. We measured reach water balances along a headwater stream in Montana, United States, during summer base flow recessions. Reach water balances were estimated from series of tracer tests in 13 consecutive reaches delineated evenly along a 2.6 km valley segment. For each reach, we estimated net change in discharge, gross hydrologic loss, and gross hydrologic gain from tracer dilution and mass recovery. Four series of tracer tests were performed during relatively high, intermediate, and low base flow conditions. The relative distribution of channel water along the stream was strongly related to a transition in valley structure, with a general increase in gross losses through the recession. During tracer tests at intermediate and low flows, there were frequent substantial losses of tracer mass (>10%) that could not be explained by net loss in flow over the reach, indicating that many of the study reaches were concurrently losing and gaining water. For example, one reach with little net change in discharge exchanged nearly 20% of upstream flow with gains and losses along the reach. These substantial bidirectional exchanges suggest that some channel interactions with subsurface flow paths were not measurable by net change in flow or transient storage of recovered tracer. Understanding bidirectional channel water balances in stream reaches along valleys is critical to an accurate assessment of stream solute fate and transport and to a full assessment of exchanges between the stream channel and surrounding subsurface.

Payn, R. A.; Gooseff, M. N.; McGlynn, B. L.; Bencala, K. E.; Wondzell, S. M.; Jencso, K. 2005. Water balance and residence time in stream functional units of differing scales. In: American Geophysical Union, fall meeting; 2005 December 5-9; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H43C-0508. Abstract. **Abstract**: We are beginning investigations of relationships between stream-groundwater interactions and valley structure. Ultimately, these analyses will generate a conceptual foundation for scaling hydraulics of a stream functional unit to

hydrodynamics of a watershed stream network. Our preliminary goal is to establish methods that quantify spatially explicit water balances and solute transport characteristics from stream reach to network scales. During summer of 2005, we employed simultaneous conservative tracer injections of Rhodamine WT at a constant rate and distributed chloride slugs. Breakthrough curves from these injections were used to characterize solute transport at spatial scales ranging from minimal mixing reaches (ca. 5-20 m) to the entire length of 2 headwater tributaries (ca. 3 km) in the Tenderfoot Creek Experimental Forest (USFS), Little Belt Mountains, Montana. In one tributary, results from multiple slug injections include net discharge changes ranging from -19% to +68% and tracer mass losses ranging from 2% to 40% over 28 adjacent 100-m reaches. In another tributary, chloride slug injections performed during plateau of a Rhodamine WT constant rate injection also suggest distributed variability in discharge change and tracer loss. Water balance variability at small scales within simultaneously measured large scale response allows us to explore how small scale hydrologic function operates within and contributes to the large scale context. In the future, terrain analysis of LIDAR and topographic survey data will be used to evaluate the dependence of hydrologic function on morphologic structure from channel to valley scales.

Payn, R. A.; Gooseff, M. N.; McGlynn, B. L.; Bencala, K. E.; Wondzell, S. M.; Jencso, K. 2007. Relationships between stream - ground water exchange and topography of the channel, valley, and watershed. In: American Geophysical Union, fall meeting; 2007 December 10-14; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H53B-1232. **Abstract**: Stream flow gains and losses represent exchange with groundwater and are commonly associated with the topography of the stream channel and contributing area. The magnitude of stream gain, i.e. runoff generation, is thought to be related to the extent and geometry of the contributing surface area. At smaller scales, the magnitude of both stream gain and loss may be related to heterogeneity in the gradient of the stream channel or valley. To validate relationships such as these between streams and their topography, we compare measurements of stream reach gains and losses to the terrain analyses of corresponding channels, valleys, and contributing areas. Comparisons are made for 26, 100-m reaches that constitute a 2.6-km long headwater stream in the Tenderfoot Creek Experimental Forest (USFS), Montana. The stream drains a 5.5 km^2 catchment with a riparian area of 0.073 km2, delineated by contributing area with elevation within 2 m of the stream channel. The study stream flows over 3 geological units with valley slopes around 6.7, 5.7, and 9.0%, from upstream to downstream. For each 100-m reach, upstream and downstream discharges were measured using conservative tracer (chloride) experiments and dilution gauging techniques. In addition, the upstream release was measured at the downstream end of each reach to determine tracer mass loss and to estimate gross hydrologic loss over the reach. To close the mass balance, gross gain was calculated from the net change in discharge and gross loss. The spatial distributions of gross gains and losses were determined at multiple times during the declining summer baseflows of the snowmelt driven hydrograph. At lower baseflow conditions, several net neutral or gaining reaches also showed a 5-15% tracer mass loss, indicating that gross gain and loss operate concurrently in these reaches. We use these water balance fluxes to indicate one scale of stream - ground water exchange,

and we compare patterns in exchange with the surrounding topography. Elevation data for the stream and watershed were collected using traditional survey techniques and aerial laser swath mapping (ALSM, 1-m resolution). Topographic metrics, such as channel sinuosity, valley slope, riparian area, and lateral contributing area, are calculated through terrain analyses of elevation data. Comparing topography with stream water balance is a spatially explicit approach to linking watershed structure with stream - ground water interaction, which is important to understanding solute fate and transport among the stream and adjacent ecosystems.

Pfister, Robert; Fiedler, Carl; Sweet, Michael. 1999. Landscape assessment of Bair lands in Tenderfoot Creek -- Executive Summary. [Missoula, MT]: [University of Montana, School of Forestry, Montana Forest and Conservation Experiment Station]. 46 p. **Abstract**: The Bair Ranch Foundation owns and manages 8,220 acres of forest and associated rangeland in the Tenderfoot Creek Watershed, 35 miles northwest of White Sulphur Springs, Montana. A total of 5,459 acres are commercial forest land. The remaining 2,761 acres are grasslands, meadows, shrublands, and steep talus slopes with scattered trees. These lands occur in a checkerboard pattern within the Lewis and Clark National Forest. The Bair Ranch Foundation was established in 1997 as a non-profit organization dedicated to conservation education and research. Formerly, the Bair Company operated as a charitable trust managed by the First Trust Company of Montana.
A Memorandum of Understanding was established among the Bair Company, the Lewis and Clark National Forest, and the School of Forestry, University of Montana in 1996. The purpose was to encourage and facilitate collaborative management of the mixed ownership within the Tenderfoot Creek drainage. A Memorandum of Understanding was established between the Bair Ranch Foundation and the School of Forestry in 1998 to develop a collaborative conservation education and research program.
Landscape assessment is a process formally established during the 1990's as a precursor to making decisions embodied in a land management plan. The purpose of the landscape assessment is to provide a shared vision of: 1) natural resource status (existing conditions), 2) risk assessment, 3) design of alternative future condition scenarios, and 4) evaluation of alternatives relative to goals and objectives. This involves gathering and evaluating inventory information, documenting goals, objectives, issues, and concerns, displaying summaries of pertinent information, creating alternatives and futuristic views of the landscape, and comparing alternatives to help guide proposed actions.
This report includes highlights from an initial 1997 landscape assessment report and results of additional analyses. Most of the analysis has focused on Bair lands south of the main stem of Tenderfoot Creek because plans are in progress for a major land exchange with the Forest Service. Concepts and technologies for conducting landscape assessments are currently emerging, so our experience on this portion of the ownership could be efficiently expanded to include lands acquired in an exchange.

Reinhardt, Elizabeth; Scott, Joe; Gray, Kathy; Keane, Robert. 2006. Estimating canopy fuel characteristics in five conifer stands in the western United States using tree and stand measurements. Canadian Journal of Forest Research. 36(11): 2803-2814.

Abstract: Assessment of crown fire potential requires quantification of canopy fuels. In this study, canopy fuels were measured destructively on plots in five Interior West conifer stands. Observed canopy bulk density, canopy fuel load, and vertical profiles of canopy fuels are compared with those estimated front stand data using several computational techniques. An allometric approach to estimating these canopy fuel characteristics was useful, but, for accuracy, estimates of vertical biomass distribution and site-adjustment factors were required. Available crown fuel was estimated separately for each tree according to species, diameter, and crown class. The vertical distribution of this fuel was then modeled within each tree crown on the basis of tree height and crown base height. Summing across trees within the stand at every height yielded an estimated vertical profile of canopy fuel that approximated the observed distribution.

Reynolds, Mitchell W.; Miggins, Daniel P.; Snee, Lawrence W. 2002. Age and tectonics of middle Tertiary basaltic volcanism and effects on the landscape of west-central Montana. In: Geological Society of America, Denver annual meeting; 2002 October 27-30; Denver, CO. Geological Society of America abstracts with programs [34(6)] Geological Society of America: 181-12. Abstract. **Abstract**: The distribution and age of basalt flows in west-central Montana, from Helena east for 125 km, define a distinct episode of eruptive igneous activity, mark the redirection of drainages of major rivers, and serve as datums by which to estimate amounts of vertical uplift of mountain blocks relative to adjacent valleys during late Tertiary and Quaternary time. New Ar40/Ar39 dates define a short time interval from 32.8 to 30.4 million years before present, during which basaltic magma erupted at the east end of Lewis and Clark tectonic zone and along recurrently active, generally west-trending faults in the Little Belt Mountains. The latter faults intersect a major fault zone beneath the northern part of the Big Belt Mountains where basalt flows are widespread. The flows are concentrated along the south side of the tectonic zone that has served as a transform fault during crustal extension. Accumulations of flows range from a few meters to 175 m thick and rest on gently undulating ancestral surfaces or broad stream valleys eroded across Middle Proterozoic and Phanerozoic strata and Mesozoic and early Tertiary intrusive igneous rocks. Distribution of the flows suggests local vertical displacement between the mountain ranges and adjacent valleys since late Oligocene time of as much as 680 m. At the north end of the Smith River Valley, ejecta from the eruptions are locally tilted 26 degrees south, and the ancestral valley, filled with remnants of basalt flows, is tilted south. Flows forced the courses of the Smith and Musselshell Rivers to migrate west and south, respectively, ultimately to incise adjacent older, harder rocks. Similarly, west-flowing Sheep Creek in the Little Belt Mountains was directed south in part by the volcanic eruptions, in part by tilting, to incise across resistant Early Proterozoic granite gneiss. West-flowing Tenderfoot Creek is incised along much of its length into the gneisses, Eocene intrusive rocks, and resistant Phanerozoic rocks directly along a fault zone that displays recurrent vertical and lateral movement. Thus, the central Montana landscape is defined in part by mid-Tertiary volcanism and younger structural activity manifested along long-lived structures.

Riveros, D. A.; Pacific, V. J.; McGlynn, B. L.; Welsch, D.; Epstein, H. 2005. On the

heterogeneity of CO2 production and efflux at the watershed scale, Tenderfoot Creek Experimental Forest, Montana. In: American Geophysical Union, fall meeting; 2005 December 5-9; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B43A-0254. Abstract. **Abstract**: The uncertainties embedded in current estimates of net ecosystem CO_2 exchange (NEE) are well acknowledged. More than two-thirds of total terrestrial C is stored below ground and exchanged to the atmosphere through plant and microbial activity, but the mechanisms of such exchange are not well understood. We investigated the variability of the environmental factors that control CO_2 production to understand the heterogeneity of soil CO_2 concentration and efflux at the watershed scale. We present measurements of CO_2 concentrations and flux over one year in mountainous, complex terrain of the 550-ha Stringer Creek watershed located in the Little Belt Mountains of Central Montana. Our results showed that the interaction of soil moisture and soil temperature plays a major role in controlling CO_2 production and efflux across topographic positions. High temporal resolution measurements showed two main trends in the variability of soil CO_2: short-term (daily) variability controlled mainly by soil temperature, and long-term variability controlled by soil moisture. Long-term soil CO_2 concentration showed similar trends at other sites across the watershed. At upland sites, soil CO_2 concentrations reached their maximum after snowmelt and decreased thereafter. At lowland sites, soil CO_2 concentrations did not peak until the late summer. Similarly, dry upland areas showed a greater relative increase in soil CO_2 concentrations after rewetting events than wet lowland areas. We seek to assess the role of topography in controlling soil temperature, soil moisture and soil nutrient status to measure and model CO_2 production and efflux at the watershed scale. Our results are the first to show watershed-scale concentrations and fluxes of CO_2 over time.

Riveros-Iregui, Diego A.; Emanuel, Ryan E.; Muth, Daniel J.; McGlynn Brian, L.; Epstein, Howard E.; Welsch, Daniel L.; Pacific, Vincent J.; Wraith, Jon M. 2007. Diurnal hysterisis between soil CO2 and soil temperature is controlled by soil water content. Geophysical Research Letters. 34: 1-5. **Abstract**: Recent years have seen a growing interest in measuring and modeling soil CO_2 efflux, as this flux represents a large component of ecosystem respiration and is a key determinant of ecosystem carbon balance. Process-based models of soil CO_2 production and efflux, commonly based on soil temperature, are limited by nonlinearities such as the observed diurnal hysteresis between soil CO_2 concentration ($[CO_2]$) and temperature. Here we quantify the degree to which hysteresis between soil $[CO_2]$ and soil temperature is controlled by soil water content in a montane conifer forest, and how this nonlinearity impacts estimates of soil CO_2 efflux. A representative model that does not consider hysteresis overestimated soil CO_2 efflux for the entire growing season by 19%. At high levels of soil water content, hysteresis imposes organized, daily variability in the relationship between soil $[CO_2]$ and soil temperature, and at low levels of soil water content, hysteresis is minimized.

Riveros-Iregui, Diego A.; McGlynn, Brian L. 2008. Measuring and modeling CO2 and H2O fluxes in complex terrain. FluxLetter: The Newsletter of FLUXNET. 1(4): 12-13. **Abstract**: The feedbacks between the water and the carbon cycles are of critical importance to global carbon balances. Forests and forest soils in northern latitudes are

important carbon pools because of their potential as sinks for atmospheric carbon. However there are significant unknowns related to the effects of hydrologic variability, mountainous terrain, and landscape heterogeneity in controlling soil carbon dioxide (CO_2) efflux. Mountainous terrain imposes large spatial heterogeneity in the biophysical controls of soil CO_2 production and efflux, including soil temperature, soil water content, vegetation, substrate, and soil physical properties. Further complications are introduced by the superimposed temporal heterogeneity (i.e., the asynchronous response of each variable to changes in environmental conditions). As a result, extrapolating from single- or multiple-point measurements to larger areas requires understanding of the emerging patterns controlled by the underlying spatiotemporal nature of biophysical drivers.

Riveros-Iregui, Diego A.; McGlynn, Brian L. 2009. Landscape structure control on soil CO2 efflux variability in complex terrain: scaling from point observations to watershed scale fluxes. Journal of Geophysical Research. 114: 1-14. **Abstract**: We investigated the spatial and temporal variability of soil CO_2 efflux across 62 sites of a 393-ha complex watershed of the northern Rocky Mountains. Growing season (83 day) cumulative soil CO_2 efflux varied from ~300 to ~2000 g CO_2 m^2, depending upon landscape position, with a median of 879.8 g CO_2 m^2. Our findings revealed that highest soil CO_2 efflux rates were observed in areas with persistently high soil moisture (riparian meadows), whereas lower soil CO_2 efflux rates were observed on forested uplands (98% of watershed area). Furthermore, upslope accumulated area (UAA), a surrogate measure of the lateral redistribution of soil water, was positively correlated with seasonal soil CO_2 efflux at all upland sites, increasing in explanatory power when sites were separated by the major aspects of the watershed (SE/NW). We used the UAA–soil CO_2 efflux relationship to upscale measured CO_2 efflux to the entire watershed and found watershed-scale soil CO_2 efflux of 799.45 ± 151.1 g CO_2 m^2 over 83 days. These estimates compared well with independent eddy covariance estimates of nighttime ecosystem respiration measured over the forest. We applied this empirical model to three synthetic watersheds with progressively reduced complexity and found that seasonal estimates of soil CO_2 efflux increased by 50, 58, and 98%, demonstrating the importance of landscape structure in controlling CO_2 efflux magnitude. Our study represents an empirical quantification of seasonal watershed-scale soil CO_2 efflux and demonstrates that UAA (i.e., landscape position) and drainage patterns are important controls on the spatial organization of large-scale (~km^2) soil CO_2 efflux, particularly in semiarid, subalpine ecosystems.

Riveros-Iregui, Diego A.; McGlynn, Brian L.; Epstein, Howard E.; Welsch, Daniel L. 2008. Interpretation and evaluation of combined measurement techniques for soil CO2 efflux: discrete surface chambers and continuous soil CO2 concentration probes. Journal of Geophysical Research. 113: 1-11. **Abstract**: Soil CO_2 efflux is a large respiratory flux from terrestrial ecosystems and a critical component of the global carbon (C) cycle. Lack of process understanding of the spatiotemporal controls on soil CO_2 efflux limits our ability to extrapolate from fluxes measured at point scales to scales useful for corroboration with other ecosystem level measures of C exchange. Additional complications are introduced by the effects of soil water content seasonality and rainfall on the performance of measurement techniques. In this paper we present

measurements of soil CO_2 efflux made at two contrasting sites within a characteristic subalpine forest of the northern Rocky Mountains. Comparison of measurements between the soil respiration chamber technique and the soil CO_2 profile technique over daily and seasonal time scales indicated that soil water content plays a major role in the magnitude and seasonality of soil CO_2 efflux, especially after snowmelt or following summer rainfall. Agreement between both techniques was limited during high soil water content conditions and after summer rainfall. Differences in diel hysteresis patterns of soil CO_2 efflux between sites were controlled by the effects of canopy cover and temporal differences in photosynthetic activity of vegetation. Our results indicate that an accurate parameterization of soil water content heterogeneity in space and time must be a critical component of realistic model representations of soil CO_2 efflux from heterogeneous landscapes.

Riveros-Iregui, Diego A.; McGlynn, Brian L.; Marshall, Lucy A.; Welsch, Daniel L.; Emanuel, Ryan E.; Epstein, Howard E. 2011. A watershed-scale assessment of a process soil CO2 production and efflux model. Water Resources Research. 47: 1-12. **Abstract**: Growing season soil CO_2 efflux is known to vary laterally by as much as seven fold within small subalpine watersheds (<5 km^2), and such degree of variability has been strongly related to the landscape-imposed redistribution of soil water. Current empirical or process models offer low potential to simulate this variability or to simulate watershed-scale dynamics of soil CO_2 efflux. We modified an existing process soil CO_2 production and efflux model to include spatially variable soil moisture, and applied it to a well-studied and moderately complex watershed of the northern Rocky Mountains. We started at the point scale and progressively modeled processes up to the watershed scale. We corroborated model performance using an independent data set of soil CO_2 efflux measurements from 53 sites distributed across the 393 ha watershed. Our approach (1) simulated the seasonality of soil CO_2 efflux at riparian sites; (2) reproduced short-term (diel) dynamics of soil CO_2 concentration ([CO_2]) at riparian sites, particularly observed hysteresis patterns in the soil [CO2]–soil temperature relationship; and (3) simulated growing season estimates of soil CO_2 efflux at dry sites across the landscape (98% of area). Model limitations included poor simulation of growing season (cumulative) soil CO_2 efflux at sites with a large drainage area, likely as a result of poorly modeled soil water content and challenges in parametrization of root and microbial activities. Our study provides important insight into coupling hydrological and biogeochemical models at landscape scales, and highlights the role of landscape structure and heterogeneity when modeling spatial variability of biogeochemical processes.

Riveros-Iregui, D. A.; McGlynn, B. L.; Pacific, V. J.; Epstein, H. E.; Welsch, D. L. 2007. Soil CO2 efflux variability in complex terrain: towards estimation of watershed-level rates. In: American Geophysical Union, fall meeting; 2007 December 10-14; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: B21D-04. Abstract. **Abstract**: Soil CO_2 efflux is a primary component of ecosystem respiration and a key determinant of net ecosystem production (NEP). One obstacle to understanding/predicting the heterogeneity of soil CO_2 efflux is the variability in patterns of soil physical and biogeochemical processes imposed by topography, particularly in

complex terrain. Extrapolating from single- or multiple-point measurements to watershed-scale efflux estimates requires an understanding of the spatial variability of environmental variables (e.g. soil temperature, vegetation, substrate, soil physical properties). Additionally, soil CO_2 efflux can vary at hourly, daily, and seasonal time scales as a result of the interaction among these variables, including the lateral redistribution of soil water. We examined the relationships between topographically-derived indices (e.g., upslope accumulated area, topographic indices, radiation indices) and the space/time variability of soil CO_2 efflux to explore the concept of biogeochemically similar areas (BSAs) for estimating watershed-scale soil CO_2 efflux. We suggest that characteristic dynamics of BSAs can be used to extrapolate from benchmark data collection locations to larger areas of the landscape and indicate watershed-level response to changes in soil temperature, soil water content, and precipitation. We use both discrete and continuous field-based observations of soil CO_2 efflux from a 380-ha watershed in the Tenderfoot Creek Experimental Forest (TCEF), a montane conifer forest characteristic of sub-alpine ecosystems of the northern Rocky Mountains. These observations, in association with terrain analysis and process-based understanding, are used to characterize and quantify the spatial and temporal variability of soil CO_2 efflux. Based on efflux measurements collected during two growing seasons (2005, 2006), there was moderate correlation between upslope accumulated area and rates of soil CO_2 efflux across 18 diverse upland areas of the watershed (r^2=0.37). However, this correlation improves significantly when analyzing efflux rates along single toposequences in moderately sloping SE aspects (r^2=0.82) and steeper NW aspects (r^2=0.96). Our results suggest that BSA analysis can facilitate estimation of watershed-level soil CO_2 efflux rates and their integration with other measures of C flux (e.g. NEP). As such, BSAs offer potential to improve process understanding and quantitative assessment and modeling of watershed scale soil CO_2 efflux in complex terrain.

Scott, Joe H.; Reinhardt, Elizabeth D. 2002. Estimating canopy fuels in conifer forests. Fire Management Today. 62(4): 45-50. **Abstract**: Crown fires occur in a variety of coniferous forest types (Agee 1993), including some that are not historically prone to crown fire, such as ponderosa pine (Mutch and others 1993). The head fire spread rate of a crown fire is usually several times faster than that of a surface fire burning under the same conditions, which leads to a significant increase in the number of acres burned during a given period. In addition, crown fires cause more severe and lasting damage than do surface fires. Consequently, predicting the behavior and effects of crown fire, determining the susceptibility of stands to crown fire, and designing treatments to mitigate the potential damage from crown fires are priorities for fire managers.

Scott, Joe H.; Reinhardt, Elizabeth D. 2005. Stereo photo guide for estimating canopy fuel characteristics in conifer stands. Gen. Tech. Rep. RMRS-GTR-145. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p. **Abstract**: Stereo photographs, hemispherical photographs, and stand data are presented with associated biomass and canopy fuel characteristics for five Interior West conifer stands. Canopy bulk density, canopy base height, canopy biomass by component, available canopy fuel load, and vertical distribution of canopy fuel are

presented for each plot at several stages of sampling, each corresponding to a level of simulated low thinning (100, 75, 50, and 25 percent of the initial basal area). This guide will help fuel managers estimate canopy fuel characteristics in similar forest conditions.

Seielstad, Carl A.; Queen, Lloyd P. 2003. Using airborne laser altimetry to determine fuel models for estimating fire behavior. Journal of Forestry. 101(4): 10-15. **Abstract**: Airborne laser altimetry provides an unprecedented view of the forest floor in timber fuel types and is a promising new tool for fuels assessments. It can be used to resolve two fuel models under closed canopies and may be effective for estimating coarse woody debris loads. A simple metric-obstacle density-provides the necessary quantification of fuel bed roughness to make these measures possible. This work highlights the need for more research in the application of laser technology to fuels mapping.

Shepard, Bradley B.; Ireland, Susan C.; White, Robert G. 1997. Fish resources within the Tenderfoot Experimental Forest, Montana: 1991-95. Final Report INT-92682-RJVA (Part 1). Bozeman, MT: Montana State University, Department of Biology, Montana Cooperative Fishery Research Unit. 35 p. (+ appendices). **Abstract**: The Montana Cooperative Fishery Research Unit at Montana State University was contracted by the USDA Forest Service's Intermountain Research Station (contract INT-RJVA-92682) to collect baseline fish resource information for Tenderfoot Creek and its tributaries within the Tenderfoot Creek Experimental Forest (TCEF). These data were collected from 1992-1995. The westslope cutthroat trout population inhabitating the upper Tenderfoot Creek drainage (within the TCEF) consists of a hybrid swarm of westslope cutthroat and rainbow trout. These *Oncorhychus* spp. are distributed downstream from Spring Park Creek. they make up a progressively larger component of the fish community down to the lower boundary of the Experimental Forest, where they comprised 35-50% of the salmonid community. Brook trout were the only fish species found in the upper portion of the Tenderfoot Creek drainage above Spring Park Creek where channel gradient was relatively low (about 3% compared to over 5% for the channel down to the TCEF boundary). The estimated biomass of *Oncorhynchus* spp. ranged from 0.11 to 4.75 g/m² where they were present and the estimated biomass of brook trout ranged from 0.33 to 6.23 g/m². Mottled sculpins inhabit the lower portion of Tenderfoot Creek up to a falls located about 0.2 km below Pack Creek that was identified as a barrier to upstream fish movement. None of the tributaries to Tenderfoot Creek within the Experimental Forest, except Sun Creek, support fish populations. Sun Creek supports only broko trout. Cascade/riffle habitat types were dominant in Tenderfoot Creek. Pools comprised a very small proportion (<3%) of the stream channel. We found few *Oncorhynchus* spp. young-of-the-year that suggests very limited recruitment. We observed numerous young-of-the-year brook trout, suggesting their recruitment may be relatively high.

Shepard, Bradley B.; Robison-Cox, Jim; Ireland, Susan C.; White, Robert G. 1996. Factors influencing retention of visible implant tags by westslope cutthroat trout inhabiting headwater streams of Montana. North American Journal of Fisheries Management. 16(4): 913-920. **Abstract**: Retention of visible implant (VI) tags by westslope cutthroat trout *Oncorhynchus clarki lewisi* inhabiting 20 reaches of 13 isolated headwater tributary drainages in Montana was evaluated during 1993 and 1994. In

1993, 2,071 VI tags were implanted in westslope cutthroat trout (100–324 mm fork length) and adipose fins were removed as a secondary mark to evaluate tag retention. Of 348 westslope cutthroat trout recaptured during the year they were tagged, 201 (58%) had retained their tags. Of 616 westslope cutthroat trout recaptured the year after tagging, 355 (58%) had retained their tags. Logistic regression analyses indicated that fish length was the most significant variable that positively influenced tag retention. Other significant variables were wetted width and channel gradient of the stream in which fish were tagged and quality of tag insertion (rated at time of tagging). Fish condition did not significantly improve deviance performance of logistic regression models that included fork length and tag insertion quality. Neither slopes nor intercepts of $\log_{10}$(length)–$\log_{10}$(weight) regressions were significantly different ($P > 0.10$) between fish that retained tags and fish that lost them. Fish condition was not significantly different ($P > 0.951$; analysis of covariance) between previously tagged and untagged westslope cutthroat trout after differences between drainages and years were accounted for. We found no significant differences in slopes ($P > 0.50$) or intercepts ($P > 0.05$) of log10(length)-log10(weight) regressions between previously tagged and untagged fish. However, for 11 drainages where comparisons could be made, we found significant differences ($P < 0.05$) in length-weight regression slopes between previously tagged and untagged fish for one drainage and in regression intercepts for an additional three drainages. Ninety-five percent of all tags were readable at recapture, A logistic regression model predicted that tag retention would be 75% or higher for westslope cutthroat trout 155 mm FL or larger if tag insertion quality was good. In spite of relatively poor tag retention (<75%) by smaller (<155 mm) westslope cutthroat trout, VI tags were a valuable tool to assess movements of those fish retaining tags.

Smith, Helen; Hardy, Colin C.; McCaughey, Ward W. 2003. The use of silviculture and prescribed fire to manage multi-aged lodgepole pine forests and reduce fuel loadings at the Tenderfoot Creek Experimental Forest, Montana. In: 2nd international wildland fire ecology and fire management congress; 2003 November 16-20; Orlando, FL. P1.13. Abstract. **Abstract**: The Tenderfoot Creek Experimental Forest (TCEF), located in central Montana, is the only Forest Service Experimental Forest that features the lodgepole pine forest type. In contrast to the common perception of lodgepole pine stands being primarily developed by stand replacement fires, many lodgepole stands across the west are multi-aged. Many of these stands are in late-successional stages, at risk to pests, and susceptible to catastrophic-scale fires due to heavy fuel loading following years of fire suppression. On the TCEF, 54 percent of the lodgepole pine stands are multi-aged, with 27 percent found to be two-aged and another 27 percent were in an indistinct mosaic of different aged groups.
The Tenderfoot Research project was developed to evaluate and quantify the ecological and biological effects of two innovative silvicultural treatments with and without the use of prescribed fire in an attempt to create two-aged stand structures in lodgepole pine. This poster will outline the experimental design, treatment details, and preliminary results.

Smith, T.; Marshall, L. 2007. A bayesian uncertainty framework for conceptual snowmelt and hydrologic models applied to the Tenderfoot Creek Experimental Forest. In:

American Geophysical Union, fall meeting; 2007 December 10-14; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H31H-0763. Abstract. **Abstract**: In many mountainous regions, the single most important parameter in forecasting the controls on regional water resources is snowpack (Williams et al., 1999). In an effort to bridge the gap between theoretical understanding and functional modeling of snow-driven watersheds, a flexible hydrologic modeling framework is being developed. The aim is to create a suite of models that move from parsimonious structures, concentrated on aggregated watershed response, to those focused on representing finer scale processes and distributed response. This framework will operate as a tool to investigate the link between hydrologic model predictive performance, uncertainty, model complexity, and observable hydrologic processes. Bayesian methods, and particularly Markov chain Monte Carlo (MCMC) techniques, are extremely useful in uncertainty assessment and parameter estimation of hydrologic models. However, these methods have some difficulties in implementation. In a traditional Bayesian setting, it can be difficult to reconcile multiple data types, particularly those offering different spatial and temporal coverage, depending on the model type. These difficulties are also exacerbated by sensitivity of MCMC algorithms to model initialization and complex parameter interdependencies. As a way of circumnavigating some of the computational complications, adaptive MCMC algorithms have been developed to take advantage of the information gained from each successive iteration. Two adaptive algorithms are compared is this study, the Adaptive Metropolis (AM) algorithm, developed by Haario et al (2001), and the Delayed Rejection Adaptive Metropolis (DRAM) algorithm, developed by Haario et al (2006). While neither algorithm is truly Markovian, it has been proven that each satisfies the desired ergodicity and stationarity properties of Markov chains. Both algorithms were implemented as the uncertainty and parameter estimation framework for a conceptual rainfall-runoff model based on the Probability Distributed Model (PDM), developed by Moore (1985). We implement the modeling framework in Stringer Creek watershed in the Tenderfoot Creek Experimental Forest (TCEF), Montana. The snowmelt-driven watershed offers that additional challenge of modeling snow accumulation and melt and current efforts are aimed at developing a temperature- and radiation-index snowmelt model. Auxiliary data available from within TCEF's watersheds are used to support in the understanding of information value as it relates to predictive performance. Because the model is based on lumped parameters, auxiliary data are hard to incorporate directly. However, these additional data offer benefits through the ability to inform prior distributions of the lumped, model parameters. By incorporating data offering different information into the uncertainty assessment process, a cross-validation technique is engaged to better ensure that modeled results reflect real process complexity.

Smith, Tyler Jon. 2008. A conceptual precipitation-runoff modeling suite: model selection, calibration and predictive uncertainty assessment. Bozeman, MT: Montana State University. 177 p. Thesis. **Abstract**: In Montana and much of the Rocky Mountain West, the single most important parameter in forecasting the controls on regional water resources is snowpack. Despite the heightened importance of snowpack, few studies have considered the representation of uncertainty in coupled snowmelt/hydrologic conceptual models. Uncertainty estimation provides a direct

interpretation of the risk associated with predictive modeling results. Bayesian inference, through the application of Markov chain Monte Carlo methods, provides a statistical means of approximating uncertainty associated with both the parameters and the model structure. This thesis addresses the complexities of predictive modeling in hydrology through the development, implementation and analysis of a suite of conceptual hydrologic models under a Bayesian inference framework. The research is presented in four main sections. First, a comparative assessment of three recently developed Markov chain Monte Carlo algorithms, based on their performance across two case studies, is performed. This study has revealed that the extreme complexity of the parameter space associated with simple, conceptual models is best explored by the Delayed Rejection Adaptive Metropolis algorithm. Second, a complete description of the models and study site incorporated in the study are presented, building on established theories of model development. Third, an investigation of the value of each model structure, considering predictive performance, uncertainty and physical realism is presented. This section builds on results of the first section, through the application of the Delayed Rejection Adaptive Metropolis algorithm for model calibration and uncertainty quantification under Bayesian principles. Finally, a discussion of the Simulation and Prediction Lab for Analysis of Snowmelt Hydrology, developed to incorporate the tasks of model selection, calibration and uncertainty analysis into a simple graphical user interface is explained. The application of a complete modeling framework from model selection to calibration and assessment presented in this thesis represents a holistic approach to the development of improved understanding of snow-dominated watersheds through prediction by coupled snowmelt/hydrologic modeling strategies.

Smith, T. J.; Jencso, K. G.; Marshall, L. A.; McGlynn, B. L. 2009. A stream network based semi-distributed model for prediction of hydrologic connectivity and runoff generation. In: American Geophysical Union, fall meeting; 2009 December 14-18; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H33B-0868. Abstract. **Abstract**: The hydrologic connectivity concept has gained traction in the realm of physical hydrology but has received little attention in rainfall-runoff modeling so far. The present study introduces a new conceptual hydrologic model that blends recent advancements in hydrologic process understanding and quantitative modeling within a connectivity domain. The model extends the empirical findings of Jencso et al. [2009], who found a strong correlation between the duration of shallow groundwater connectivity across hillslope, riparian, and stream zones (HRS) and the upslope accumulated area (UAA) associated with each transect (r^2 = 0.91). This relationship, when extrapolated to the entire study area, resulted in a “connectivity duration curve” (CDC) that was very strongly correlated to the flow duration curve of the watershed (r^2 = 0.95). Incorporation of these findings into a simple runoff model was achieved by rethinking model development from a stream-centric standpoint. We use landscape analysis as the foundation of our description of watershed behavior and aim to quantify the control landscape topology/topography exerts on hydrologic connectivity. A semi-distribution approach was taken to discretize the watershed according to the distribution of UAA along the stream network. Discharge from each landscape unit is proportional to the duration that it is hydrologically

connected to the stream and stream discharge is a result of the frequency of connections along the stream network. The model was applied to the Stringer Creek watershed of the Tenderfoot Creek Experimental Forest (TCEF), located in central Montana, USA. Detailed field observations collected by Jencso et al. [2009] were used to inform the underpinnings of the model and to corroborate internal consistency of the model's simulations. For this application, the model shows good agreement between the observed and predicted stream discharge as well as between the observed and simulated connectivity duration curves. The ability of the model to simulate internal dynamics without conditioning the parameters on these data indicate the potential of this model to be more convincingly extrapolated to other hydrologic conditions and transferred to additional watersheds of varying topographic structure than traditional conceptual hydrologic models.

Smith, T. J.; Marshall, L. A. 2008. Development and application of a parsimonious snow-hydrologic modeling suite: investigating the link between model complexity and predictive uncertainty. In: American Geophysical Union, fall meeting; 2008 December 15-19; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H23B-0964. Abstract. **Abstract**: The simulation and modeling of snowmelt and hydrologic drivers is desirable for prediction of different hydrologic variables, most significantly streamflow at the catchment outlet. This is particularly true of mountainous regions where snowmelt drives major hydrologic events and water resource predictability. We have developed a suite of parsimonious models of first-order snow and hydrologic processes to investigate the link between overall model complexity (both snow and hydrologic elements) and predictive performance. The use of simper models is motivated by the desire to capture first-order processes, in line with a top-down modeling philosophy. Such models have the capability to be more efficient in modeling the system by having less uncertainty with similar predictive power when compared to more complex model structures. Constructed in a modular fashion, the modeling suite has the ability to assess the interaction between each snowmelt and hydrologic base structure coupling, as well as to separate error between each component. The modeling suite was applied to the Stringer Creek watershed of Tenderfoot Creek Experimental Forest (TCEF), located in central Montana, USA. Making use of meteorological data collected at one of the two NRCS SNOTEL stations within TCEF's borders and streamflow data from the USFS Rocky Mountain Research Station (TCEF's managing agency), we compare the performance of different model combinations using 6 years of available data. Implementation of a Markov chain Monte Carlo approach to parameter estimation and uncertainty estimation provides the ability to characterize errors in the models (including non-stationarities), explore complex parameter spaces and interdependence, and incorporate multiple sources of data for model conditioning. The necessity of such abilities becomes especially critical in the application of a top-down modeling approach, where conceptual models are used that often involve highly interdependent model parameters. Further, the flexibility and design of the coupled, modular framework allows for the separation of uncertainty with regard to both snow and hydrologic process components.

Smith, Tyler Jon; Marshall, Lucy Amanda. 2010. Exploring uncertainty and model

predictive performance concepts via a modular snowmelt-runoff modeling framework. Environmental Modelling and Software. 25(6): 691-701. **Abstract**: Model selection is an extremely important aspect of many hydrologic modeling studies because of the complexity, variability, and uncertainty that surrounds the current understanding of watershed-scale systems. However, development and implementation of a complete precipitation-runoff modeling framework, from model selection to calibration and uncertainty analysis, are rarely confronted. This paper introduces a modular precipitation-runoff modeling framework that has been developed and applied to a research site in Central Montana, USA. The case study focuses on an approach to hydrologic modeling that considers model development, selection, calibration, uncertainty analysis, and overall assessment. The results of this case study suggest that a modular framework is useful in identifying the interactions between and among different process representations and their resultant predictions of stream discharge. Such an approach can strengthen model building and address an oft ignored aspect of predictive uncertainty; namely, model structural uncertainty.

Solorzano, Lucia. 1997. Many ways to manage lodgepole pine forests. In: Eco-Report: Bitterroot Ecosystem Management Research Project. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 5. **Abstract**: This article highlights the restoration effort in the Tenderfoot Creek Experimental Forest. Treatments will include shelterwood harvests followed by low-severity underburns on some sites, and mixed-severity broadcast underburns on sites that are not logged. Logging will produce two stand structures: evenly spaced, and groups of unevenly spaced trees.

Stewart, Cathy. 1996. Restoring historic landscape patterns through management: restoring fire mosaics on the landscape. In: Hardy, Colin C.; Arno, Stephen F., eds. The use of fire in forest restoration : a general session at the annual meeting of the Society for Ecological Restoration; 1995 September 14-16; Seattle, WA. Gen. Tech. Rep. INT-GTR-341. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 49-50. **Abstract**: Demonstration treatments that are developed on the Bitterroot National Forest will be applied on the Tenderfoot Creek Experimental Forest in central Montana in collaboration with Ward McCaughey, Intermountain Research Station, Bozeman, Montana. The array of treatments will include use of commercial harvest methods with low, medium, and high levels of tree removal. Harvests will be applied with and without prescribed fire. Controls will also be established for comparison. These treatments will provide detailed monitoring and comparison that will provide valuable information for future management.

Varhola, Andres; Coops, Nicholas C.; Weiler, Markus; Moore, R. Dan. 2010. Forest canopy effects on snow accumulation and ablation: an integrative review of empirical results. Journal of Hydrology. 392(3-4): 219-233. **Abstract**: The past century has seen significant research comparing snow accumulation and ablation in forested and open sites. In this review we compile and standardize the results of previous empirical studies to generate statistical relations between changes in forest cover and the associated changes in snow accumulation and ablation rate. The analysis drew upon 33 articles

documenting these relationships at 65 individual sites in North America and Europe from the 1930s to present. Changes in forest cover explained 57% and 72% of the variance of relative changes in snow accumulation and ablation, respectively. The incorporation of geographic and average historic climatic information did not significantly improve the ability to predict changes in snow processes, mainly because most of the studies did not provide enough information on site characteristics such as slope and aspect or meteorological conditions taking place during the experiments. Two simple linear models using forest cover as the sole predictor of changes in snow accumulation and ablation are provided, as well as a review of the main sources of variation that prevent the elaboration of more accurate multiple regression models. Further studies should provide detailed information regarding the main sources of variation influencing snow processes including the effect of year-to-year changes in weather variables during the monitoring period.

Williams, K. M.; Locke, W. 2007. High resolution, spatial distribution of unit stream power using ALSM-derived stream networks. In: American Geophysical Union, fall meeting; 2007 December 10-14; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H52E-08. Abstract. **Abstract**: Unit stream power is a measure of energy expenditure, as the channel does the work of transporting sediment and modifying channel morphology. The distribution of energy through the channel network creates a distribution of channel morphologic types by taking disorganized hillslope inputs of wood and sediment and creating channel structure, organization, and regularly spaced bedforms. Unit stream power has been used as a proxy for fluvial process, to establish causality between channel form and process. However, spatial distributions of unit stream power have been constrained by the coarseness of the available topographic data. ALSM data was used to create high resolution spatial distributions of unit stream power on a reach of headwater mountain stream. Spatial distribution of unit stream power at fine scales was used to detect spatial organization in a reach of Spring Park Creek, Tenderfoot Creek Experimental Forest, Montana. ALSM-derived digital elevation models of varying resolution were used to delineate stream networks. Channel slope derived from stream networks, discharge data from an in-situ gaging station, and field surveys of channel width were used to calculate unit stream power distributions at 0.5, 1.0, and 5.0 meter resolution. As a secondary method of calculating unit stream power, a HEC-RAS hydraulic model of the reach was created by cutting cross-sections through the ALSM-derived topography and inserting thalweg elevations to define channel inverts. This model was calibrated by stage- discharge data and field-derived roughness values. The HEC-RAS-calculated values of unit stream power were used to create spatial distributions of unit stream power. Spatial distributions of unit stream power derived by both methods were analyzed by spectral analysis for periodic behavior. The relative dominance of alluvial versus colluvial forcing constrains the degree of organization.

Woods, S.; Ahl, R.; Sappington, J.; McCaughey, W. 2005. Effects of forest thinning on snow accumulation in lodgepole pine stands, Montana, USA. In: American Geophysical Union, fall meeting; 2005 December 5-9; San Francisco, CA. Washington, DC: Eos Transactions, American Geophysical Union: H41D-0434. Abstract. **Abstract**:

Alternative silvicultural treatments such as thinning are being increasingly used to reduce wildfire hazards in forested watersheds, but the hydrologic effects of forest thinning are not well defined. We evaluated the effect of even thinning (SE) and group-retention thinning (SG) treatments, both with 60 % basal area removal, on snow accumulation in lodgepole pine stands at the Tenderfoot Creek experimental forest, west-central Montana. The snow water equivalent (SWE) close to the seasonal peak was measured at >250 locations in the SE and SG treatments and a control in 2003, 2004 and 2005. Reduced interception in SE resulted in a significant ($P < 0.0001$), 20 to 35 % increase in SWE relative to the control in 2003 and 2004. In 2005, prolonged high intensity snowfall prior to sampling overwhelmed the canopy interception, so that the SWE in SE was just 9 % greater than the control, and the treatment effect was not significant. In the SG treatment, increased losses due to sublimation from south facing group edges and wind scour losses in the openings offset gains due to reduced interception. Consequently, SG always accumulated significantly less snow than SE ($p < 0.0001$), and the SG treatment and control means were not significantly different. Differences in snow accumulation between groups and openings meant that the SWE in SG was up to 3 times more variable than in either SE or the control. The contrasting responses in the SE and SG treatments demonstrate that thinning can have substantially different effects on snow accumulation depending on the spatial arrangement of tree removal.

Woods, Scott W. 2007. Calibration of streamflow gauging stations at the Tenderfoot Creek Experimental Forest. Final Technical Report. USDA Joint Venture Agreement No, 02-JV-11222022-183. Missoula, MT: University of Montana, College of Forestry and Conservation, Department of Ecosystem and Conservation Sciences. 37 p. **Abstract**: We used tracer based methods to calibrate eleven streamflow gauging stations at the Tenderfoot Creek Experimental Forest in western Montana. At six of the stations the measured flows were consistent with the existing rating curves. At Lower and Upper Stringer Creek, Upper Sun Creek and Upper Tenderfoot Creek the published flows, based on the existing rating curves, were higher than the actual flows, while at Lower Sun Creek the published flows were lower than the actual flows. At the Lower and Upper Stringer Creek and Upper Tenderfoot Creek sites we recommend that the flumes be examined for evidence of the cause of the inaccurate measurements and that appropriate remedial action be taken. Specific points include 1) verifying that the flume geometry is correct, that the flume is straight and horizontal, and that the flume has not been damaged; 2) clearing debris from within or around the flume; and 3) comparing electronically recorded stage values to those observed on the flume staff plate. In the event that there is no evidence of the cause of the observed measurement discrepancy, we recommend additional measurements at these flumes to verify the measurements already obtained and to develop new rating curves. At the Upper Sun Creek we recommend that additional measurements be taken across a wider range of flows so that a new rating curve can be developed. At Lower Sun Creek we recommend that the flume installation be checked for leaks and appropriate remedial action taken.

Woods, Scott W.; Ahl, Robert; Sappington, Jason; McCaughey, Ward. 2006. Snow accumulation in thinned lodgepole pine stands, Montana, USA. Forest Ecology and

Management. 235(1-3): 202-211. **Abstract**: Alternative silvicultural treatments such as thinning can be used to restore forested watersheds and reduce wildfire hazards, but the hydrologic effects of these treatments are not well defined. We evaluated the effect of two shelterwood-with-reserve silvicultural prescriptions, one leaving residual trees evenly distributed (SE) and the second leaving residual trees in groups (SG), both with similar to 50% basal area removal, on snow accumulation in lodgepole pine stands at the Tenderfoot Creek Experimental Forest, west-central Montana. The snow water equivalent (SWE) close to the seasonal peak was measured at > 250 locations in the SE and SG treatments and a control in 2003, 2004 and 2005. Reduced interception in SE resulted in significant ($P < 0.0001$) 7.2 and 5.6 cm increases in SWE relative to the control in 2003 and 2004, respectively, and a 1.7 cm increase in 2005. Predictive models for the mean peak SWE in the control and the SE treatment were based on an inverse-exponential relationship between interception efficiency and mean storm intensity, and the average percent deviation for the two models was 9.4 and 7.6%, respectively. In the SG treatment, increased solar radiation and wind resulted in sublimation losses that offset gains due to reduced interception in the openings between groups. Consequently, SG always accumulated significantly less snow than SE ($P < 0.0001$), and the SG treatment and control means were not significantly different. Differences in snow accumulation between groups and openings and between the north and south sides of groups meant that the SWE in SG was up to three times more variable than in either SE or the control. The contrasting responses in the SE and SG treatments demonstrate that thinning can have substantially different effects on snow accumulation depending on the spatial arrangement of tree removal.

Wright, David K.; Glasgow, Lance S.; McCaughey, Ward W.; Sutherland, Elaine K. 2011. Tenderfoot Creek Experimental Forest annual precipitation data: 1993-2010, [Online]. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station (Producer). Available:http://www.fs.fed.us/rm/data_archive/dataaccess/contents_expforests.shtml [2011, December 15]. **Abstract**: This data product contains annual precipitation at ten locations on the Tenderfoot Experimental Forest. The ten locations are Bubbling Creek, County line, Dry Park, Farnes Meadow, Lonesome Creek, Lower Sun Creek, Upper Stringer Creek, Passionate Creek, Lower Stringer Creek and Onion Park. Precipitation values were collected in storage gauges kept on site year long. Storage gauges were checked on or near September 30 coinciding with the end of the water year (historic period of low flow in the Tenderfoot Creek watershed).