Summary of Research
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Summary of Accomplishments

We originally proposed to study and discover the changes that have occurred in soil carbon pools, as a result of tree mortality due to beetle infection, and the ease by which those pools release CO_2 to the atmosphere in mountain forests in the Western US. We studied forest plots at two sites – the Niwot Ridge AmeriFlux site and the Fraser Experimental Forest site, both in Colorado. At the Niwot Ridge site we used a series of plots on which trees were killed by simulated beetle attack over 10 years. At the Fraser Forest site we used forest plots that experienced widespread tree mortality due to natural beetle outbreaks over the past decade. We used advanced analysis techniques utilizing stable isotope (^{13}C and ^{12}C) dynamics in atmospheric CO_2, radioactive isotope dating (using ^{14}C in soil organic matter) and pyrolysis-gas chromatography-mass spectrometry to analyze patterns of soil CO_2 release and changes in the soil carbon pools as a result of tree death due to simulated or real beetle attacks. An additional goal that was stated in the original proposal was to use observations as the framework for modifying computer simulation models and explore potential interactions among future beetle outbreaks, climate change and forest CO_2 uptake in the Rocky Mountain region. The modeling studies concerning climate change and ecosystem CO_2 exchange were initiated through the support of this grant, and have been published in three papers. These studies, however, were not able to take up the issue of pine beetle disturbance because some of the critical insight (concerning radiocarbon dating and chemical composition of respiratory substrates) is still forthcoming. Currently, a post-doctoral student has continued the goal of modifying the Community Land Model as part of an NSF grant under the leadership of Professor David Moore (one of the Co-Is of this DOE grant), and this effort has thus been sustained in a new project. Over the four-year course of this grant, we have published eleven papers in the peer-reviewed literature that discuss the results of the proposed studies. Four additional papers are in preparation; two of those papers are 90% completed and will be submitted by June, 2015, and two papers are 60% completed and will be submitted by September 2015. Below, we present a synopsis of the published work that has been accomplished; including the three papers that are still in preparation.

Papers published using support from this grant

1. Blonquist, J. M., Montzka, S. A., Munger, J. W., Yakir, D., Desai, A. R., Dragoni, D., Griffis, T. J., Monson, R. K., Scott, R. L. and Bowling, D. R. (2011) The potential of carbonyl sulfide as a proxy for gross primary production at flux tower sites, Journal of Geophysical Research G: Biogeosciences, 116, G04019, doi:10.1029/2011JG001723

2. Moore, D.J.P., Trahan, N.A., Wilkes, P., Quaife, T., Stephens, B.B., Elder, K., Desai, A.R., Negron, J. and Monson, R.K. (2013) Persistent reduced ecosystem respiration after insect disturbance in high elevation forests. Ecology Letters 16: 731-737. doi 10.1111/ele.12097

3. Scott-Denton, L.E., Moore, D.J.P., Rosenbloom, N.A., Kittel, T.G.F., Burns, S.P., Schimel, D.S. and Monson, R.K. (2013) Forecasting net ecosystem CO_2 exchange in a subalpine forest using model data assimilation combined with simulated climate and weather generation. Journal of Geophysical Research – Biogeosciences 118: 549-565. doi 10.1002/jgrg.20039

4. Shao, P., Zeng, X., Sakaguchi, K., Monson, R.K. and Zeng, X.D. (2013) Terrestrial carbon cycle - climate relations in eight CMIP5 earth system models. Journal of Climate 26: 8744-8764. doi 10.1175/JCLI-D-12-00831.1

Papers published using support from this grant (contd.)

5. Bowling, D. R., Ballantyne, A. P., Miller, J. B., Burns, S. P., Conway, T. J., Menzer, O., Stephens, B. B. and Vaughn, B. H. (2014) Ecological processes dominate the ^{13}C land disequilibrium in a Rocky Mountain subalpine forest, Global Biogeochemical Cycles, 28(4), 2013GB004686, doi:10.1002/2013GB004686, 2014.

6. Maurer, G. E. and Bowling, D. R. (2014) Dust effects on snowpack melt and related ecosystem processes are secondary to those of forest canopy structure and interannual snowpack variability, Ecohydroogy, (published on-line in Early View). doi:10.1002/eco.1558.

7. Maurer, G. E. and Bowling, D. R. (2014) Seasonal snowpack characteristics influence soil temperature and water content at multiple scales in interior western U.S. mountain ecosystems, Water Resources. Research 50(6), 5216–5234, doi:10.1002/2013WR014452.

8. Burns, S.P., Molotch, N.P., Williams, M.W., Knowles, J.F., Seok, B., Monson, R.K., Turnipseed, A.A. and Blanken, P.D. (2014) Snow temperature changes within a seasonal snowpack and their relationship to turbulent fluxes of sensible and latent heat. Journal of Hydrometeorology 15: 117-142. doi 10.1175/JHM-D-13-026.1

9. Zobitz, J., Moore, D.J.P., Quaife, T., Braswell, R., Bergeson, A., Anthony, J. and Monson, R.K. (2014) Joint data assimilation of satellite reflectance and net ecosystem exchange data constrains ecosystem carbon fluxes at a high-elevation subalpine forest. Agricultural and Forest Meteorology 195: 73-88. doi 10.1016/j.agrformet.2014.04.011

10. Knowles, J.F., Burns, S.P., Blanken, P.D. and Monson, R.K. (2015) Ecosystem fluxes of energy, water, and carbon dioxide from mountain ecosystems at Niwot Ridge, Colorado. Plant Ecology & Diversity (published on-line in Early View) doi 10.1080/17550874.2014.904950

11. Trahan, N.A., Dynes, E.L., Moore, D.J.P. and Monson, R.K. (2015) Changes in soil biogeochemistry and microclimate following disturbance by mountain pine beetles in subalpine forests. Oecologia (in press).

Papers in preparation

12. Bowling, D.R., Egan, J., Hall, S.J., and Risk, D.A. (in prep) Environmental forcing does not lead to diel or synoptic variability in carbon isotope content of forest soil respiration, to be submitted to Biogeosciences (90% complete)

13. Maurer, G.E., Chan, A.M., Trahan, N. A., Moore, D.J.P., and Bowling, D.R. (in prep) Soil carbon cycle ^{13}C responses in the decade following bark beetle and stem girdling forest disturbance, to be submitted to Plant, Cell, and Environment (90% complete).

14. Trahan, N.A., Lehman, S., Moore, D.J.P., Grandy, S. and Monson, R.K. (in prep) Radiocarbon content and chemical analysis reveal changes in the age of carbon substrates used for ecosystem respiration following pine beetle disturbance in subalpine forest ecosystems, to be submitted to Journal of Geophysical Research G: Biogeosciences (60% complete).

15. Albert, L.P., Keenan, T.F., Huxman, T.E., Burns, S.P. and Monson, R.K. (in prep) Tradeoffs among temperature, precipitation and light as serial and parallel climate controls over net ecosystem productivity in a high-elevation subalpine forest: an artificial neural network analysis, to be submitted to Oecologia (60% complete).

Summaries of research reported in each paper

Blonquist, J. M., Montzka, S. A., Munger, J. W., Yakir, D., Desai, A. R., Dragoni, D., Griffis, T. J., Monson, R. K., Scott, R. L. and Bowling, D. R. (2011) The potential of carbonyl sulfide as a proxy for gross primary production at flux tower sites, Journal of Geophysical Research G: Biogeosciences, 116, G04019. The Niwot Ridge AmeriFlux site was used in a multisite study to investigate the potential use of carbonyl sulfide as a tracer for gross primary productivity. The PIs of this proposal participated in this analysis. Seasonal dynamics of atmospheric carbonyl sulfide (OCS) at regional and continental scales and plant OCS exchange at the leaf level have shown a close relationship with those for CO_2. CO_2 has both sinks and sources within terrestrial ecosystems, but the primary terrestrial exchange for OCS is thought to be leaf uptake, suggesting potential for OCS uptake as a proxy for gross primary production (GPP). We explored the utility of OCS uptake as a GPP proxy in micrometeorological studies of biosphere-atmosphere CO_2 exchange by applying theoretical concepts from earlier OCS studies to estimate GPP. We partitioned measured net ecosystem exchange (NEE) using the ratio of measured vertical mole fraction gradients of OCS and CO_2. At the Harvard Forest AmeriFlux site, measured CO_2 and OCS vertical gradients were correlated and were related to NEE and GPP, respectively. Estimates of GPP from OCS-based NEE partitioning were similar to those from established environmental regression techniques, providing evidence that OCS uptake can potentially serve as a GPP proxy. Measured vertical CO_2 mole fraction gradients at five other AmeriFlux sites, including the Niwot Ridge site, were used to project anticipated vertical OCS mole fraction gradients to provide indication of potential OCS signal magnitudes at sites where no OCS measurements were made. Projected OCS gradients at sites with short canopies were greater than those in forests, including measured OCS gradients at Harvard Forest, indicating greater potential for OCS uptake as a GPP proxy at these sites. This exploratory study suggests that continued investigation of linkages between OCS and GPP is warranted. This study allowed us to develop a new tool for estimating the rate at which forest ecosystems extract CO_2 from the atmosphere, which has previously only been possible through computer models, with considerable uncertainty; now, we have hope for a direct observation of this CO_2 uptake rate.

Moore, D.J.P., Trahan, N.A., Wilkes, P., Quaife, T., Stephens, B.B., Elder, K., Desai, A.R., Negron, J. and Monson, R.K. (2013) Persistent reduced ecosystem respiration after insect disturbance in high elevation forests. Ecology Letters 16: 731-737. Amid a worldwide increase in tree mortality, mountain pine beetles (*Dendroctonus ponderosae* Hopkins) have led to the death of billions of trees from Mexico to Alaska since 2000. This is predicted to have important carbon, water and energy balance feedbacks on the Earth system. Counter to current projections, we showed that on a decadal scale, tree mortality caused no increase in ecosystem respiration from scales of several square meters up to an 84 km^2 valley. Rather, we found comparable declines in both gross primary productivity (GPP) and respiration (Re) suggesting little change in net CO_2 flux, with a transitory recovery of respiration 6-7years after mortality associated with increased incorporation of leaf litter C into soil organic matter, followed by further decline in years 8-10. The mechanism of the impact of tree mortality caused by these biotic disturbances is consistent with reduced input (through reductions in GPP) rather than increased output of carbon (through increased Re). This study provided a contrasting view of how forest carbon cycles will change in response to widespread beetle disturbances, compared to studies from the past. In a high profile analysis published in the journal Nature, the predicted impact of the most recent mountain pine beetle outbreak is the transition of western North American forests from a sink to a substantial source of CO_2 to the atmosphere (Kurz et al. 2008, Nature 452, 987–990.). Our findings do not support this prediction.

Scott-Denton, L.E., Moore, D.J.P., Rosenbloom, N.A., Kittel, T.G.F., Burns, S.P., Schimel, D.S. and Monson, R.K. (2013) Forecasting net ecosystem CO_2 exchange in a subalpine forest using model data assimilation combined with simulated climate and weather generation. Journal of Geophysical Research – Biogeosciences 118: 549-565. Forecasting the carbon uptake potential of terrestrial ecosystems in the face of future climate change has proven challenging. Process models, which have been increasingly used to study ecosystem-atmosphere carbon and water exchanges when conditioned with tower-based eddy covariance data, have the potential to inform us about biogeochemical processes in future climate regimes, but only if we can reconcile the spatial and temporal scales used for observed fluxes and projected climate. In this paper, we used weather generator and ecosystem process models conditioned on observed weather dynamics and carbon/water fluxes, and embedded them within climate projections from a suite of six Earth Systems Models. Using this combination of models, we studied carbon cycle processes in a subalpine forest within the context of future (2080-2099) climate regimes. The assimilation of daily averaged, observed net ecosystem CO_2 exchange (NEE) and evapotranspiration (ET) into the ecosystem process model resulted in retrieval of projected NEE with a level of accuracy that was similar to that following the assimilation of half-daily averaged observations; the assimilation of 30min averaged fluxes or monthly averaged fluxes caused degradation in the model's capacity to accurately simulate seasonal patterns in observed NEE. Using daily averaged flux data with daily averaged weather data projected for the period 2080-2099, we predicted greater forest net CO_2 uptake in response to a lengthening of the growing season. These results contradict our previous observations of reduced CO_2 uptake in response to longer growing seasons in the current (1999-2008) climate regime. The difference between these analyses is due to a projected increase in the frequency of rain versus snow during warmer winters of the future. Our results demonstrate the sensitivity of modeled processes to local variation in meteorology, which is often left unresolved in traditional approaches to earth systems modeling, and the importance of maintaining similarity in the timescales used in ecosystem process models driven by downscaled climate projections. More generally, our studies showed that our computer models of how this forest ecosystem is likely to respond to future climate change are wrong, given our past observations; the models predict more CO_2 uptake from the atmosphere in the future, whereas our observations suggest there will be less CO_2 uptake. The key to resolving this difference appears to be to develop a better knowledge of how the snowpack melts in the spring; a key event that dictates how this forest will respond in terms of CO_2 uptake.

Shao, P., Zeng, X., Sakaguchi, K., Monson, R.K. and Zeng, X.D. (2013) Terrestrial carbon cycle - climate relations in eight CMIP5 earth system models. Journal of Climate 26: 8744-8764. Eight Earth System Models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) were evaluated, focusing on both the net carbon dioxide flux and its components and their relation with climatic variables (temperature, precipitation, and soil moisture) in the historical (1850-2005) and representative concentration pathway 4.5 (RCP4.5; 2006-2100) simulations. Thus, we were able to evaluate future changes in climate on the carbon exchange dynamics of global ecosystems. While model results differed, their median globally averaged production and respiration terms from 1976 to 2005 agreed reasonably with available observation-based products, such as those from satellite remote sensing. Disturbances such as land use change were roughly represented but crucial in determining whether the land is a carbon source or sink over many regions in both simulations. While carbon fluxes varied with latitude and between the two simulations, the ratio of net to gross primary production (GPP), representing the ecosystem carbon use efficiency, was less dependent on latitude and did not differ significantly in the historical and RCP4.5 simulations. The linear trend of increased land carbon fluxes (except net ecosystem production) was accelerated in the twenty-first century. The cumulative net ecosystem production by 2100 was positive (i.e., carbon

sink) in all models and the tropical and boreal latitudes became major carbon sinks in most models. The temporal correlations between annual-mean carbon cycle and climate variables varied substantially (including the change of mathematical sign) among the eight models in both the historical and twenty-first-century simulations. The ranges of correlations of carbon cycle variables with precipitation and soil moisture were also quite different, reflecting the important impact of the model treatment of the hydrological cycle on the carbon cycle. Our results showed that the existing generation of earth systems models produces significant error in predicting rates of atmospheric CO_2 uptake, especially when disturbance, such as insect outbreaks occur across broad spatial areas of the globe.

Bowling, D. R., Ballantyne, A. P., Miller, J. B., Burns, S. P., Conway, T. J., Menzer, O., Stephens, B. B. and Vaughn, B. H. (2014) Ecological processes dominate the ^{13}C land disequilibrium in a Rocky Mountain subalpine forest, Global Biogeochem. Cycles, 28(4), 2013GB004686. Fossil fuel combustion has increased atmospheric CO_2 by approximately 115 μmol mol^{-1} since 1750 and decreased its carbon isotope composition ($\delta^{13}C$) by 1.7-2 parts per thousand (the so-called C-13 Suess effect). Because carbon is stored in the terrestrial biosphere for decades and longer, the $\delta^{13}C$ of CO_2 released by terrestrial ecosystems is expected to differ from the $\delta^{13}C$ of CO_2 assimilated by land plants during photosynthesis. This isotopic difference between land-atmosphere respiration (Re) and photosynthetic assimilation (A) fluxes gives rise to the $\delta^{13}C$ land disequilibrium (D). Contemporary understanding suggests that over annual and longer time scales, D is determined primarily by the Suess effect, and thus, D is generally positive (i.e., Re >A). We used a seven-year record of biosphere-atmosphere carbon exchange from the Niwot Ridge AmeriFlux site to evaluate the seasonality of (A) and (Re), and the $\delta^{13}C$ land disequilibrium, in a subalpine conifer forest. A novel isotopic mixing model was employed to determine the $\delta^{13}C$ of net land-atmosphere exchange during day and night and combined with tower-based flux observations to assess (A) and (Re). The disequilibrium varied seasonally and when flux-weighted was opposite in sign than expected from the Suess effect (i.e., D was negative, not positive). Seasonality in D appeared to be driven by photosynthetic discrimination responding to environmental factors. Our studies revealed a previously unrecognized error in our use of carbon isotope ratios to understand forest CO_2 uptake dynamics. Possible explanations for negative D include (1) changes in canopy photosynthesis over decades as atmospheric CO_2 and temperature have risen, and/or (2) post-photosynthetic fractionation processes leading to sequestration of isotopically enriched carbon in long-lived forest carbon pools like wood and soil.

Maurer, G. E. and Bowling, D. R. (2014) Dust effects on snowpack melt and related ecosystem processes are secondary to those of forest canopy structure and interannual snowpack variability. Ecohydrology (published on-line in Early View). Dust deposition lowers the albedo of snow and can significantly alter snowpack energy balance. Investigation of aeolian dust deposition in the mountains of the western U.S. has shown that these effects advance the timing of snowpack melt and spring runoff across much of the region. This is an important modifier of potential future climate change and its influence on ecosystem-atmosphere CO_2 exchanges in western US forests. Past studies have focused primarily on alpine snowpacks with little to no overstory vegetation. To evaluate the impacts of aeolian dust on ecohydrological processes in forests, we conducted a manipulative experiment in a subalpine conifer forest in Utah's Wasatch Mountains.Funding for this study was derived from the DOE grant. During the spring of 2010–2012, we added dust to the snow surface in forested plots every 1 to 2 weeks, roughly doubling the natural dust loading. We then measured snowpack ablation in control and dust addition plots, along with below-snowpack and warm season soil temperature (T_{soil}), soil water content (θ), litter decomposition rate (D), soil

respiration rate (R_s), and tree xylem water potential (ψ). Differences in ablation between control and dust addition plots were similar in magnitude to differences associated with the canopy structure of the forest. Seasonal patterns in T_{soil} and θ were similar between dust treatments and canopy structure groups. D, R_s, and ψ varied little between dust treatments, but there were significant differences between years. During our 3-year study, an unusual level of interannual variability in snowfall had the greatest effect on the soil environment and ecosystem processes. The effects of aeolian dust on snowpack mass and energy balance in our forest were slightly smaller than those associated with canopy structure, but significant. Thus, drier conditions in the western US, due to future climate change, and the increase in dust transport associated with such changes, are likely to affect ecosystem CO_2 uptake by changing the melt dynamics of the snowpack.

Maurer, G. E. and Bowling, D. R. (2014) Seasonal snowpack characteristics influence soil temperature and water content at multiple scales in interior western U.S. mountain ecosystems, Water Resour. Res., 50(6), 5216–5234. Mountain snowpacks directly and indirectly influence soil temperature (T-soil) and soil water content (θ). Vegetation, soil organisms, and associated biogeochemical processes certainly respond to snowpack-related variability in the soil biophysical environment, but there is currently a poor understanding of how snow-soil interactions vary in time and across the mountain landscape. Using data from a network of automated snowpack monitoring stations in the interior western U. S., we quantified seasonal and landscape patterns in T-soil and theta, and their dependence on snowpack characteristics over an eleven year period. This research was highly relevant to evaluating the response of carbon fluxes at the Niwot Ridge AmeriFlux tower site to climate changes involving reduced winter snowpack. Elevation gradients in T-soil were absent beneath winter snowpacks, despite large gradients in air temperature (T-air). Winter T-soil was warmer and less variable than T-air, but interannual and across-site variations in T-soil were likely large enough to impact biogeochemical processes, such as ecosystem-atmosphere CO_2 fluxes. Winter θ varied between years and across sites, but during a given winter at a site it changed little between the start of snowpack accumulation and the initiation of spring snowmelt. Winter T-soil and θ were both higher when early winter snow accumulation was greater. Summer θ was lower when summer T-air was high. Depending on the site and the year examined, summer θ was higher when there was greater summer precipitation, a larger snowpack, later snowpack melt, or a combination of these factors. We found that snowpack-related variability in the soil environment was of sufficient magnitude to influence ecosystem-atmosphere CO_2 exchange rates in snow-dominated ecosystems, such as the forest at Niwot Ridge.

Burns, S.P., Molotch, N.P., Williams, M.W., Knowles, J.F., Seok, B., Monson, R.K., Turnipseed, A.A. and Blanken, P.D. (2014) Snow temperature changes within a seasonal snowpack and their relationship to turbulent fluxes of sensible and latent heat. Journal of Hydrometeorology 15: 117-142. Snowpack temperatures from the subalpine forest at the Niwot Ridge AmeriFlux site were examined with respect to atmospheric conditions and the 30-min above-canopy and subcanopy eddy covariance fluxes of sensible Q(h) and latent Q(e) heat. In the lower snowpack, daily snow temperature changes that were greater than 1 degree C per day occurred about 1-2 times in late winter and early spring, which resulted in transitions to and from an isothermal snowpack. Past studies have shown that the timing of the isothermal snowpack at this site determines the timing of the initiation of seasonal CO_2 uptake from the atmosphere by this forest. Though air temperature was a primary control on snowpack temperature, rapid snowpack warm-up events were sometimes preceded by strong downslope winds that kept the nighttime air (and canopy) temperature above freezing, thus increasing sensible heat and longwave radiative transfer from the canopy to the snowpack. There was an

indication that water vapor condensation on the snow surface intensified the snowpack warm-up. In late winter, subcanopy Q(h) was typically between -10 and 10 W m^{-2} and rarely had a magnitude larger than 20 W m^{-2}. The direction of subcanopy Q(h) was closely related to the canopy temperature and only weakly dependent on the time of day. The daytime subcanopy Q(h) monthly frequency distribution was near normal, whereas the nighttime distribution was more peaked near zero with a large positive skewness. In contrast, above-canopy Q(h) was larger in magnitude (100-400 W m^{-2}) and primarily warmed the forest-surface at night and cooled it during the day. Around midday, decoupling of subcanopy and above-canopy air led to an apparent cooling of the snow surface by sensible heat. Our results demonstrate sensitivity in the production of an isothermal snowpack to warmer winds during the early spring, which may become more prevalent in the future due to climate change at this forest site. This type of climate change is likely to produce an isothermal snowpack earlier in the winter, and at this site this type of change will cause less summertime CO_2 uptake from the atmosphere due to earlier disappearance of the snowpack and greater mid-summer drought, which reduces forest gross primary productivity.

Zobitz, J., Moore, D.J.P., Quaife, T., Braswell, R., Bergeson, A., Anthony, J. and Monson, R.K. (2014) Joint data assimilation of satellite reflectance and net ecosystem exchange data constrains ecosystem carbon fluxes at a high-elevation subalpine forest. Agricultural and Forest Meteorology 195: 73-88. We utilized an ecosystem process model (SIPNET, simplified photosynthesis and evapotranspiration model) to estimate carbon fluxes of gross primary productivity and total ecosystem respiration of a high-elevation coniferous forest at the Niwot Ridge AmeriFlux site. The data assimilation routine incorporated aggregated twice-daily measurements of the net ecosystem exchange of CO_2 (NEE) and satellite-based reflectance measurements of the fraction of absorbed photosynthetically active radiation (fAPAR) on an eight-day timescale. From these data we conducted a data assimilation experiment with 15 different combinations of available data using twice-daily NEE, aggregated annual NEE, eight-day fAPAR, and average annual fAPAR. Model parameters were conditioned on 3 years of NEE and fAPAR data and results were evaluated to determine the information content from the different combinations of data streams. Across the data assimilation experiments conducted, model selection metrics such as the Bayesian Information Criterion and Deviance Information Criterion obtained minimum values when assimilating average annual fAPAR and twice-daily NEE data. Application of wavelet coherence analyses showed higher correlations between measured and modeled fAPAR on longer timescales ranging from 9 to 12 months. There were strong correlations between measured and modeled NEE (R^2, coefficient of determination, 0.86), but correlations between measured and modeled eight-day fAPAR were quite poor (R^2 = -0.94). We concluded that this inability to determine fAPAR on eight-day timescale would improve with the considerations of the radiative transfer through the plant canopy. Modeled fluxes when assimilating average annual fAPAR and annual NEE were comparable to corresponding results when assimilating twice-daily NEE, albeit at a greater uncertainty. Our results supported the conclusion that for this coniferous forest twice-daily NEE data are a critical measurement stream for the data assimilation. The results from this modeling exercise indicate that for this coniferous forest, average annuals for satellite-based fAPAR measurements paired with annual NEE estimates may provide spatial detail to components of ecosystem carbon fluxes in proximity of eddy covariance towers. Inclusion of other independent data streams in the assimilation will also reduce uncertainty on modeled values. This study represents a breakthrough in developing our ability to combine remotely-sensed data from satellites with flux tower data on ecosystem CO_2 uptake, to understand the seasonality of how changes in climate affect CO_2 sequestration.

Knowles, J.F., Burns, S.P., Blanken, P.D. and Monson, R.K. (2015) Ecosystem fluxes of energy, water, and carbon dioxide from mountain ecosystems at Niwot Ridge, Colorado. Plant Ecology & Diversity (published on-line in Early View). This paper represents a synthesis of climate-CO2 flux interactions derived from fourteeen years of studies at the Niwot Ridge AmeriFlux site and at an alpine flux site just upslope from the primary Niwot Ridge site. The eddy covariance (EC) technique provides a direct measure of water vapour and carbon dioxide fluxes between ecosystems and the atmosphere. This synthesis article highlights the findings of various studies that have integrated EC observations into basic meteorological, hydrological and ecological research questions in two ecosystems near Niwot Ridge, Colorado, and synthesizes these studies into a catchment-scale model of water and carbon cycling, within the context of regional disturbance and environmental change. EC was implemented continuously over subalpine forest and alpine tundra vegetation at Niwot Ridge, and resulting data were compared with discrete measurements and modelling studies. Sensible heat fluxes were generally in excess of latent heat fluxes, indicating that the forest and tundra ecosystems were moisture limited. Snow cover regulated the annual sum of primary productivity in the forest, and beneath-snow respiration represented a significant portion of ecosystem respiration at both locations. Changes in the magnitude, timing, or spatial distribution of snow are likely to have the greatest impact on ecological processes in these semi-arid mountain catchments, but possibly in compensatory ways. From this synthesis, we concluded that the tundra ecosystem, which is located upslope from the subalpine forest ecosystem, has the potential to lose carbon over time and offset forest carbon sequestration. The tradeoffs in CO2 exchange between these two neighboring ecosystems has the potential to determine the future magnitude of the Western United States carbon sink, and the existence of the tradeoffs emphasizes the need for regional perspectives on carbon budgets.

Trahan, N.A., Dynes, E.L., Moore, D.J.P. and Monson, R.K. (2015) Changes in soil biogeochemistry and microclimate following disturbance by mountain pine beetles in subalpine forests. Oecologia (in press). A recent unprecedented epidemic of beetle-induced tree mortality has occurred in lodgepole pine forests of Western North America. Here, we present the results of studies in two subalpine forests in the Rocky Mountains, one that experienced natural pine beetle disturbance and one that experienced simulated disturbance imposed through bole girdling. We assessed changes to soil microclimate and biogeochemical pools in plots representing different post-disturbance chronosequences. High plot tree mortality, whether due to girdling or beetle infestation, caused similar alterations in soil nutrient pools. During the first four years after disturbance, sharp declines were observed in soil dissolved organic carbon (DOC) concentration (45-51%), microbial biomass carbon concentration (33-39%), dissolved organic nitrogen (DON) concentration (31-42%) and inorganic phosphorus (PO43-) concentration (53-55%). Five to six years after disturbance, concentrations of DOC, DON, and PO43- recovered to 71-140% of those measured in undisturbed plots. Recovery was coincident with observed increases in litter depth and the sub-litter, soil O-horizon. During the four years following disturbance, soil ammonium, but not nitrate, increased to 2-3 times the levels measured in undisturbed plots. Microbial biomass N increased in those plots where increased ammonium was available. Our results show that previously observed declines in soil respiration following beetle-induced disturbance is accompanied by losses in key soil nutrients. Recovery of the soil nutrient pool occurs only after several years following disturbance, and is correlated with progressive mineralization of dead tree litter.

Work that remains to be covered in the manuscripts that are in preparation

In the four manuscripts that will be completed over the next few months, two concern our ongoing analysis of stable isotope composition of soil respired CO_2 in forest plots that have

experienced a pine beetle disturbance for over a decade. These two studies report data from observations made with a tunable diode laser instrument that was located in plots of a chronosequence of pine beetle disturbance. The results that will be discussed in these two papers are consistent with a shift in soil organic matter substrates that support respiration as a function of time since beetle disturbance. In the third manuscript (Trahan et al 2015), we will report on the results of our radiocarbon (^{14}C) dating of different soil organic matter chemical fractions, and on the chemical composition of these fractions (as studied using gas-chromatography pyrolysis techniques). These results largely support the conclusions from the stable isotope measurements; that a shift exists in the soil carbon cycle to favor more recalcitrant organic substrates to support soil respiration, as the less recalcitrant substrates are depleted in the first few years following a beetle disturbance. In the final manuscript (Albert et al. 2015), we describe a study using Artificial Neural Network modeling techniques to elucidate and prioritize the climate drivers of CO2 fluxes in the Niwot Ridge AmeriFlux site using fifteen years of continuous flux data. The results of this study provide independent support of the hypothesis we have derived from the other studies described above, in which winter snowpack is recognized as the primary driver linking CO2 uptake to climate variability.