Section 1. Results from Prior Support

The Niwot Ridge LTER program, the only high-elevation alpine site in the network, is located in the Colorado Front Range (COFR) and extends to the Continental Divide. Long-term monitoring at Niwot Ridge began in the 1950s with the installation of meteorological stations at the C1 subalpine forest site (3,022 m) and the D1 alpine site (3,739 m), the longest high-elevation long-term climate record in the US. The primary objective of the 2004-2010 proposal was to investigate the propensity of high-elevation areas to amplify environmental changes and to examine the potential of high-elevation ecosystems to accumulate and redistribute exogenous materials from the atmosphere and endogenous materials from the mountains. This analysis led us to a conceptual model of the coupled relationships among high-elevation ecosystems that emphasizes the importance of transport processes: the Landscape Continuum Model (LCM) (Seastedt et al. 2004). We also proposed to expand our research area from the alpine zone to include the down-gradient subalpine forest area, to extend our research footprint both regionally and internationally, and to increase our collaboration with other LTER programs.

Our 2007 site review was "highly laudable of the NWT and broadly endorses its achievements and progress across all of the five review criteria", while recommending that we would significantly benefit from (a) replacing retiring hydrologist Nel Caine; (b) maintaining the current PI as the lead on the NWT LTER renewal; and (c) identifying the appropriate role for modeling in synthesis activities. We have replaced Nel Caine's faculty position on this renewal with Noah Molotch, a snow hydrologist and modeler; Caine remains an active participant in the NWT LTER program. The PI of the 2004-2010 renewal, Williams, is the lead on this proposal. We believe that this proposal will demonstrate that the NWT LTER program has made major strides towards developing and using models in synthesis activities, while acknowledging that there is room for further improvement.

Publications. We have continued to maintain the quantity and quality of publications since the previous funding period. Peer-reviewed publications totaled 137, compared to 120 in 1998-2003, and included 10 publications in Nature, Science, PNAS, and Frontiers in Ecology and the Environment. The total number of peer-reviewed publications, books and book chapters, and graduate dissertations/theses was 164, similar to the previous funding period. The impact of our publications can be evaluated in part by a recent bibliometric analysis using the Web of Science that showed that the University of Colorado-Boulder, led by NWT LTER, was the fourth leading institution worldwide in peer-reviewed research on alpine topics (Körner 2009).

Data Sets. Searches of our data sets by keyword or investigator have increased by 300%, an average of 85 times per week in 2004-2009 compared to 26 times per week in 1998-2003. Our data sets have been accessed on average 980 times per week in 2004-2009, compared to 600 times per week in 1998-2003. Spatial data, assessed independently of other data, currently averages 120 downloads per week. A major accomplishment in 2009 was the acquisition of twelve "timeslices" of high-resolution orthophoto mosaics that span seven decades – from 1938 to 2008 – at 1.0 m to 30 cm resolution. The new imagery along with associated DEMs (2 m resolution) and other map layers has been accessed nearly 1,000 times since posting in late October 2009. We are continuing to post climate data in real time on our web site from the D1, Saddle (3,528 m), and C1 meteorological stations, and have added climate data from the Albion townsite (3,259 m), Green Lake 4 (3,570 m), and Arikaree (3,814 m) meteorological stations.

Long-Term Measurements. A recent evaluation of our climate record from 1954 to 2006 shows that Niwot Ridge is experiencing abrupt and asynchronous climate change, with the subalpine forest warmer and drier during all seasons, while the alpine tundra has experienced longer growing seasons, warmer summers, and cooler and wetter winters. We also focused on the time period 1983–2007, which roughly corresponds to the initiation of snowpack measurements in the Rocky Mountains by the SnoTel program, and found that average annual air temperatures increased by 1.1°C per decade at C1 and by 1.0°C per decade at D1 (Clow in press). These results suggest that alpine and subalpine climate signals are not as decoupled as they appear, but rather that across a relatively short elevational gradient (700 m elevation change, 6 km distance), synoptic and landscape-scale processes react differently to and differentially modify a prevailing hemispheric signal.

Shifts in the thickness and duration of lake ice cover over the last three decades are consistent with this apparent differential response of alpine and subalpine climate. At subalpine Silver Lake, the lowest in the system, the duration of ice cover has been reduced by 1.4 days/year, whereas at alpine Green Lakes 4 and 5 the reduction has been only 0.65 days/year. The sensitivity of alpine areas to changes in climate, and the potential for nonlinear responses, is also illustrated by the response of Arikaree Glacier to a severe drought at the turn of the century. From the mid 1960s to the late 1990s, the annual net balance varied around zero. From 1997 to 2007, it was consistently negative, most markedly in the drought years of 2001 and 2002 when the glacier lost about 5.2 m of ice. In contrast, the last two years have shown a slight positive mass balance. The general decrease in mass balance on this and other glaciers in the Colorado Front Range appears to be driven by increases in summer air temperatures over the last decade and to be independent of winter snowfall amounts or air temperatures (Hoffman et al. 2007).

The NWT LTER program has participated in the National Atmospheric Deposition Program (NADP) since the early 1980s, maintaining the highest-elevation site in the US at 3,520 m at the Saddle site on Niwot Ridge (CO02), and also the forested Sugarloaf site (CO94) at 2,524 m. We added a third site in 2008, CO90 at 3022 m, which is co-located with the climate station at C1 and provides information on atmospheric deposition to support our expanded research activities in the subalpine forest ecosystem. Annual deposition of inorganic nitrogen (N) in wetfall at the Niwot Ridge NADP site and other areas in and near the Colorado Front Range has increased significantly over the last several decades (Williams and Tonnessen 2000; Burns 2004; Porter and Johnson 2007). Regional patterns of nitrate sources in precipitation and effects on high-elevation lakes from Glacier National Park south to the Colorado/New Mexico border were evaluated using the dual isotope approach of nitrate (δ^{18}O-NO3 and δ^{15}N-NO3), showing that the southern Rockies are a hot spot of high nitrate deposition from anthropogenic sources and that deposition of nitrate in wetfall may enhance the amount of nitrate in lakes through a combination of direct and indirect processes such as enhanced nitrification (Nanus et al. 2008). Nutrient enrichment experiments in mesocosms at Green Lake 4 showed that this phytoplankton community is phosphorus (P)-limited throughout the summer and that additional inputs of N are not expected to directly alter the productivity of the phytoplankton community (Gardner et al. 2008). A comprehensive study showed atmospheric deposition of N has increased the stoichiometric ratio of N and P in high-elevation lakes in Norway, Sweden, and Colorado (including NWT LTER), and, as a result, patterns of ecological nutrient limitation (e.g., phytoplankton growth) have shifted from generally N-limited to consistently P-limited (Elser et al. 2009a). Work at our highest-elevation snow-dominated sites (talus soils) shows that the microbial community is co-limited by P and C (King et al. 2008) and that these soils are dominated by organisms (e.g., chytrids) that are normally thought to be aquatic (Freeman et al. 2009a). These observations revealed an unexpected connection between aquatic and terrestrial systems that we will further explore in the coming years.

Within the Saddle, snow depth has been measured bimonthly since 1982 on a research grid 550 m long and 400 m wide, marked by 88 stakes on 50-m centers, which encompasses the six major plant communities (Litaor et al. 2008). At each of the saddle grid points, permanent 1 m^2 plots were established in 1989 to measure species composition, and primary productivity has been measured at specific points along a 10 m line transect associated with each grid point. A point-quadrat method was initiated in 1989, providing consistent data collection that permits comparisons across years. Over the last 16 years, *Acomastylis* has declined by 12% in permanent plots (P=0.03) and *Deschampsia* cover has shown an increasing trend (P=0.08). While we cannot be sure what is driving the changes in these permanent plots, rising N deposition is one possibility. These results are consistent with the hypothesis that increased N availability results in a threshold pattern of response in this system, similar to what has been found in some (but not all) long-term N fertilization experiments (Aber et al. 1998; Fenn et al. 1998; Shaver et al. 2001; Pregitzer et al. 2004; Sinsabaugh et al. 2005; Zeglin et al. 2007), and suggest that a shift in feedbacks could be occurring.

Litaor et al. (2008) modeled the interrelationships of snow depth, snow water equivalent (SWE), snow disappearance rate, soil moisture, attributes of alpine plant communities, and selected terrain factors at the Saddle site over the 20+ years of record. They reported that soil moisture was significantly correlated ($r^2 = 0.7$, $P < 0.001$) with snowfall amounts and terrain factors; in turn, a species richness index was significantly correlated with snow depth and soil moisture ($r^2 = 0.7$, $P < 0.001$), thereby confirming the importance of snow for some attributes of alpine plant communities. Species richness has increased significantly over Saddle all plots ($p < 0.05$) from 1995 to 2008. We've supplemented these long-term measurements of plant species composition at the Saddle site by participating in the international Global Observation Research Initiative in Alpine Environments (GLORIA). The goals of GLORIA are to establish a global network of monitoring sites using uniform procedures to evaluate global climate change effects on mountain biodiversity for the next 100 years, and to contribute this information in an international effort to help mitigate loss of plant diversity and habitat in mountain ecosystems. We established GLORIA monitoring plots on the summits of Albion, Kiowa, and Niwot Peaks during the summer of 2006 with LTER supplemental funds.

Long-term N-fertilization plots (8 years) were used to empirically estimate the N critical load for changes in alpine plant community composition at the Saddle site on Niwot Ridge. Bowman et al. (2006) estimated that N critical loads (total deposition) were 4 kg N ha^{-1} yr^{-1} for change in individual species and 10 kg N ha^{-1} yr^{-1} for overall community change. A recently completed study on Niwot Ridge at these experimental plots showed the potential for loss of acid neutralizing capacity and decrease in pH in alpine soils is high at moderate levels of N deposition (> 20 kg N ha^{-1} yr^{-1}) (Lieb et al. in review). As part of a joint Niwot LTER - Slovak ILTER project in the Tatra mountains, we found that the addition of NH_4NO_3 led to soil acidification and expected losses in nutrient base cations, but also unexpected losses of extractable aluminum (Al^{3+}) while soil acidity and extractable iron (Fe^{3+}) concentrations increased (Bowman et al. 2008). Experimental manipulations of plant communities in long-term N-fertilization plots indicate that (i) after several years of tolerance to high N availability, the abundance of the N-conservative species in our study starts to rapidly decline (from 40 to 10%), and (ii) the changes in plant species abundance at high N is accompanied by a decline in microbial biomass and changed extracellular enzyme activities (Suding et al. 2008). Chronic N fertilization at NWT induced significant shifts in soil carbon dynamics that correspond to shifts in microbial community structure and function (Nemergut et al. 2008). Fifteen years of microbial research at Niwot Ridge has shown that microbial turnover of soil nutrients is about 10 times faster than by plants. This new understanding of the year-round turnover and succession of microbial communities allows us to propose, for the first time, a temporally explicit N cycle that provides mechanistic hypotheses to explain both the loss and retention of dissolved organic N (DON) and inorganic N (DIN) throughout the year in terrestrial ecosystems, not just alpine tundra (Schmidt et al. 2007).

Process-Based Research Highlights. NWT LTER has long been a leader in biogeochemical cycling under the seasonal snowpack (Brooks et al. 1996; 1997; 1998; Schadt et al. 2003), and we continued that research tradition with a special issue of Biogeochemistry (Williams et al. 2009a). A novel *in situ* experimental system was developed at the 3,340 m Soddie site to continuously sample trace gases at hourly time-steps from above and within the snowpack for the duration of seasonal snow cover (Seok et al. 2009). The suite of chemical species investigated includes carbon dioxide (Liptzin et al. 2009), nitrous oxide (Filippa et al. 2009), nitrogen oxides (Helmig et al. 2009a), ozone (Bocquet et al. 2007), and volatile inorganic and organic gases (Helmig et al. 2009b).

At the C1 subalpine forest site, we used eddy covariance measurements along with beneath-snow measurements of CO_2 flux and found that soil respiration under the snowpack in the winter was estimated to contribute 35–48% of the total wintertime ecosystem respiration, and 7–10% of the total annual ecosystem respiration (Monson et al. 2006a). We used a six-year record of net ecosystem CO_2 exchange from the same flux tower to show that years with a reduced winter snowpack are accompanied by significantly lower rates of soil respiration because of a unique soil microbial community that exhibits exponential growth and high rates of substrate utilization at the cold temperatures that exist beneath the snow; e.g., less snow and longer growing seasons decrease annual net carbon accumulation because of water stress (Monson et al. 2006b). We complemented the eddy covariance tower at C1 with a similar tower in the alpine tundra, which to our knowledge is the highest-elevation alpine tundra eddy covariance site in the world (Blanken et al. 2009). Surprisingly, winter respiration loss at the alpine site of 164 g C m^{-2} was an order of magnitude larger than the net uptake of 16 g C m^{-2} during the summer, clearly a situation not sustainable over centuries.

Liu et al. (2004) used geochemical and water isotope tracers to show that less than half of the annual streamflow in the Green Lakes Valley is “new water” from snowmelt; groundwater is much more important in high-elevation catchments than previously thought. Based on these results, seven groundwater wells were installed in the fall of 2005 with supplemental funding. Using applied tracers, Miller et al. (2006) showed that fulvic acids are involved in rapid electron-transfer processes in and near the stream channels, and may be important in determining ecological energy flow at the catchment scale. The high nitrate levels exported from rock glaciers are believed to be a result of microbial activity within the glacier (Williams et al. 2006; 2007), another example that microbes can live in the most extreme environments. Perhaps most importantly, McKnight’s group has found a way to control slippery aquatic algae – known as “rock snot” – that pester tubers, fishers, and native insects in Boulder Creek. High creek flows keep *Didymosphenia geminata* (informally “didymo”) in check, and controlled flow releases from reservoirs during summer could limit the impact of this nuisance species in streams in the Colorado Front Range (Miller et al. 2009).

Network Participation, Cross-site Research, and Synthesis. NWT LTER has continued to be a strong participant in network activities, including the following: (a) Seastedt was co-chair of the 2006 ASM and Williams was a member of the 2009 ASM planning committee; (b) NWT currently sits on the LTER Executive Board; (c) Ackerman served on the IM Executive Committee; (d) several NWT personnel participated in LTER expansion activities over the last several years, with Williams chairing the working group on climate change and participating in writing the decadal plan; (e) Bourgeron was elected in August 2006 to a 5-year term as chair of the ILTER science committee (concomitant with his term as co-USA ILTER chair); (f) NWT participated in producing the NSF brochure "*Translating Science for Society*", contributing four of the published pictures and one of the case studies; (g) Williams gave a plenary talk at the 3rd Annual LTER mini-symposium and Neff gave one at the 8th Annual LTER mini-symposium.

Suding was the lead on "*Cross-site Synthesis on Species Response to Nitrogen Fertilization*", which aims to understand effects of enhanced N fertilization at the species level. That effort has lead to the formation of the productivity-diversity-traits network, which has compiled a database of 575 species responses to fertilization from 35 nitrogen experiments conducted at 10 sites in the LTER network (Cleland et al. 2008). It has generated important findings related to species loss, trait relationships, and environmental contingencies related to increased N availability (Suding et al. 2005; Collins et al. 2008; Pennings et al. 2005; Clark et al 2007). NWT was one of four LTER sites to participate in a program to conduct simulations of hydrochemical responses to atmospheric N deposition for mountain sites around the US (Hartman et al. 2009). Taylor and Townsend (in press) evaluated stoichiometric controls of organic carbon-nitrate ratios along a hydrologic continuum from Niwot Ridge to the sea (including 8 LTER sites) and found evidence that resource stoichiometry (organic C:NO3), rather than bulk supply, may be the predominant influence on nitrate in surface and soil waters by regulating a suite of microbial processes which couple DOC and nitrate cycling. Data sets (379) from three cold-region LTER sites were used in an exciting breakthrough to understand the components of dissolved organic matter (DOM) using fluorescence characteristics modeled by parallel factor analysis (Cory and McKnight 2005). Building on this approach, an LTER intersite comparison of the chemical quality of DOM was conducted by R. Jaffe (FCE-LTER) and McKnight based on a meeting hosted by NWT LTER in 2005; results from 20 LTER sites showed that DOM quality varied greatly among environments, even those with similar DOC concentrations (Jaffe et al. 2008). We have begun a cross-site collaborative effort through supplemental funding with other LTER sites to (a) use spatial representations of land cover and land use to identify patterns of landscape change in regions in and around LTER sites; and (b) integrate existing social data into theories and models of ecological change and their implications for human livelihood.

During this last renewal, NWT LTER has strongly increased its international collaboration: NWT hosted University of Torino graduate student Gianluca Filippa to conduct research on trace gas flux through snow (Filippa et al. 2009; Liptzin et al. 2009), along with his advisor Michele Freppaz, a high-elevation soil scientist (Maggioni et al. 2009; Freppaz et al. in press). Chris Randin from the University of Lausanne conducted two stints as a post-doc from September 2007 to September 2008 and again from January 2009 to May 2009: "Towards mechanistic models to predict the distributions of alpine plant species under climate change". Yanmei Xiong is a Ph.D. candidate in her fifth year at the South China Botanical Garden, and joined the LTER group and Seastedt's lab in January of 2009 to work on soil processes in response to the mountain pine beetle outbreak (Xiong et al. submitted). Brian Seok, a graduate student at NWT LTER with Helmig, had an internship in 2009 at the Crown Research Institute in New Zealand, with funding from the NSF East Asia and Pacific Summer Institute (EAPSI) program, to study carbon-atmosphere exchanges. NWT LTER hosted two international workshops with supplemental funding from NSF OISE: (a) a workshop on alpine ecology in Lausanne, Switzerland from 6-10 October 2008 in collaboration with the University of Lausanne (Williams et al. 2009b); and (b) a workshop on mountain hydrology in Kathmandu Nepal from 26 October to 1 November 2009 in collaboration with Kathmandu University.

Section 2. Proposed Research

INTRODUCTION AND CONCEPTUAL FRAMEWORK

Human-driven alterations of the global environment – including changes to climate, atmospheric composition, nutrient cycles, hydrologic cycling, and ecosystem structure – are now pervasive throughout the world, and accelerating (e.g., Steffen et al. 2007; IPCC 2007; Galloway et al. 2008; Röckstrom et al. 2009). While such changes have brought substantial benefits to humanity (e.g., Smil 2001; Kareiva et al. 2007; Townsend and Howarth 2010), they are often accompanied by increasingly detrimental outcomes for both people and ecosystems (Galloway et al. 2008; Carpenter 2009), including those in and around the NWT LTER (Bowman and Steltzer 1998; Williams and Tonnessen 2000; Bowman et al. 2006). Indeed, while some remote portions of high-elevation ecosystems manage to avoid direct transformation via land use change (Bourgeron et al. 2009), taken as a whole, alpine tundra and montane forests have been identified as particularly sensitive to, and impacted by, the array of human-induced environmental changes that currently challenge society (IPCC 2007; Williams et al. 2002).

More than one-sixth of the world's population lives in river basins fed by snow or glacier melt, and thus seasonal shifts in stream flow and possibly reduced low flows caused by glacial retreat or decreased snow water storage are likely to adversely affect human and ecosystem functioning, particularly in semiarid regions (Parry et al. 2007). As a result, it is urgent that we improve our understanding of how hydrologic processes, biogeochemical cycling, and species distribution and abundance in high-elevation catchments will respond to a combination of changes in climate, atmospheric deposition of pollutants such as dissolved inorganic nitrogen ($NH_4^+ + NO_3^- =$ DIN), and potential changes in the quantity and quality of dust deposition. Atmospheric deposition of DIN in high-elevation lakes of Colorado has already altered ecological processes, such as biogeochemical cycling, trophic dynamics, and biological diversity – even in systems far from direct human disturbance (Elser et al. 2009a,b). Neff et al. (2008) report that following the increased western settlement of the United States during the nineteenth century, dust load levels in the Colorado Rockies increased by 500% above the late Holocene average (see Figure 1 for examples). This larger dust flux resulted in a more than fivefold increase in inputs of K, Mg, Ca, N, and P to alpine ecosystems, with implications for surface-water alkalinity, aquatic productivity, and terrestrial nutrient cycling. Continued increases in mean air temperature and drought severity in the Western U.S. are expected to increase dust emissions (Marshall et al. 2008), which in turn will affect snowmelt (Painter et al. 2007) and the phenology of seasonally snow-covered areas (Steltzer et al. 2009). Further, rising temperatures and the associated upward advance of treeline (Grace et al. 2002) may mobilize larger amounts of biological aerosols, such as bacteria, fungi, and pollen.

Small changes in the flux of energy, chemicals, and water to high-elevation catchments may invoke large changes in climate, ecosystem dynamics, and water quantity and quality (Williams et al. 2002). The presence of a seasonal snowpack in alpine environments may amplify climate signals because of the storage and release of liquid water, solutes, and particulates from the seasonal snowpack (Seastedt et al. 2004). Moreover, meteorological, hydrological, cryospheric, and ecological conditions change greatly over relatively short distances in alpine areas because of their rugged terrain, and thus the boundaries between these systems are sensitive to small environmental changes (e.g., Erickson et al. 2005). The harsh conditions characteristic of these environments suggest that organisms in alpine ecosystems are on the razor's edge of tolerance (Williams et al. 1998). Consequently, organisms – and the biogeochemical processes mediated by them in high-elevation catchments – are notably vulnerable to small changes in climate and other environmental parameters (Williams and Tonnessen 2000; Bowman et al. 2006).

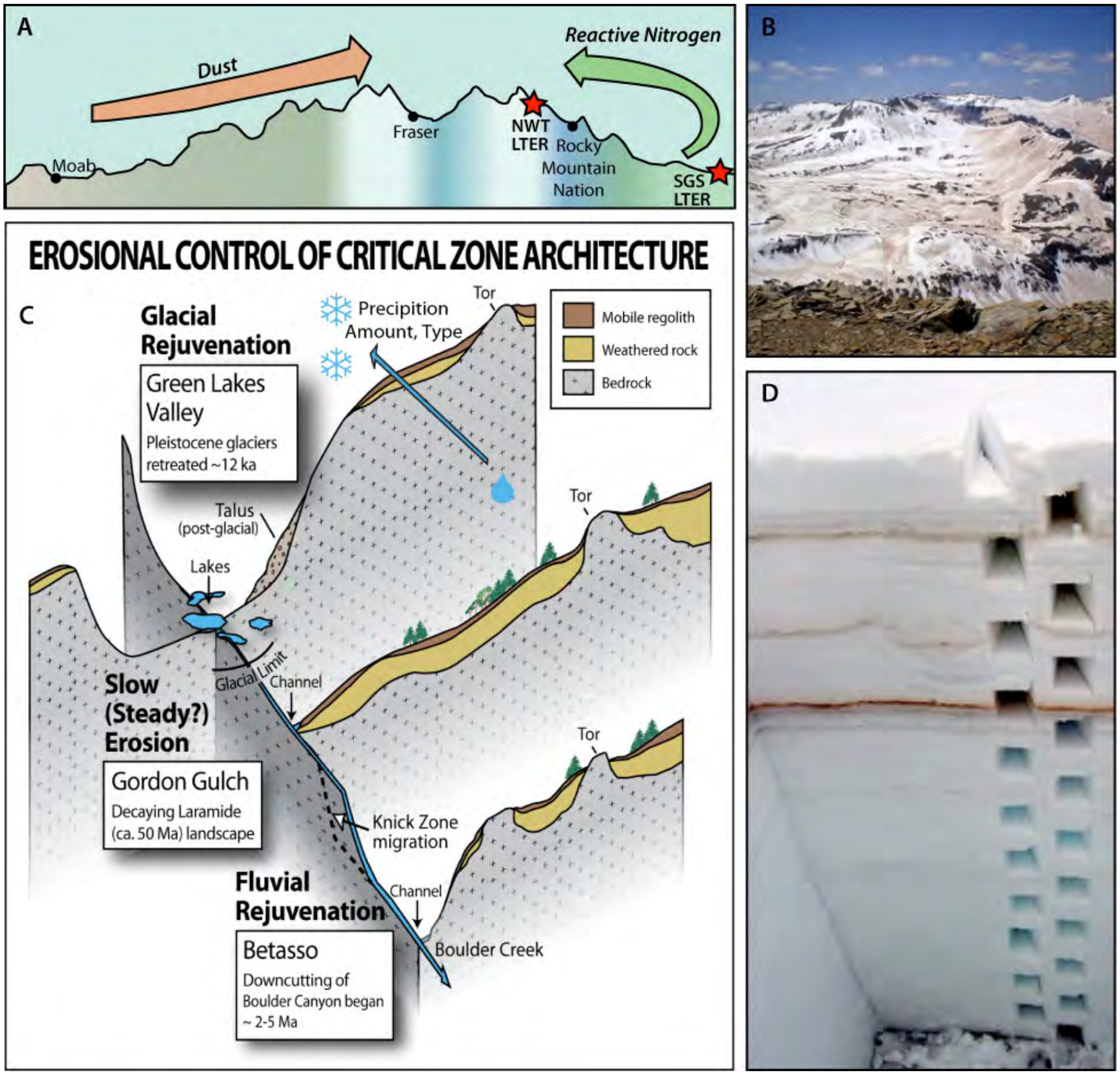

Figure 1. Regional activities of the NWT LTER program. **A)** NWT LTER is partnering with NEON to establish a transect across the mountains from the Great Plains to the Colorado Plateau to address source-receptor relationships among land-use change, climate change, and human activities on movement of dust, nutrients, and water. We call this area the Prairie, Peak, Plateau (P3) region of the U.S. west. **B)** Dust-laden snow in the San Juan Mountains, Colorado (McKenzie Skiles, Snow Optics Laboratory). **C)** NWT LTER is one of three headwater catchments that comprise the Boulder Creek Critical Zone Observatory (BC-CZO). D) Dust layers in the seasonal snowpack of the Colorado Rocky Mountains (Chris Landry, Center for Snow and Avalanche Studies).

And yet, not all aspects of the alpine realm are likely to display such high sensitivity. The very harshness that characterizes such systems can lead to the development of community and ecosystem types that are notably resilient to some aspects of change. For example, in the dry meadow tundra that characterizes some portions of NWT, we find that plant species use resource cycling to their own advantage, creating plant-soil feedbacks that boost the system's resilience to external changes (Steltzer and Bowman 1999; Suding et al. 2004; Suding et al. 2008). In contrast, many other portions of the landscape – ranging from alpine meadows, to subalpine forests, to aquatic ecosystems – demonstrate a worrisome sensitivity to human-induced change (Williams et al. 2002; Bowman et al. 2006; Monson et al. 2006b; Flanagan et al. 2009). Here, we argue that the heterogeneity of NWT's landscape provides a unique setting for testing general ecological notions of resilience and sensitivity (e.g. Holling 1986; Pfisterer and Schmid 2002; Walker et al. 2004; Cumming and Collier 2005; Seastedt et al. 2008), as well as for improving our ability to forecast how and where high-elevation systems will change in the coming decades.

Forecasting such change presents significant challenges, as we believe many portions of the high-elevation landscape display non-linear or "abrupt" behavior, meaning that they are more easily pushed or "tipped" across critical thresholds. The notion of tipping points was originally developed by Malcolm Gladwell (Gladwell 2000) in the context of epidemiology. The term is used in various ways, including the recent discussion of planetary boundaries to environmental change as described in Röckstrom et al. (2009). Here, we use the definition advanced by the Advisory Committee for Environmental Research and Education in a report to NSF (AC-ERE, 2009), which describes a tipping point as: "The occurrence of a critical threshold at which even a small stress or perturbation can result in an abrupt shift in the state of a system or in its dynamics." For example, terrestrial amplification of high-latitude warming caused by changes in the albedo of snow cover (Chapin et al. 2005) has pushed Arctic tundra beyond a "tipping point" (Foley 2005) that may mark the system's departure from behavior known in recent Earth history (Overpeck et al. 2005). Similarly, we believe the amplification of drivers such as climate change, N deposition, and dust deposition may be propelling high-elevation ecosystems at mid-latitudes into states not experienced in modern times.

Our ongoing research at the NWT LTER, and our attempts to discern which portions and aspects of high elevation regions are most sensitive to change, are shaped heavily by the interface of two conceptual models. The Landscape Continuum Model (LCM) (Seastedt et al. 2004) describes high-elevation systems as strongly influenced by both climatic and topographic drivers (Figure 2). The model explicitly links terrestrial ecosystems to each other and to aquatic ecosystems. The crux of the model posits strong linkages among landscape components as a result of transport processes caused by high-elevation systems' extreme topography. These transport agents are what cause the biogeochemical amplification and attenuation of processes unique to alpine landscapes. For example, hot spots of DIN accumulation were proposed to be in alpine aquatic systems and at treeline in terrestrial ecosystems (circles in Figure 2). The second conceptual model focuses on the resilience concepts offered in the Panarchy Model put forward by Gunderson and Holling (2001), which, when examined in the context of global environmental change, gave rise to the novel ecosystems concept (e.g., Hobbs et al. 2006; Seastedt et al. 2008). The interplay of these two models argues that the biogeochemistry of ecosystems can be moved into wholly new states by human actions, but that these new states generally require both new abiotic and biotic conditions (Hobbs et al. 2009) (Figure 2).

Applying these concepts to the NWT region, we expect that the combination of changes in climate, atmospheric deposition, and biological community composition will create rapid shifts in

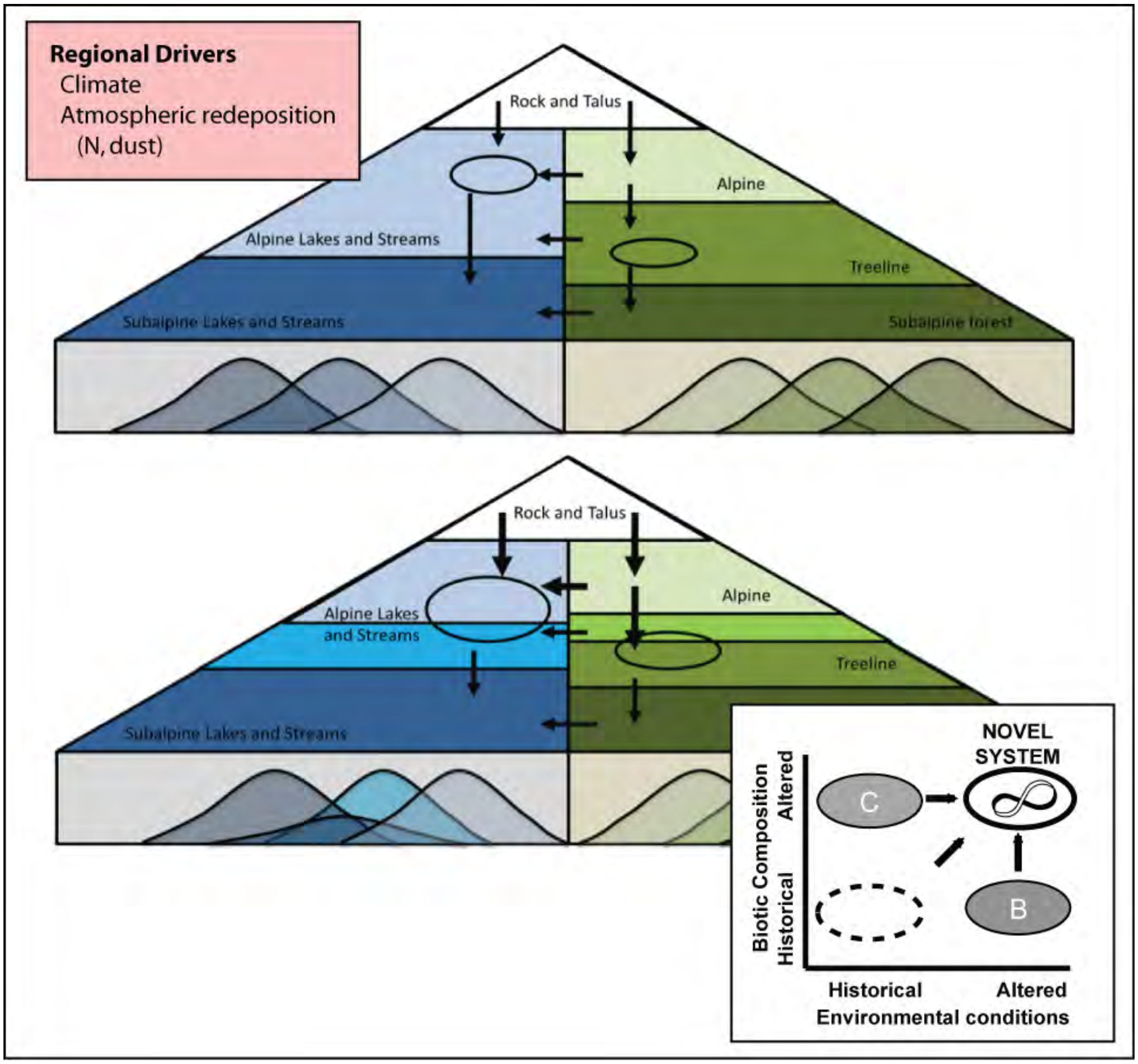

Figure 2. Graphic of the landscape continuum model (LCM). Blue is aquatic, green terrestrial; on an elevational gradient. **Top panel:** arrows represent nutrient flows, circles are hot spots of DIN accumulation. **Bottom panel:** Hypothesized changes due to climate change, deposition of N, and dust. Species will move up the mountain, particularly invasives. System will get leakier (larger arrows) and the zones of DIN accumulation will grow and represent tipping points where new states may emerge (the brighter blue and green). These changes may "tip" the current ecosystem into new states not experienced in recent Earth history, so-called "novel ecosystems".

biogeochemical and hydrologic conditions. For example, we expect that rising N deposition will rapidly increase the transport of DIN from terrestrial to aquatic portions of the landscape (larger arrows, Figure 2), not only for hydrologic and topographic reasons (e.g., unvegetated areas combined with snowmelt pulses), but also because of deposition-driven shifts in vegetation that foster quicker rates of N turnover, and hence, greater overall N loss (Miller et al. 2007). In addition, rock and talus areas near mountaintops will grow in area as glaciers recede and permafrost melts, resulting in the export of even more nitrate (Schmidt et al. 2008). The zones of DIN accumulation will therefore grow and represent tipping points where new states may emerge (the brighter blue and green in Figure 2). Similarly, the combination of climate change with direct human disturbance of forested regions may cause species to move up the mountain, with the advent of invasive species potentially tipping treeline and alpine areas into novel ecosystems. The tendency for changes in climate and atmospheric deposition to be amplified in the wettest portions of the landscape may make wet meadows and aquatic ecosystems especially vulnerable to non-linear change. Thus, there is a debate about whether high-elevation species may be pushed off the top of mountains by climate change and other perturbations (Thuiller et al. 2005; Colwell et al. 2008; Loarie et al. in review) versus high-elevation ecosystems being much more resilient (Randin et al. 2009).

The Front Range of the Rocky Mountains of Colorado and the western Great Plains include the mountains east of the Continental Divide, which flatten into the foothills and eastward through the plains. This region has been shaped by numerous anthropogenic disturbances and conflicts between property rights, conservation efforts, and public policy. For example, the area was hard hit by the Dust Bowl in the 1930s, while concurrently one of the largest federally sponsored water projects diverted water from the Rocky Mountains' western slope to Front Range communities, paving the way for an explosion in population in more recent decades that has significantly altered air quality, regional climate, plant communities, soils, and the distribution of wildlife in the region (AC-ERE, 2009). The alpine/subalpine systems in the Colorado Front Range provide important and critical ecosystem services, including cultural services (aesthetic value, recreation/ecotourism), provisioning (freshwater), and regulating (water regulation, climate regulation (C storage), and natural hazard regulation (fire, insect outbreak). A regime shift or a tipping point, then, initially represents a loss of resilience, in that former functions, structures, feedbacks, and therefore identities (Cumming and Collier 2005) give way to new stable states, some representing novel ecosystems (Williams and Jackson 2007; Seastedt et al. 2008). The impact of such changes on ecosystem structure and function – including the creation of new stable states and/or novel ecosystems – will extend to ecosystem services, their interactions, and trade-offs. For example, compromised resiliency of mountain landscapes has resulted in large-scale insect outbreaks (Kurz et al. 2008) and fires (Westerling et al. 2006) in the last ten years, both in Colorado and throughout the Mountain West.

Our over-arching research priority is to *anticipate* tipping points in high-elevation systems. Because this system is both dynamic and extraordinarily heterogeneous when it comes to the abiotic and biotic drivers that affect core ecosystem function (*sensu* Townsend et al. 2008), we cannot simply look to the past to predict the future. Thus, we will continue and augment long-term, on-going studies to provide baseline information on the velocity of rates of change (e.g., Loarie et al. 2009). We will also conduct manipulative experiments to help define boundaries of likely change or alternate states that high-elevation ecosystems could assume if pushed past their tipping point(s). Our aim is to recognize early warnings, define boundaries of potential impacts, and begin developing mitigation plans for ecosystem services, allowing us to answer questions like the following:

1. Do manipulations that mimic future climate effects result in shifts predicted by the "uphill" suite of global environmental change factors? For example, as temperatures rise, are

ecosystems with 'nowhere to go,' such as mountains, more threatened (Thuiller et al. 2005; Nogués-Bravo et al. 2006; Colwell et al. 2008)?

2. If not, where does the space-for-time substitution break down? What processes impart resilience or lead to tipping points that cannot be predicted from current patterns in species distribution and ecosystem processes?

3. We expect tipping points a) when abiotic tolerances of organisms that have particularly strong ecosystem effects are exceeded, and b) when strong fine-scale feedbacks that may initially confer resilience break down as broad-scale drivers overwhelm fine-scale processes (e.g., Chapin et al. 2006; Groffman et al. 2006; Smith et al. 2009). In addition, we expect biogeochemical and hydrologic transfer processes and spatial heterogeneity to either amplify or attenuate system response to broad-scale drivers (Peters et al. 2007).

We organize this proposal on the hydrological connectivity of terrestrial-aquatic systems, and around the environmental components that give high-elevation systems their unique heterogeneity: land-atmosphere interface, barren soils, alpine tundra, forest-alpine ecotone (treeline), subalpine forests, and aquatic systems (Figure 3). Common among all environments is that hydrological transitions, either episodic changes in water availability or hydrologic transport of reactants, result in disproportionately high rates of C and N cycling and variable responses of flora and fauna.

LAND-ATMOSPHERE INTERACTIONS

We will continue our extensive monitoring of climate, snow properties, and the chemistry of precipitation (see Figure 4 for site locations), which have shown large changes and have tipped the Arikaree Glacier into a negative mass balance (Figure 5), as described in the prior section. We propose to supplement these long-term measurements of land-atmosphere interactions with the following studies.

Eddy covariance measurements of net ecosystem exchange (NEE). We have successfully completed two years of automated (30-min) measurements of NEE over alpine tundra using the eddy covariance technique. Our preliminary results (Blanken et al. 2009) revealed that at NWT carbon loss through ecosystem respiration is much greater than by carbon uptake through photosynthesis, indicating that the alpine tundra is no longer at steady state and that carbon loss to the atmosphere is occurring at a much faster rate than previously thought. We will evaluate the hypothesis that climate change is already affecting the alpine tundra of Niwot Ridge by forcing 'old' soil carbon (likely stored over decades to millennia) to be rapidly respired and released into the atmosphere. We propose to complement the eddy covariance methods by a) instrumenting five soil automated respiration sites within the footprint of the eddy covariance tower using techniques described by Riveros-Iregui et al. (2008), b) using a portable static chamber to capture the spatial variability in soil CO_2 emissions, and c) using $\delta^{14}C$ to determine the age of the respired carbon following the techniques developed for NWT soil carbon by Neff et al. (2002).

Mercury. We propose to add a Tekran Model 2537 gaseous elemental mercury (GEM) monitor to the suite of trace gases (CO_2, N_2O, O_3, etc.) we measure under the snowpack at the Soddie site (Figure 6). Mercury is a worldwide pollutant that has been shown to accumulate in mountain snowpacks (Ferrari et al. 2002) and bioaccumulate in fish and amphibians at remote sites (Bank et al. 2007). Following Dommergue et al. (2003), as much as 90% of the mercury content of a snowpack may enter watersheds, particularly in combination with DOC (Mast et al. 2005). The snowpack can act both as a sink and a source of mercury to the atmosphere depending on the environmental conditions (e.g., temperature, irradiation, presence of water layers around snow

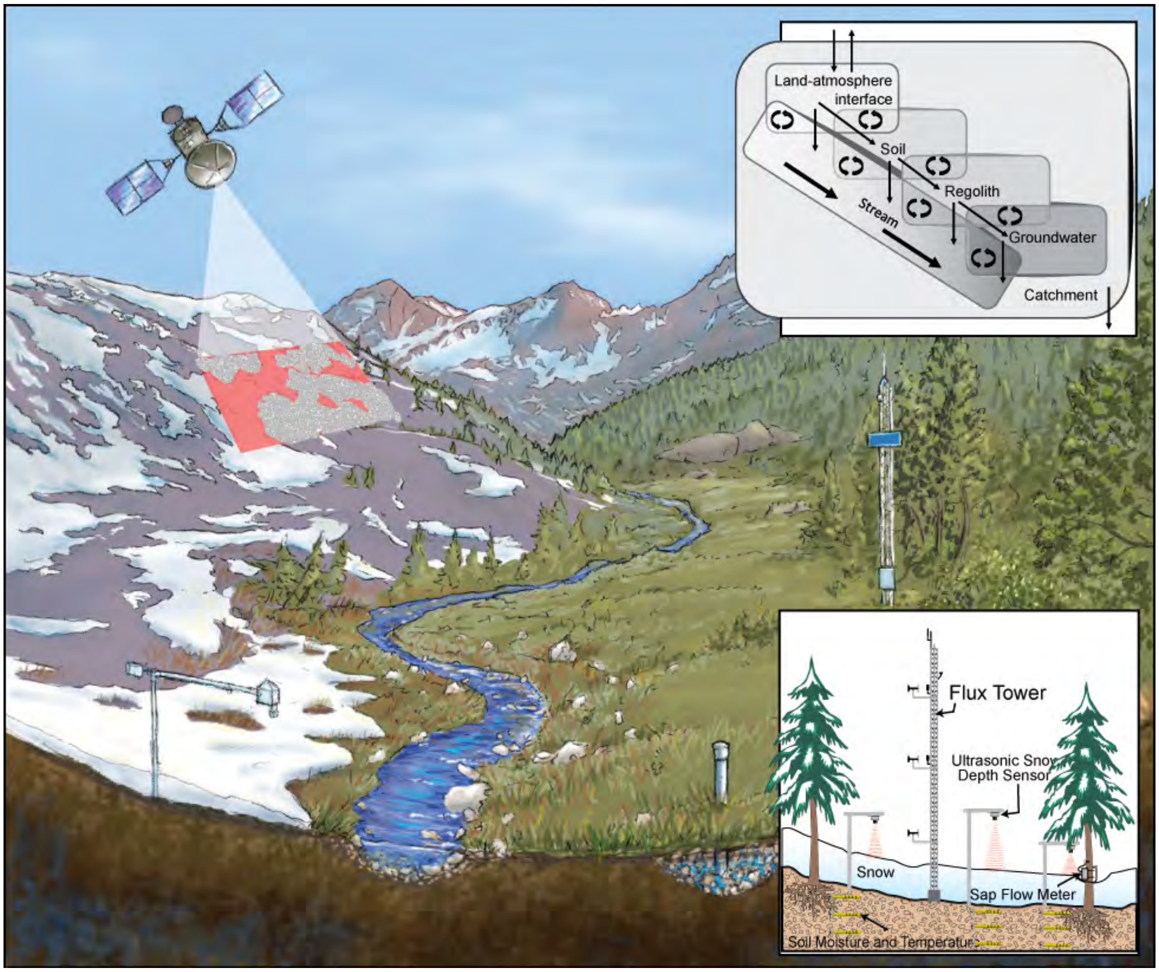

Figure 3. A graphic that illustrates how we can synthesize and integrate our understanding of hydrological, ecological, and socio-economic processes into a predictive understanding of our key ecosystem services at the catchment scale, and then use that understanding at the regional scale. Our approach is based on a multiscaled sampling strategy, using systematically deployed ground-based sensors, experimental manipulations, remote sensing of snow and other variables, and emphasis on consistent data standards.
Upper panel: hydrological connectivity of terrestrial-aquatic systems, around those environments that characterize the heterogeneity of high-elevation systems: land-atmosphere interface, barren soils, alpine tundra, forest-alpine ecotone (treeline), subalpine forests, and aquatic systems. Common among all environments is that hydrological transitions, either episodic changes in water availability or hydrologic transport of reactants, result in disproportionately high rates of C and N cycling and thus responses of flora and fauna (adapted from Lohse et al. 2009).
Lower panel: ecohydrologic instrument clusters designed to observe sub-flux footprint variability in water and energy fluxes across gradients in vegetation cover. Each cluster consists of nine ultrasonic snow depth sensors positioned in a stratified sampling pattern with respect to proximity to trees, with three sensors in each of three classes: under-canopy, canopy-edge, and open areas. Beneath each ultra-sonic snow depth sensor are vertical profiles of soil moisture and soil temperature measurements down to 1-m below the surface.

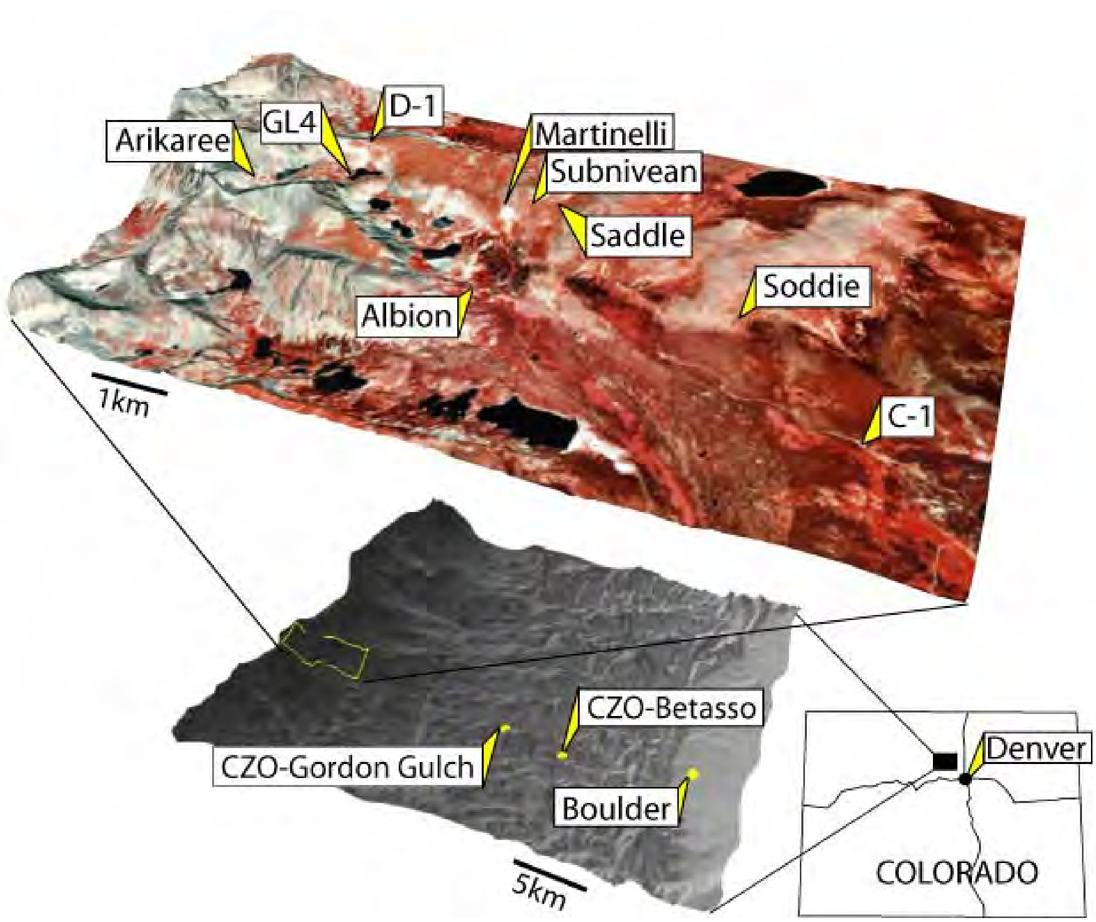

Figure 4. Site map of the NWT LTER program. C1 and D1 are historical meteorological sites. Much of the alpine tundra research is conducted on and near the Saddle site. There is an Ameriflux eddy covariance tower at C1 and an alpine tundra eddy covariance site between the Saddle and Soddie areas. Arikaree is the Arikaree Glacier. GL4 is the main aquatic site in the Green Lakes Valley. Gordon Gulch and Betasso are test basins within the Boulder Creek Critical Zones Observatory (BC-CZO), as is the NWT LTER.

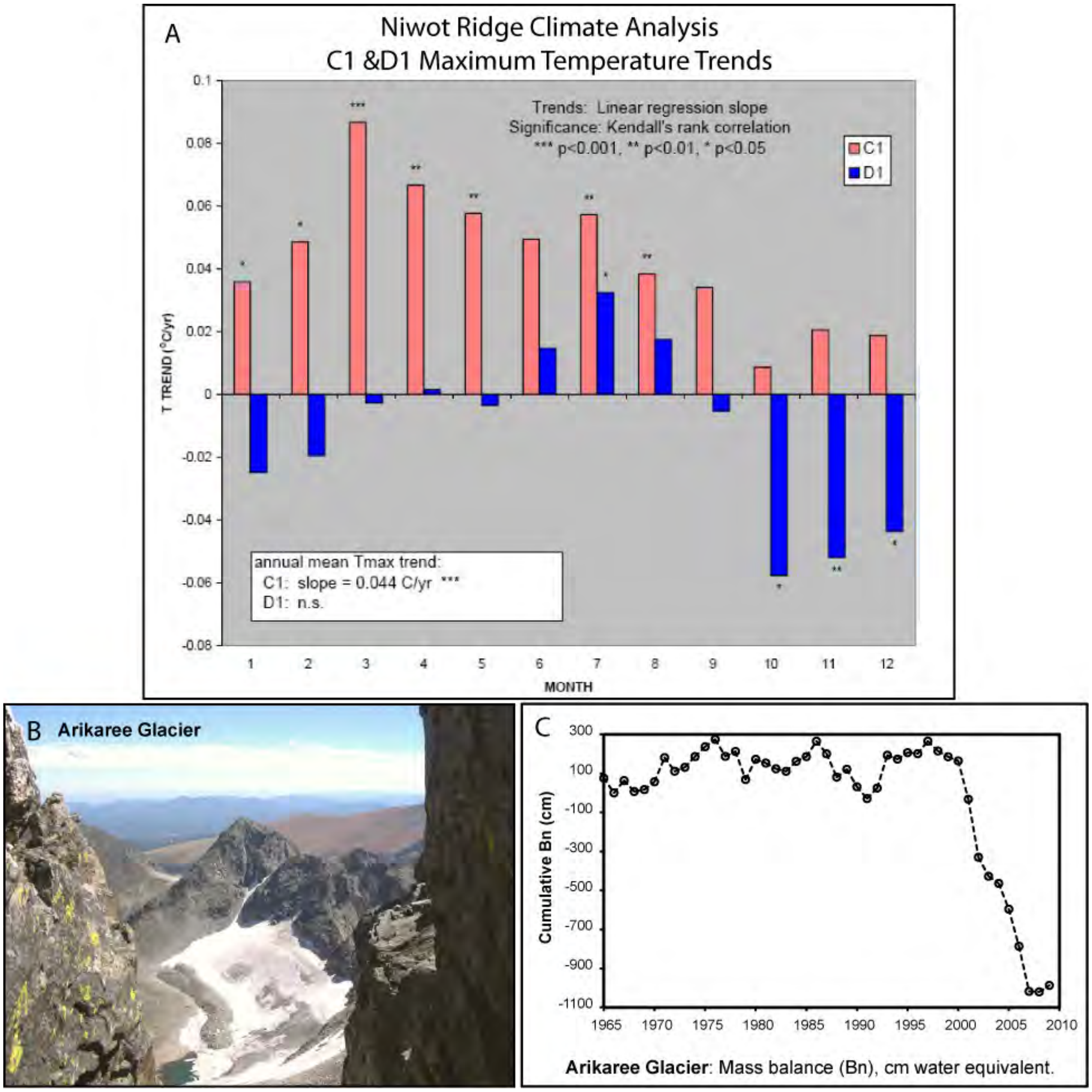

Figure 5. Long-term climate at the NWT LTER site. **A)** A recent evaluation of our climate record from 1954 to 2006 shows that Niwot Ridge is experiencing abrupt, but asynchronous, climate change. The subalpine forest has been warmer and drier across all seasons, while the alpine tundra has experienced longer growing seasons, warmer summers, but cooler and wetter winters. By focusing on the time period 1983–2007, we found that average annual air temperatures increased by 1.1°C per decade at C1 and by 1.0°C per decade at D1 (Clow, in press). **B)** Arikaree Glacier. **C)** From the mid-1960s to the late-1990s, Arikaree's annual net balance varied around zero. From 1997 to 2007, it was consistently negative, however – most markedly in the drought years of 2001 and 2002 when the glacier lost about 5.2 m of ice.

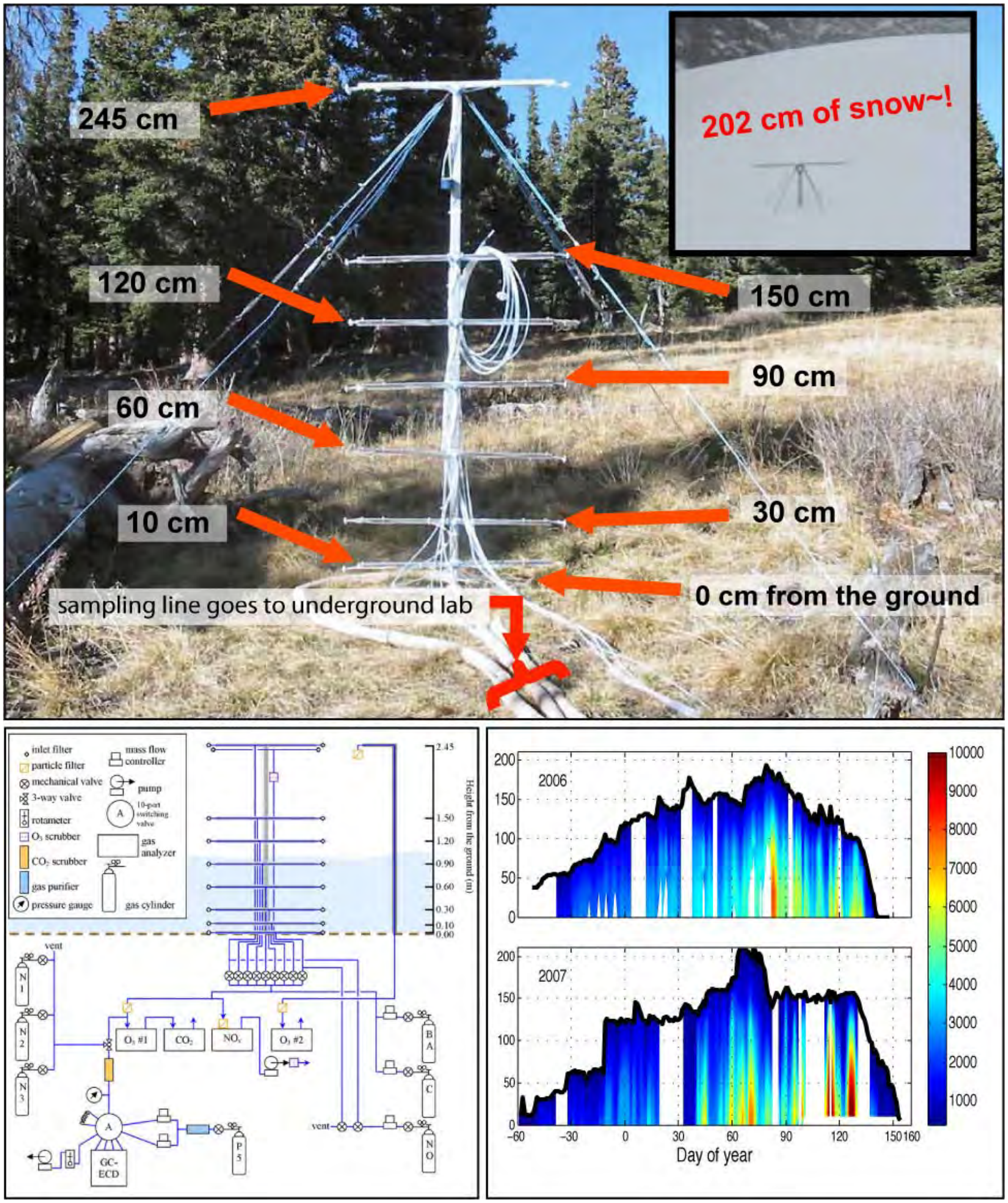

Figure 6. Trace gas facility at the Soddie site. **Upper panel** shows inlets that are connected to an underground laboratory; snow accumulates naturally at the site as shown by the upper inset. Air is pulled through the inlets into an *in situ* system located in an underground laboratory that automatically analyzes for carbon dioxide, nitrous oxide, ozone, and other gases. The **lower right figure** shows how concentrations of carbon dioxide varied with time and depth of the snowpack for 2006 and 2007.

grains) and the chemical composition of the snow (e.g., presence of halogens, organic substances) (Steffen et al. 2008). Our intent is to develop a conceptual model of how snow grain processes including deposition, condensation, reemission, sublimation, and turbulent diffusive uptake influence mercury concentrations in snow and ice. Findings will be compared, evaluated, and incorporated into the ECHAM-4 Chemistry and Climate Model for assessing regional and global impacts of these chemical snow exchanges.

Dust quantity and quality. Although many forms of atmospheric deposition are relatively well measured in the U.S., dust deposition is not. At the NWT LTER, we know that aeolian (wind-generated) deposition is an important source of both base cations (Litaor et al. 1987) and nutrients (Ley et al. 2004) (Figure 1). To address this current gap in deposition measurements, The National Ecological Observatory Network (NEON) is developing new protocols for the measurement of total suspended particulates in deposition that will be deployed at all NEON core sites. This prototype is scheduled to be field tested and operated at the Saddle site by NWT LTER in the summer of 2010. Even less is known about the quality or quantity of organic carbon deposition to high-elevation landscapes. Mladenov et al. (2008; 2009; 2010) used spectroscopic techniques in combination with parallel factor analysis (PARAFAC) and air parcel backward trajectories to demonstrate that dust-derived water soluble organic carbon in both wet and dry deposition at a high-elevation site in Europe contained substantial amounts of labile amino acid-like fluorescent compounds. Mladenov is a postdoctoral researcher on this proposal and will use those and related spectroscopic techniques to evaluate the quality and sources of carbon in wet and dry deposition to NWT; proof-of-concept analyses from 2009 provide support that these techniques will work at NWT (Figure 7).

Lastly, we will continue the development of a high-risk, high-reward project to evaluate the strengths and limitations of GPS as a potential snow sensor. Recently, we showed that integrated changes in snow depth over an area of approximately 7,500 m^2 can be clearly tracked in the corresponding multipath modulation of the GPS signal (Larson et al. 2009). We have just been awarded an instrumentation grant through NSF-EAR to advance our understanding of GPS to measure snow properties and soil moisture at the NWT LTER, the contribution of NWT LTER will be to operate field instruments and conduct “ground-truth” of snow properties for model development and validation.

BARREN SOILS

Changes in climate at NWT are causing glacial retreat (Figure 5) and freeing up new “barren soils.” Research on life in plant-free ecosystems has accelerated in recent years, especially with regard to microbial diversity and biogeochemical function of cold, barren soils of the high Arctic and in Antarctica (Parsons et al. 2004; Kaštovská et al. 2005; Aislabie et al. 2006). Less well studied are high-elevation soils that can be even harsher than high-latitude soils because they exist under lower atmospheric pressures, higher ultraviolet irradiance, and drier conditions (Daly and Wania 2005; Schmidt et al. 2009). Interestingly, however, even soils that have been newly deglaciated manage to rapidly attain the soil microbes needed to both bring new N into the system (Schmidt et al. 2008) and convert that N to nitrate (Schmidt et al. 2009). However, at present, it remains unclear how the microbiology of these so-called “barren” soils relates to the C and N fluxes within them (Figure 7).

In addition to understanding C and N imports and exports from barren soils, we also want to understand what organisms are responsible for processes such as nitrification and C fixation. Such an understanding will help to predict future responses of the system to perturbations such as increasing temperatures and N loading. Evidence is accumulating in other systems that soil Crenarchaeota are responsible for much of the nitrification that occurs in natural ecosystems

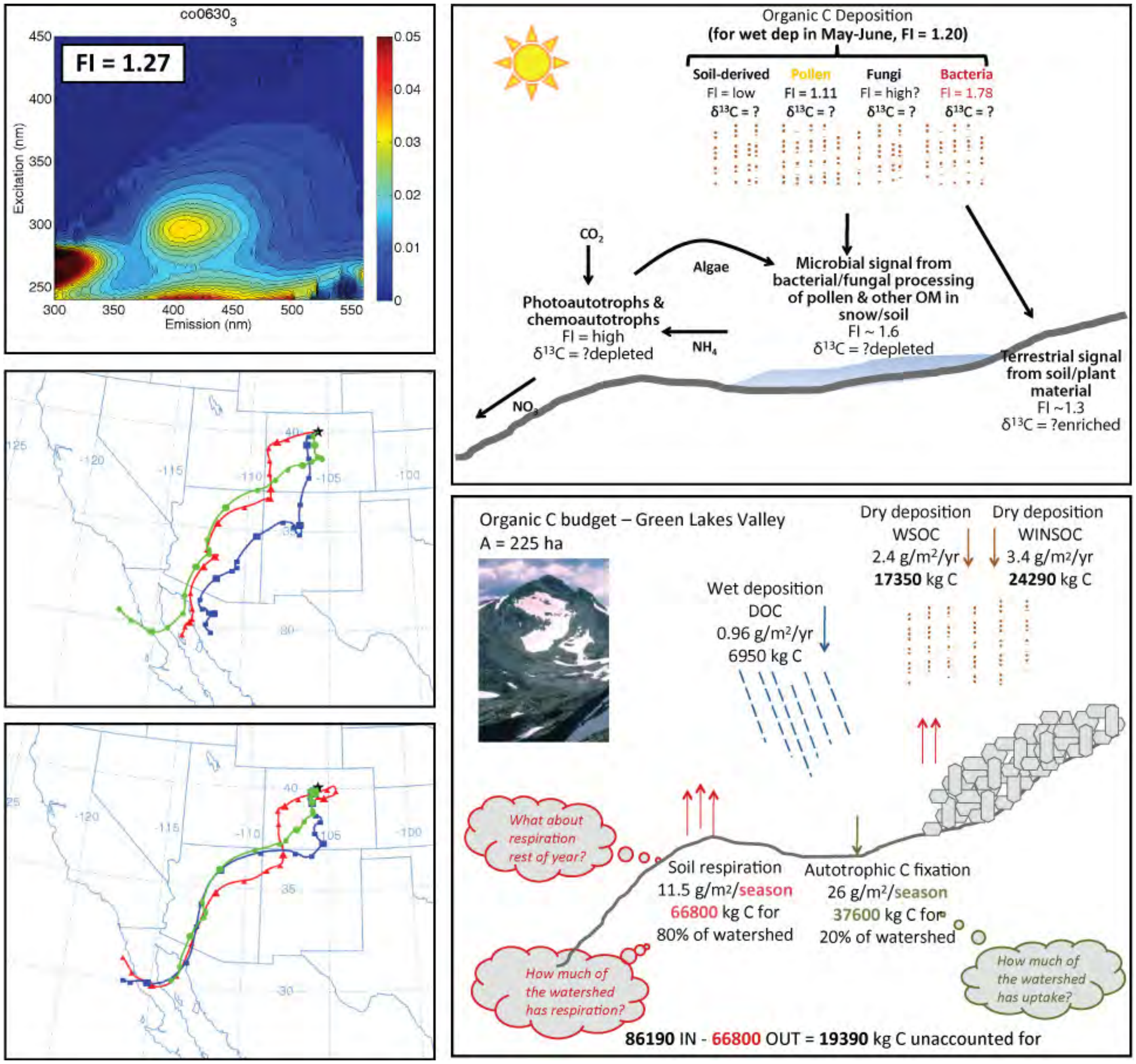

Figure 7. Carbon quality and quantity in wet and dry deposition to barren soils at NWT. **Left panel** is preliminary spectroscopic data from DOM in wet deposition samples collected at Green Lakes Valley in 2009, which reveals the presence of labile amino acid-like compounds with a relatively low degree of aromaticity ($\varepsilon_{250} < 10$ L mmol^{-1} m^{-1}) compared to surface waters (aquatic ε_{250} ranged from 22 to 69 m^2 mmol^{-1}). Amino acid-like (AA-like) fluorescence accounts for almost 60% of the fluorescence. Back trajectories for the airmass are plotted. **Upper right panel** illustrates that at present, how the microbiology of these "barren" soils relates to C and N fluxes from the soils remains an unsolved mystery. **Lower right panel**: preliminary calculations for a carbon mass balance suggest that atmospheric deposition could represent an input of organic C to the catchment that approaches that of biological C fixation in magnitude. Also, the relative importance of each input in the C budget varies seasonally, and such seasonal changes likely influence the quantity and quality of organic C available for heterotrophic decomposition.

(Leininger et al. 2006; Prosser and Nicol 2008), however these creatures are finely adapted to the low N concentrations that have prevailed in many ecosystems for eons. This adaptation is demonstrated by the very high affinity of their ammonium monooxygenase (AMO) enzymes (extremely low Michaelis-Menten half-saturation constants or k_m), in contrast to known bacterial nitrifiers, which have low affinity (high k_m) AMOs (Martens-Habbena et al. 2009). Thus, one would expect that increases in availability of ammonium would shift the nitrifying community from dominance by Archaea to dominance by Bacteria. Such a shift could be a warning sign of N saturation in an ecosystem – a major tipping point. We also expect that the novel fungal community of Chytridiomycota (or "chytrids") recently reported in barren soils at both NWT and the Himalayas (Freeman et al. 2009b) will be adversely affected by future increases in N-deposition, similar to the effects we have recently documented in alpine tundra soils (Nemergut et al. 2008).

King et al. (2008) have shown that barren soils are carbon limited, but contain unexpectedly high levels of microbial biomass for a plant-free system. Building on this work, Freeman et al. (2009b) made an initial attempt to quantify carbon pools for barren soils at Green Lakes Valley, and report that after microbial fixation of C, the next largest C contributors were organic carbon in pollen, followed by water-extractable DOC and microbial biomass. Order-of-magnitude calculations (Figure 7) show that the C budget is currently not well constrained. These preliminary calculations suggest that atmospheric deposition could represent an input of organic C to the catchment that approaches that of biological C fixation in magnitude (Figure 7). We expect that biological C fixation will predominate during summer and autumn months when exposed soil areas become available for photosynthesis, whereas atmospheric wet and dry C deposition will predominate during winter and spring months (Figure 7).

Carbon budget. The first-ever high-elevation carbon budget will be calculated for winter, spring, summer, and fall seasons. The quantity and quality of carbon in atmospheric deposition will be measured as above and is expected to be more or less uniform across the watershed. King et al. (submitted) has shown that enzyme activity and DOC levels are correlated to microbial biomass and that microbial biomass and diversity have a geospatial lag distance of about 250 m. Information on microbial biomass and measurements of respiration and C fixation rates, combined with spatial and seasonal GPS surveys of landscape types, will then be extrapolated to the watershed scale to estimate C input and loss from C fixation and respiration, respectively.

Microbial activity. We will use molecular approaches (clone libraries) to identify and quantify (with quantitative polymerase chain reaction, or qPCR) archaeal and bacterial nitrifiers in soils from our sites, following protocols developed by the Alpine Microbial Observatory (http://amo.colorado.edu/). To summarize them briefly: a subunit of bacterial ammonium monooxygenase (bAMO) genes will be amplified using primers amoA-1F and AMOa-2R, and archaeal ammonium monooxygenase (aAMO) will be amplified using Arch-AMOaF and Arch-AMOaR, so that the relative abundance of AMO and N-fixing genes can be compared across the landscape using qPCR. Rates of N fixation will be estimated in the field using a modified acetylene reduction assay as described by Belnap (1996) and tested in oligotrophic high-elevation soils as described by Schmidt et al. (2008). In order to estimate rates of nitrification and biological NH_4^+ production, we will measure gross N-mineralization and nitrification rates in soils using an *in situ* pool dilution technique (Stark 2000) that has been successfully tested at high elevation sites in the Andes (Schmidt et al. 2009). The extent to which the microbial community is limited by Aeolian inputs of C and or atmospheric deposition will be investigated with laboratory experiments using a full-factorial design with three replicates for each treatment combination of pollen, dust, N and P. We have used a similar approach to show that C and P (but not N) are co-limiting of microbial respiration in barren soils at NWT (King et al. 2008).

ALPINE TUNDRA

We will continue to monitor our long-term alpine tundra plots on the Saddle grid, but we intend to change sampling frequency to annual measurements of primary productivity and species composition in order to discern changes over time and how these adjustments relate to climate shifts at NWT, as well as to support modeling activities (Figure 8). This sampling scheme parallels that employed at other herbaceous LTER sites (i.e., KNZ, SEV, KBS, JRN) and puts us in compliance with the LTER network production and species composition core areas. Production will be estimated by clip harvests at peak season by plant community for ANPP. Composition will be estimated by point quadrat frame sampling, including all species that contact each point (Johnson and Billings 1962). Production measurements will follow established protocols, used since 1992 (http://culter.colorado.edu/exec/.extracttoolA?saddbiom.mw). We will continue the long-term N-addition manipulations, and have recently begun the same manipulations at nearby Rocky Mountain National Park with funding from the National Park Service.

A major initiative is to test how plant-soil feedbacks and directional environmental change influence community dynamics, extending previously developed theory on threshold effects or tipping points to alpine ecosystems (May 1977; Bever et al. 1997; Steltzer and Bowman 1998; Suding et al. 2004; Bestelmeyer 2006; Groffman et al. 2006) (Figure 9). Microbial community structure and function is emerging as one key link between exogenous changes in N and plant community response. We hypothesize that microbial interactions can often be an important determinant of plant diversity decline in response to N enrichment – even more important, perhaps, than the simple plant resource competition widely assumed to be the primary driver of diversity decline. Along these lines, N fertilization could result in a) altered carbon allocation between host plant-symbionts in mycotrophic N-conservative species, resulting in increased parasitism in the "loser" species, and b) accumulation of inhibitory secondary metabolites (in this case phenolic substances), associated with shifts in microbial decomposition activity away from recalcitrant soil organic matter. While these mechanisms are indirectly supported by findings in many systems in addition to our own, neither has been tested before at NWT. To test these hypothesized mechanisms, we will conduct microbial surveys of long-term fertilization plots, tissue culture experiments, and field manipulations in the moist meadow tundra at NWT (Figure 9), supported with additional funding from NSF (DEB 0919569).

Secondly, we will expand on a project initiated in 2006 to further develop the snow-shrub feedback model developed for the Arctic (Sturm et al. 2005) to include a fully-factorial experiment to manipulate summer air temperature (via open-top chambers), snowpack (via replicate snowfences), and nitrogen availability (via N addition) to test the causal link between climate changes, the increasing distribution of a woody shrub, *Salix glauca*, and the subsequent decline in the alpine tundra community (Figure 9). *Salix* is common to arctic and alpine regions throughout the Northern Hemisphere and is thought to be rapidly increasing in abundance in the Rocky Mountains. The experiment will enable us to determine if increasing temperatures and feedbacks between temperature and snow pack or nutrient availability favor the growth and establishment of *Salix* over the existing herbaceous alpine community and if these changes can drive rapid conversion, including the loss of alpine species and increase *Salix* distribution. However, it is also possible that herbaceous species will respond in a similar manner to these changes, suggesting that the long-term impacts may be via longer-term changes to microbial communities' structure or soil organic matter.

Additionally, a combined N deposition/warming experiment will be initiated in the summer of 2010, with full implementation in 2011, to evaluate how a warming climate will influence the capacity of vegetation and soils to mitigate effects of N deposition. The experiment will test the

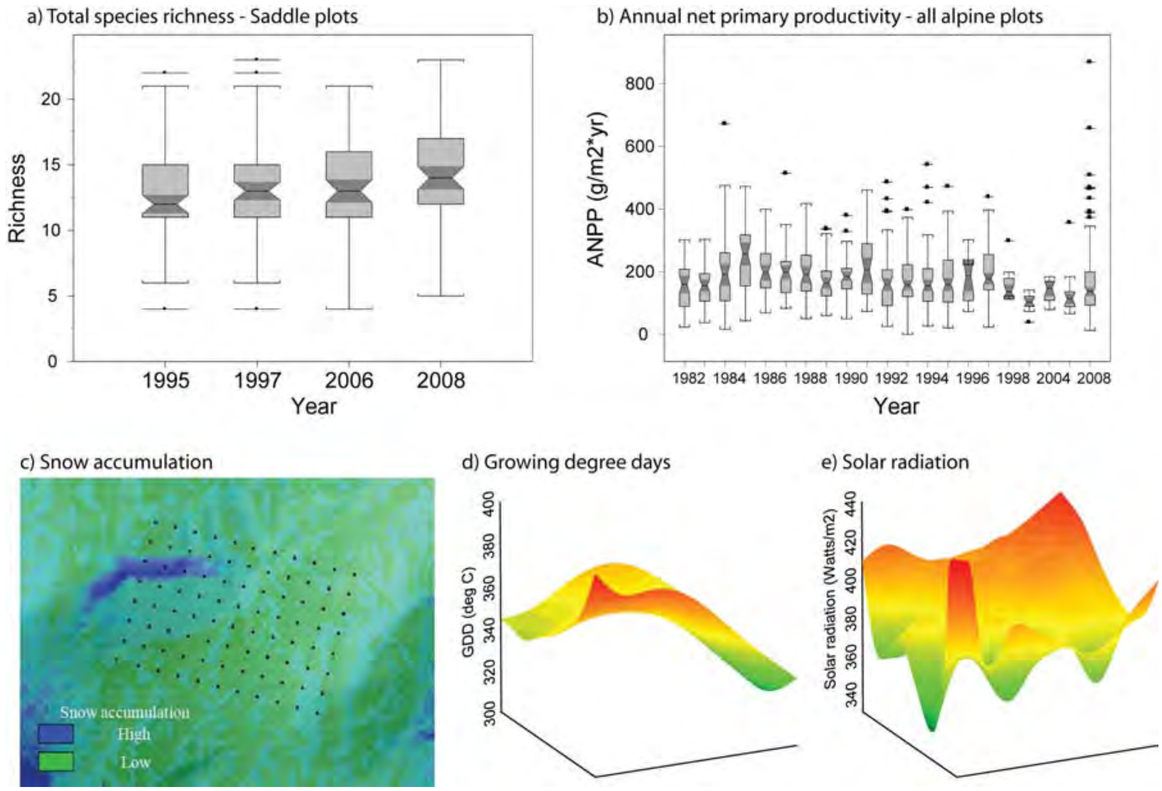

Figure 8. **a)** Total vascular plant species richness for Saddle plots. Notches (dark grey) in box plots show 95% confidence intervals. **b)** Annual net primary productivity (g/m^2*yr) for all alpine plots (in and near the Saddle). Notches show 95% confidence intervals. **c) to e)** Spatially-explicit simulation of environmental variables in the Saddle: **c)** Spatial distribution of snow simulated using SnowModel; 1997 spatial distributions of **d)** growing degree days (^{o}C); **e)** solar radiation (Watts/m^2) simulated using MTCLIM.

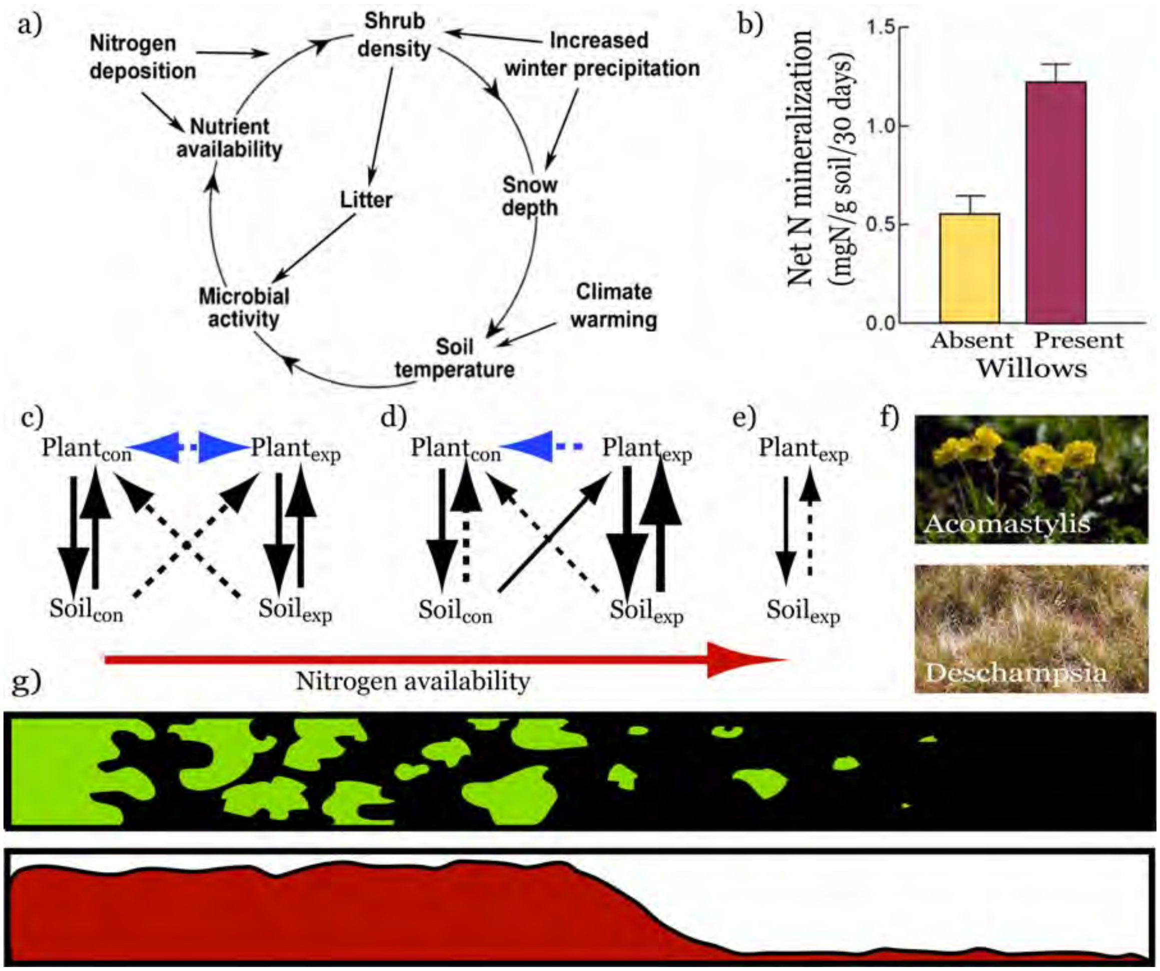

Figure 9. **a)** Feedbacks between willow encroachment and snow, temperature, and N; **b)** Net N mineralization in presence and absence of willows; **c) to g)** General conceptual model. Solid lines indicate positive effects, dashed lines are negative effects, and line thickness indicates strength of interactions. Indirect effects are shown between two plant types: one with N-conservative traits ($Plant_{con}$) and the other with N-exploitative traits ($Plant_{exp}$). We consider $Soil_{con}$ and $Soil_{exp}$ to represent soil environments including microbes (pathogens, mutualists), structure (e.g., texture, SOM), and resources (e.g., N, P). In ambient low N conditions **c)** positive reciprocal feedbacks between the N-conservative species and its associated soil and the N-exploitative species and its soil can maintain stable patch coexistence. Increased nitrogen can cause negative feedback to develop **d)** for the N-conservative species, or can cause positive feedback for the N-exploitative species to increase in strength, causing a decline in the abundance of N-conservative species. Where N continues to increase **e)**, we predict the loss of the N-conservative species. **f)** Our focal species, representative of N-conservative (*Acomastylis rossii*) and N-exploitative (*Deschampsia caespitosa*) species or functional group types. **g)** Expected changes in abundance of the two species (top) and community-wide diversity (bottom) along the N gradient.

hypothesis that warming will enhance turnover of soil organic matter more than plant growth and uptake of N, leading to greater sensitivity to N deposition impacts (such as changes in biodiversity and acidification). Warming will be accomplished by using open-top shields developed as part of the ITEX project and previously used at NWT (Welker et al. 1999; Walker et al. 2006). N deposition treatments will consist of ambient (control) treatments of 5 -10 - 30 kg N $ha^{-1}yr^{-1}$, which will be added to 1m x 1m plots as NH_4NO_3 in solution in three applications during the growing season. Each treatment (total of eight: two warming, four N additions) will be replicated five times in each community, for a total of 80 plots. Response variables will include plant diversity, primary production, plant chemistry, microbial biomass N, and N biogeochemistry.

Pikas. The distribution of the American pika (*Ochotona princeps*) is in rapid and accelerating decline across a large portion of its range, and the species is currently being considered for protection under the Federal Endangered Species Act (USFWS 2009). Recent research implicates climate change in the extirpation of pika populations throughout the Great Basin (Beever et al. 2010; Loarie et al. submitted; Wilkening et al. submitted) and in the central Sierra Nevada (Moritz et al. 2007). We are working with postdoctoral researcher Chris Ray to test hypotheses that pikas at NWT experience higher physiological stress in microhabitats with higher summer temperatures, lower winter temperatures, and lower relative forb cover. To test these hypotheses, pikas will be marked and (non-lethally) sampled at sites differing in latitude, altitude, and slope aspect in order to estimate survival rates and physiological parameters (Figure 10). At each site, pikas will be sampled from both north- and south-facing slopes, and at NWT pikas will also be sampled from different altitudes. Samples of blood, urine, feces, saliva, and hair will be used to characterize relative levels of stress hormones (e.g., cortisol and TNFa) and other metrics of metabolic stress. The microhabitat associated with each marked pika will be characterized in terms of microclimatic variables and patterns of available forage including relative forb cover and nutritional and other chemical analyses of cached forage. Patterns of activity will also be monitored for each marked pika, in order to compare behavioral responses that may mitigate climatic influences. Using LTER supplemental funds in 2008 and 2009, the program was initiated by sampling at the NWT LTER site and a long-term pika research site in the Gallatin Range of south-central Montana. Accounting for detection probability (~0.9), 95% confidence intervals for survival were only 13-21% at NWT ($n = 39$), compared to 55-73% at Gallatin ($n = 11$). Results from analyses of plasma glucose, which provides energy for the fight-or-flight response, also suggest that NWT pikas were more stressed than Gallatin pikas, with plasma glucose levels significantly ($P = 0.013$) higher at NWT than Gallatin. These methods will allow us to examine: a) whether reduced individual survival and signs of physiological stress correspond to extreme microclimates, b) if episodes of widespread mortality suggest disease, c) if there is a lasting decline in survival evidenced by a declining ratio of adults to juveniles, and d) if there is a shifting phenology in pika foraging behavior over time.

Modeling. Since we began point-quadrant sampling of landscape, community and species levels at the Saddle site in 1989 (Walker et al. 1993), our overall objective has been to assess changes in alpine vegetation. Our specific targets are to a) dynamically model the distributions of snow cover, temperature, and solar radiation for the Niwot Ridge study site, b) use modeled environmental variables to develop spatially-explicit predictions of alpine plant species distributions over time, and c) integrate the effects of plant species traits and interactions into predictions of distribution changes. The spatial distribution of snow on a daily time step will be developed using the simulation model known as SnowModel (Liston and Elder 2006), which is calibrated using snow depths measured over each snow season at each of the 88 points in the saddle grid from 1986 to 2006 (Figure 8). The microclimate simulator MTCLIM version 4.3 (Hungerford et al. 1989; Thornton et al. 2000) is then used to estimate daily temperature and

Figure 10. Pika research at NWT. The **upper panel** shows two REU students setting traps for pikas. **Lower left panel** shows a pika, and **lower right panel** shows a pika being released after tagging.

solar radiation values from 1986 to 2006 over the sampling domain (Figure 8). Partial triadic analysis (PTA; Blanc et al. 1998) will be performed in R's ade4 package to extract landscape-and community-level patterns including sampling year ordination. The Wilcoxon signed-rank test is then used to detect the degree and direction of changes in species cover over time. Multivariate statistical analyses (e.g., multivariate spatio-temporal clustering, multivariate repeated measures regression) will use snow depth-, temperature-, and solar radiation-derived variables as predictors of changes in species distributions in time and space. Preliminary results reveal a consistent, although small, directional change in species composition from 1990 to 2006 at both the community and landscape levels. Individual species differed in the degree and direction of changes in cover over time. Once we have confidence in this modeling approach, our intent is to add N and dust deposition as drivers, incorporating the results from the experiments and long-term measurements above.

FOREST-ALPINE TUNDRA ECOTONE (TREELINE)

The extent to which disturbances, topography, and climate control tundra-tree patterns – and the consequences of these patterns on the biogeochemistry of the ecotone in conjunction with climate change concerns – was identified as an area of interest in the last renewal. We want to know whether climate change is causing forests to march uphill, for example, what the effect of mountain beetle kill on limber pine is having on the species composition of this ecotone, and whether invasive species are moving uphill in tandem with increases in air temperature. Humphries et al. (2008) show that "treeline" is actually a misnomer: areas of treeline characterized by high relief and associated physical disturbances are home to fragmented and patchy tree distributions, while treeline areas with low topographic relief, meadows and wetlands show intermediate levels of tree aggregation. Somewhat counter-intuitively, Withington and Sanford (2007) report that decomposition rates of buried substrates increased with altitude in the ecotone, while Liptzin and Seastedt (2009) showed that exchangeable acid cation concentrations (total soil C and soil C:N) increased from alpine tundra to forest and across the krummholz zone, demonstrating ecotone and distance effects. However, Darrouzet-Nardi (in press) shows that reduced heterogeneity and strong relationships between C and N in older soil organic matter suggests that landscape variation in the chemical composition of soil organic matter in mineral soils of the ecotone converges over time, possibly as a result of greater chemical variation in plant inputs relative to the products of decomposition reactions.

For this renewal, the relative influence on richness and composition of landscape-level versus site-level conditions at treeline (i.e., type of ecotone versus variability in topography, substrate, and tree density) will be evaluated using a) Multiresponse Permutation Procedures tests to determine significant differences in species richness among ecotone types (Mielke and Berry 2001), b) Jaccard's coefficient to determine species overlap between and within transects, and c) regression tree analysis to predict richness as a function of environmental variables and tree density classes. The LCM predicts that the ecotone is an area of more intense N cycling. We intend to look at process-level response to N cycling hot spots and hot moments using ion exchange resin bags along with nitrogen isotopic signatures in soil organic matter. A normal distribution under these experimental parameters would suggest that landscape-level N cycling is less influenced by hot spots.

We build on process-level research at treeline to add long-term monitoring to the ecotone. We are particularly concerned about several invasive species a) the nonnative grass, Timothy (*Phleum pratense*) that is moving uphill, b) a non-native weevil, *Rhinocyllus conicus,* that is attacking native thistles and potentially altering their distribution and abundance (Korth et al. submitted), and c) three introduced earthworm species studied by Gonzalez et al. (2003). Annual monitoring will build on the point-intercept transect system developed by Buckner (e.g., Bush et al. 2007), with information collected every 0.5 m perpendicular to the transect line. Under this protocol, sampling points are identified with a non-invasive technique involving an optical point-projection apparatus mounted on a movable tripod positioned astride the transect line. All vegetation and non-vegetation intercepted by the projected 0.07mm point described by the intersection of reticle crosshairs are identified and tallied. In keeping with this method (originated by Winkworth et al. 1962), data will be collected as interceptions of the projected point with live vegetation (which is identified by species), bare soil, standing dead plant matter produced in previous years, litter, or rock (mineral fragments > 1cm maximum diameter). Plant abundance data in the form of both absolute cover (number of hits of that plant or group of plants per 200 observations) and relative cover (number of hits of that plant or group divided by total plant hits) can be evaluated. We propose to install five of these transects and co-locate them where existing data sets have been collected on plant or soil variables (Darrouzet-Nardi, in press; Humphries et al. 2008; Liptzin 2007; Liptzin and Seastedt 2009).

SUBALPINE FOREST

The impacts of climate change on subalpine forests remains unknown, although a reasonable hypothesis is that earlier snowmelt will lead to intensified and prolonged periods of water stress (Bales et al. 2006), which in turn will affect carbon cycling (Monson et al. 2006b). Research conducted at the stand scale in the last decade shows that understanding of ecological and hydrologic processes in seasonally snow-covered catchments is not sufficient to predict how forested ecosystems will change in response to climatic and/or anthropogenic changes in energy, water, and chemical inputs (Monson et al. 2002; Molotch et al. 2007; 2009). In recognition of this problem, the National Research Council (2005) has stressed the need for improved understanding of how global change will affect ecohydrological interactions and associated impacts to energy, water, and carbon cycling.

Our research plan on this front is informed by the hypothesis that future increases in air temperature will a) increase snowpack sublimation, accelerate snowmelt, and therefore reduce water availability during the growing season; b) the sensitivity to climate change will be greatest in mid-elevation forests and in areas with relatively high forest density; and c) forest vulnerability to beetle infestation and fire will vary systematically, based on ecohydrological feedbacks. Essentially, we will evaluate whether warmer temperatures and earlier, more rapid snowmelt reduces soil moisture during the growing season, enhances vegetation water stress, and reduces carbon uptake. To address these hypotheses we now seek to a) bring the Niwot Ridge AmeriFlux and LTER programs into a closer collaborative relationship, b) supplement the eddy correlation towers with ecohydrologic instrument clusters, and c) conduct process-level research on the ecological effects of the mountain pine beetle outbreak.

Measurements of CO_2, H_2O, and energy fluxes using a full-canopy eddy covariance tower have been made at the NWT AmeriFlux site at C1 for ten consecutive years as part of the DOE-funded AmeriFlux program. In 2009, an NSF Long Term Research in Environmental Biology (LTREB) grant was awarded for partial maintenance of the flux measurements at C1 after the AmeriFlux program was discontinued (Monson PI). Now, we seek to more formally integrate the measurements of surface-atmosphere fluxes using eddy correlation instruments at the subalpine forest AmeriFlux site with those at the alpine tundra LTER site to standardize flux measurements within the two efforts by sharing personnel, developing common calibration and analysis systems, and providing data in common formats. Both programs have focused on within-biome processes for most of their existence. Now, as NWT aims to expand the scope to include regional processes, it is critical to make connections between distributed observation systems that support spatial and temporal integration (e.g., Figure 3).

The C1 AmeriFlux data are posted as five-minute averages and variances, as well as 30-minute averages for each day of the year (http://urquell.colorado.edu/data_ameriflux/), and then submitted to the national AmeriFlux site as Level 4 processed data for use in regional-to-global modeling. Moreover, the site has participated in across-network AmeriFlux calibration exercises every three to four years. The C1 site has pioneered the use of SIPNET to simultaneously estimate parameters, which is an improvement over traditional approaches in which parameters are estimated independently and covariances are ignored. By using simultaneous parameter estimation, we have opportunities to evaluate parameter adjustments in parallel, resolve covariances among parameters, and because the process generates sets of parameters that provide nearly equal solutions to the maximum likelihood problem, we can assign standard errors to each parameter estimate (Sacks et al. 2006). NWT LTER will help support field and data analysis personnel who will maintain both the forest and tundra eddy covariance systems so that instruments are cross-calibrated, data display is similar for both sites, data for the tundra site meets Level 4 AmeriFlux standards, and SIPNET is used for parameter estimation.

Next, we propose to deploy a network of ecohydrologic instrument clusters developed from community-wide planning activities associated with NSF's Critical Zone Observatories and developed for snow-dominated systems. The clusters are designed to observe sub-flux footprint variability in water and energy fluxes across gradients in vegetation cover (Figure 3). In this regard, each cluster consists of nine ultrasonic snow depth sensors positioned in a stratified sampling pattern with respect to proximity to trees, with three sensors in each of three classes that cover under-canopy, canopy-edge, and open areas. Beneath each ultra-sonic snow depth sensor, vertical profile measurements of soil moisture and soil temperature are taken down to 1 m below the ground surface. Trees adjacent to these profiles are instrumented with continuous heat sap flow meters. These instrument clusters will allow us to measure ecohydrological responses to shifts in climate and vegetation change that largely depend on snowpack processes and complex interactions between vegetation distribution, snow redistribution, variability in solar irradiance, snowmelt, soil moisture, and soil temperature. To fully grasp critical zone variability, these states and fluxes must be observed directly and continuously from the onset of snow accumulation through to the end of the snowmelt infiltration period.

Recent outbreaks of mountain pine beetles (MPB, *Dendroctonus ponderosae*) have been widespread in western North American and unprecedented in the extent of their frequency, impact, and range (Kurz et al. 2008). The forest at NWT is in the initial stages of infestation by MPB and we expect that we will have the rare opportunity to observe every stage of an outbreak in an intact forest ecosystem across decadal time scales. In addition to continuing NEE measurements using eddy covariance at C1, we strive to understand how a beetle outbreak will alter the soil food web and fluxes of water, C, and N in the soil system (Figure 11). We hypothesize that soil labile C will decline following tree death due to the termination of root exudates, but that labile N and soil organic matter will increase because of the termination of root uptake of N and increased dead root input, respectively. We hypothesize that soil food web structure might then change due to the shifted C resource from root exudates to root litter and the concomitant altered availability of C and N. Initial research using traditional soil measurements shows that tree mortality reduced soil microbial biomass, but did not change soil nematode and microarthropod densities (Xiong et al. submitted). The soil food web shifted to be more bacterial-based, with an increased fraction of bacterial-feeding nematodes and a decrease in the relative abundance of fungal and plant feeders. Additionally, the accumulation of soil inorganic N, the reduction in microbial biomass, and the more bacterial-based soil food web increases the expectation of enhanced and continued N loss from affected ecosystems to aquatic systems (Figure 11).

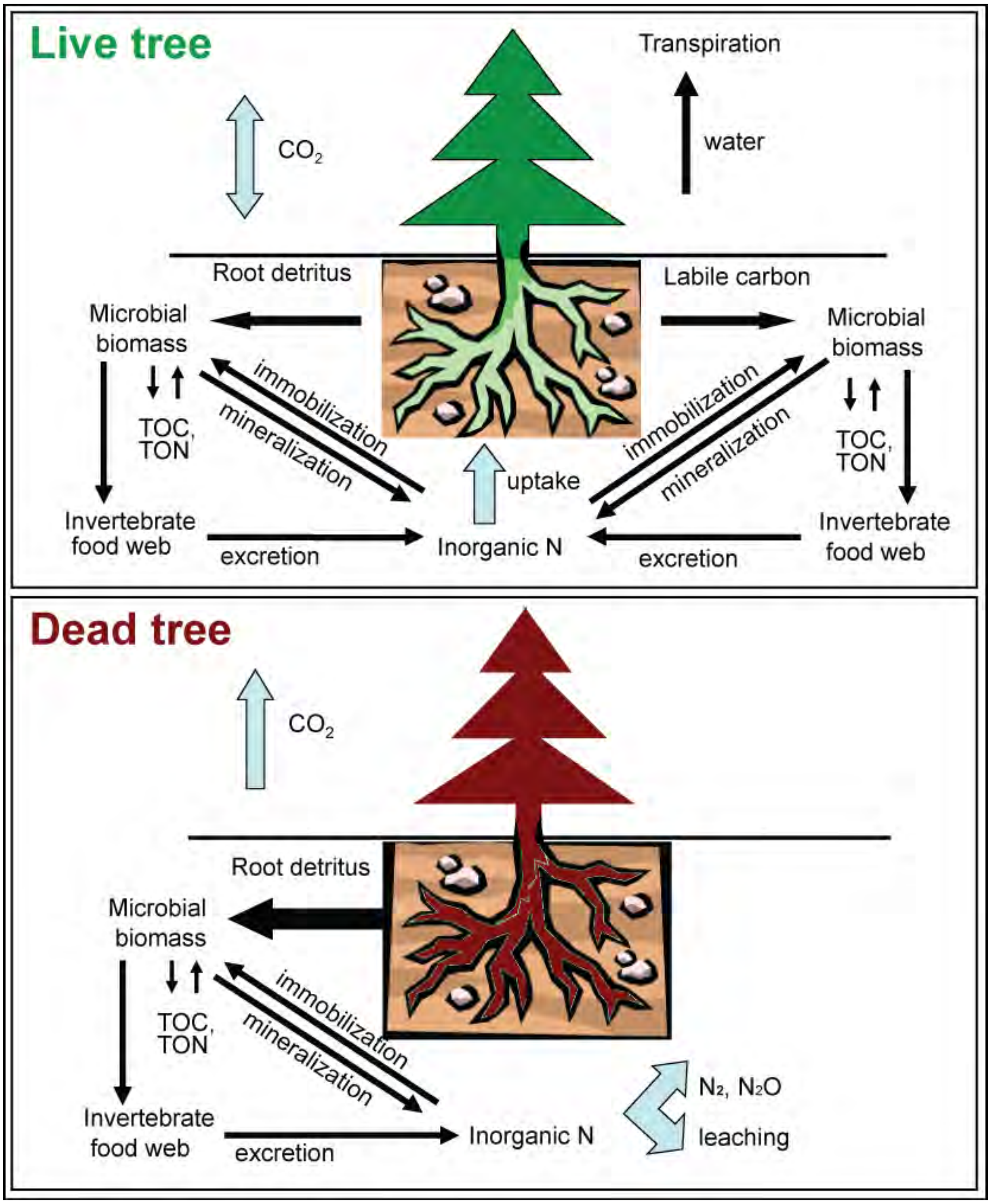

Figure 11. Schematic of water, C, and N cycling in the subalpine forest at NWT under live trees and trees killed by the mountain pine beetle. We hypothesize that soil labile C would decline following tree death due to the termination of root exudates, but labile N and soil organic matter would increase because of the termination of root uptake of N and increased dead root input, respectively. We expect that soil microbial biomass will decrease because soil microorganisms are believed to be limited by C availability but not N in most soils and also because that C from root exudates can be more important to fuel soil food web than litter input.

AQUATIC SYSTEMS

Our overarching hypothesis is that ecosystem processes in the alpine and subalpine lakes in the Green Lakes Valley have been approaching a tipping point driven by progressive increases in N inputs (Williams and Tonnessen 2000; Bowman et al. 2006), decrease in winter ice thickness (Caine 2002), warming summer climate (Clow in press), and increase in the area of new barren soils. We seek to improve our understanding of the hydrological connectivity of terrestrial and aquatic ecosystems, in particular the space/time patterns of water, C, and N stores and fluxes along flowpaths (e.g., Figure 3). We know that nitrate concentrations are high in streams draining barren soils at NWT and that nitrate decreases and DOC increases as basin area increases and elevation decreases (Figure 12). Williams et al. (2006; 2007) have shown that hydrologic mixing models in combination with end-member mixing analysis (EMMA) can be useful in discriminating sources of nitrate to surface waters in these high-elevation catchments (Figure 12). We intend to use two independent methods to evaluate the fate and transport of atmospheric and terrestrial nitrate along elevation and landscape gradients at NWT: a) hydrologic mixing models parameterized using EMMA, and b) dual isotopes of nitrate. The dual isotopic composition ($\delta^{15}N-NO_3^-$ and $\delta^{18}O-NO_3^-$) of nitrate is well suited for studies of nitrate contributions to streams and lakes and provides an independent tool to help discriminate atmospheric from watershed sources of nitrate in surface waters (Durka et al. 1994). We've successfully used that approach here at NWT for lakes (Nanus et al. 2008) and proof-of-concept analyses suggest that it will work at multiple sites, with high-frequency sampling able to capture seasonal changes in nitrate sources (Figure 12). To achieve these goals, we'll complement existing hydrology infrastructure with additional soil lysimeters (both tension and zero-tension) and groundwater wells to better understand surface/groundwater interactions and aquatic/terrestrial connections.

Lakes represent biogeochemical hotspots in high-elevation areas (Figure 2). In the Green Lakes Valley (GLV), which contains five interconnected alpine and subalpine lakes (Figure 4), the streamflow leaving the valley integrates the allochthonous inputs from the terrestrial ecosystem such as N and DOC (Williams et al. 2001; Seastedt et al. 2004; Hood et al. 2005; Taylor and Townsend in press) with the biogeochemical consequences of autochthonous production of new organic material by phytoplankton and associated uptake of N and P in the lakes (Gardner et al. 2008). Phytoplankton production in the lakes is important for both a) transformations of the excess N loading coming from the watershed (Gardner et al. 2008) and b) DOM production during the summer phytoplankton bloom. For example, monitoring of the chemical quality of DOM in GL4 during spring and summer has shown that once the ice cover breaks up, the DOM pool changes composition from being primarily highly colored, terrestrially derived DOM to being less colored, algal-derived DOM (Hood et al. 2005). The drivers behind these shifts in DOM quality were recently evaluated in a quantitative reactive transport model (Miller et al. 2009). The results indicate that loss of terrestrial DOM is driven by photolysis of the colored DOM and production of algal DOM is proportional to the algal biomass (measured as chlorophyll a). Importantly, the summer drought in 2002 increased the residence time of water in the lake, and in association with increases in N deposition, caused a dramatic increase in the population of the pennate diatom *Fragilaria cyclopum* (Flanagan et al. 2009). Furthermore, the diatom species that bloomed during the drought is generally associated with zooplankton, such as Daphnia, and is present in the sediment record. This result suggests that there may be a greater importance of "top-down" controls on the phytoplankton under drought, low-flow, high lake residence time conditions compared to historical "bottom-up" controls caused by lake flushing during snowmelt – a major tipping point.

Alongside, and in response to, abiotic changes in climate and nutrient concentrations, biotic disturbances such as species invasions and infectious diseases have enormous potential to tip ecosystem properties and dynamics into novel circumstances. In aquatic environments, both

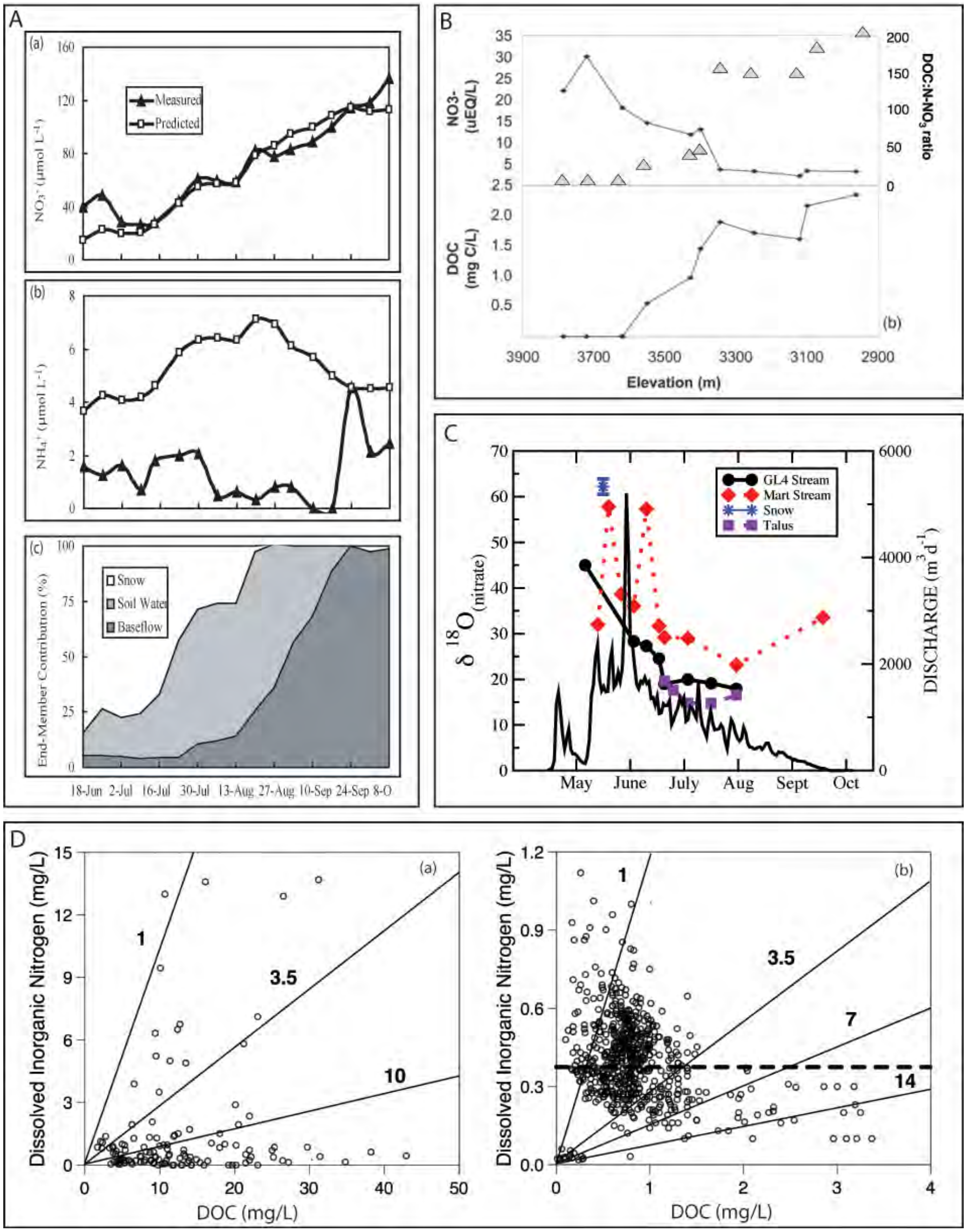

Figure 12. Coupled aquatic-terrestrial nutrient transport processes at NWT. **A**) Sources of nitrate (a) and ammonium (b) in the outflow of rock glacier 5 were evaluated by plotting observed versus predicted concentrations based on end-member mixing analysis (Williams et al. 2007). The lower panel (c) represents source waters in the outflow of RG5 for 2003 presented in Williams et al. (2006). **B**) **Upper panel** shows nitrate and DOC concentrations across a high to low elevation gradient at NWT. Blue triangles represent the molar ratio of DOC:N-NO3. **Lower panel** shows changes in δ^{18}O-NO3 as a function of the hydrograph (unpublished). **C**) DOC versus DIN for (a) soils and (b) lakes at the Niwot Ridge LTER. (a) Soil lysimeter and (b) lake column data show that DIN only accumulates at resource C:N ratios between roughly 1 and 10. The dotted line in Panel B is the EPA nutrient concentration guideline for Nr in ecoregion II. In these systems, DIN dominates the dissolved Nr pool.

disease and invasions influence host population dynamics, community composition, biogeochemical cycling, and physical structure (Edgerton et al. 2004; Koel et al. 2005; Cottingham and Butzler 2006; Johnson et al. 2006; Lafferty et al. 2008) in ways that contribute to novel ecosystem development. Such changes are not always independent of shifts in the abiotic environment, however. For example, increased nutrient enrichment can enhance infectious diseases in both human and wildlife populations (Johnson and Carpenter 2008; Johnson et al. in press), while climate change has already been linked to increased risk of infectious diseases and species invasions (Stachowicz et al. 2002; Harvell et al. 2004). Of particular interest is the presence and abundance of the invasive chytrid *Batrachochytrium dendrobatidis*, which causes chytrid epidemics in amphibians which are often most severe in high elevation systems (Kilpatrick et al. 2010). In 2009, we launched preliminary efforts to examine the importance of ongoing changes in climate and N deposition in affecting patterns of disease and invasions in alpine and subalpine lakes in the Colorado Rockies. We added zooplankton sampling to the existing GLV lakes monitoring program using a modified Schindler-Patalas trap, and sampled an additional 45 lakes and wetlands in the region for amphibians, crayfishes, and *Batrachochytrium*. These data already suggest that a) amphibians have disappeared from many historical sites, b) *Batrachochytrium* is patchily distributed, and c) crayfishes (*Orconectes virilis* and *O. immunis*) have expanded to many higher elevation sites relative to the historical record.

In order to gain a greater understanding of the response of the lakes to the presses and pulses described above, as well as the linkages between the terrestrial and aquatic environments in GLV, we will expand the lake ecosystem studies in the current proposal in several important ways. We will bring in a new investigator, Pieter Johnson, who conducted his PhD research at the NTL LTER program and is now an assistant professor at CU-Boulder, to complement the McKnight limnology team by adding an expert on zooplankton and invasive species. We will expand our use of *in situ* water quality measurements to include *in vivo* fluorescence sensors for phytoplankton and CDOM sensors, in collaboration with NTL LTER and GLEON. We will use two primary approaches to examine the importance of biotic disturbances in alpine and subalpine lake systems. First, we will expand the biological sampling performed on the Green Lakes to include zooplankton, crayfishes, amphibians, and selected chytrid pathogens. Second, we will conduct broad-scale surveys of alpine and subalpine lakes across gradients of both elevation and N deposition following Elser et al. (2009b) and Williams and Tonnessen (2000). To enhance comparisons with other LTER sites, we will follow the sampling protocol used by NTL for crayfishes and zooplankton (http://lter.limnology.wisc.edu/protocols.html). For subsamples of collected zooplankton and phytoplankton, we will also record the prevalence of chytrid fungal infections using standard microscopy techniques (Johnson et al. 2006).

Modeling. We have successfully developed a reactive transport model for lakes that resolves quantitatively the differences in sources of DOM and the within-lake reactivity of both the DOM which entered the lake from the landscape and the DOM that was produced in the lake (Miller at al. 2009). This model uses simple spectroscopic characterization of the DOM, which could eventually be accomplished using *in situ* sensors, to follow the rising input of algal-derived DOM in summer, for example. We plan to use this model to retrospectively analyze spectral data collected beginning in 2001 to determine the differences between years in production and degradation of DOM in Green Lake 4, and relate these differences to the climatic conditions. Once developed, we will then use this model to evaluate the potential response, in terms of DOM quantity and quality, to changes in the hydrology and climate under future climate regimes.

At the catchment scale, we will use remotely sensed snow cover data and a physically based snowmelt model to estimate the spatial distribution of energy fluxes, snowmelt, snow water equivalent, and snow cover extent over the different land cover types within the Green Lakes

Valley (e.g., Figure 3). The spatially explicit snowpack model is then coupled to the Alpine Hydrochemical Model (AHM) to estimate the quantity and quality of water at specific discharge points in the catchment (Meixner et al. 2000). This modeling activity is funded in part through a separate NSF grant (EAR 0738780). Preliminary results show that a comparison of baseline results from AHM compared to the coupled model significantly improved estimates of calcium and nitrate fluxes from 70% to 82% (Molotch et al. 2008). Separately, we are developing a coupled fluid flow and heat transport groundwater model driven by field data collected by NWT LTER (EAR-0934647) that will add to our understanding of surface/groundwater connections in high-elevation catchments. One major outcome from this modeling effort is that we will obtain an infiltration rate that will offer insights on mountain recharge from melt waters. Improvements in our understanding of flowpaths, nitrate cycling, within-lake DOM production and transport, and other factors will be incorporated into this watershed modeling approach.

COUPLED SOCIAL-ECOLOGICAL SYSTEMS IN THE COLORADO FRONT RANGE (COFR): THRESHOLDS, STABLE STATES, AND TRADE-OFFS ACROSS ECOSYSTEMS SERVICES.

Mountain ecosystems provide important ecosystem services worldwide, including clean water, wood, minerals, livestock forage, and recreation, among others (Price 2006; Körner and Spehn 2002). As an overarching conceptual science framework, we have developed a feedback loop model and addressed questions for the COFR (bounded on the west by NWT LTER and on the east by SGS LTER) that is based on the LTER strategic research initiative “Integrative Science for Society and the Environment” (ISSE) (Collins et al. 2007; Figure 13a). Crossing a single threshold between alternative regimes often leads to a “cascading effect” in which multiple thresholds across scales of space, time, and social organization, and across ecological, social, and economic domains may be breached (Kinzig et al. 2006). The impact of such changes on ecosystem structure and function – including the creation of new stable states and or novel ecosystems – will extend to ecosystem services, their interactions, and trade-offs. Figure 13b represents the interactions between ecosystem services as a result of management for each of several individual ecosystem services (green = positive; red = negative). To illustrate one trade-off example, as climate regulation (C storage) has increased as a function of increasingly closed and dense forests, the capacity of landscapes to mitigate the size and intensity of disturbances (such as fires and insect outbreaks) has decreased. Trade-offs in ecosystem services, then, occur across space and time with different degrees of reversibility. But more than that, they often result in multiple ecosystem services being compromised for the benefit of a solitary ecosystem enhancement (Rodriguez et al. 2006). Figure 13c represents the relative change in ecosystem services since European settlement. A positive value (between 0 and 1) represents an increase in supply of that ecosystem service and negative value (between 0 and -1) represents a decrease. Recreation value, for example, has increased at the expense of both water availability and natural hazards.

We propose to build on the momentum of recent social science supplements — along with welcoming to NWT LTER economist Catherine Keske at CSU — to evaluate the interactions shown in Figure 13 by a) expanding the current imagery analysis and statistical modeling of land-use change in the COFR, b) using the COFR as a case study in the new ILTER synthesis project on ecosystem services, and c) adding a socio-economic component in collaboration with SGS LTER. Here we provide more information on the socio-economic component, which is new, by evaluating Q5 in Figure 13, which focuses on the interaction between human behaviors and human outcomes. Behaviors affecting natural resources in the COFR region (traditional mining, grazing, logging, road development, wildlife management, and recreation) have an impact on human outcomes such as government regulations, water quality/quantity, land management, and job creation. The relationship is bidirectional, it should be noted, since human outcomes yield

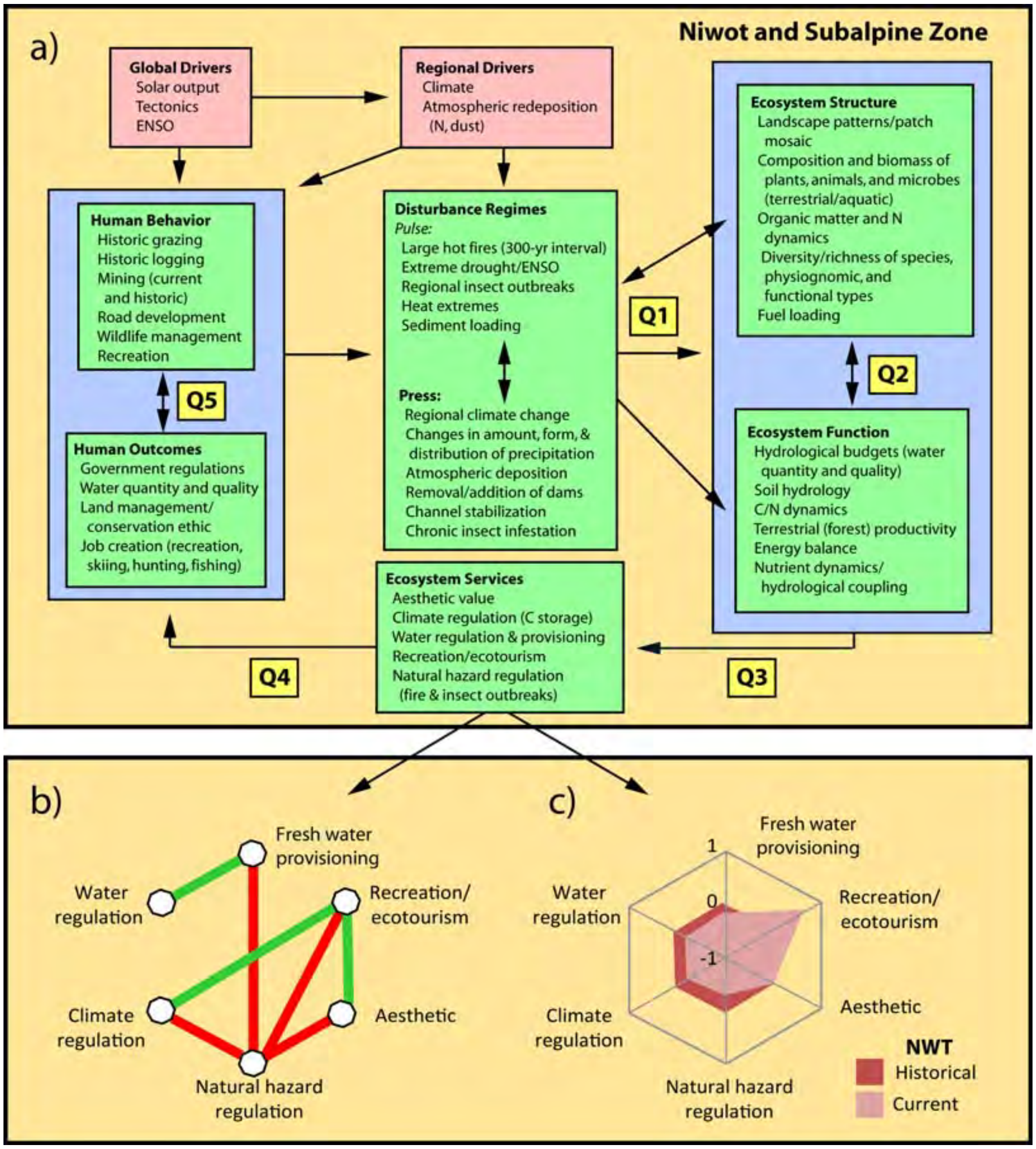

Figure 13. **a)** Feedback loop model and questions for the Colorado alpine-subalpine regional ecosystems. Q1: How do the pulse disturbances of extreme droughts and large/high intensity disturbances interact with long-term disturbances to influence threshold behavior and associated state changes in ecosystem structure and function? Q2: How are the feedbacks between landscape patterns and community structure and function affected by extreme and long-term changes in climate, fire regimes, and land-use? Q3: How do ecological changes affect regional climate and fire regulation, regional water budgets, and the supply of economic and recreational resources to residents? Q4: How will management of water systems and fire/insect outbreak landscapes for products and amenities be adjusted to observed, perceived, and predicted changes? Q5: How do perceptions and outcomes affect human behavior?
b) Interactions between ES as a result of management for each individual ES (green: positive; red: negative).
c) Relative change in ES since European settlement. A positive value (between 0 and 1) represents an increase in the supply of a particular ES. A negative value (between 0 and -1) represents a decrease in supply.

reactive human behaviors, and because the human dimension writ large impacts disturbance regimes, even for passive recreation activities. While the impact of human behaviors and outcomes on the feedback loop is profound and can be modeled a number of ways, the socio-economic aspect of this project will primarily leverage economic modeling to evaluate the interaction between human behaviors and human outcomes. Direct, indirect, and induced economic impacts from the identified human behaviors will be measured using input-output modeling (MIG 2003) which will yield information that includes economic growth, employment and a multiplier effect. Secondary data will be obtained from the National Park Service, US Geological Survey, USDA Forest Service, Bureau of Land Management, and US Fish and Wildlife Service pertaining to the respective industries and agencies within the COFR study area. These data will be integrated into a financial analysis (Stermole and Stermole 2009), which may include real options modeling (Davis and Samis 2006), and a benefit-cost model (Pearce 1997; Sassonne and Schaefer 1978). These models may also be integrated to assess economic impact on the primary aspects of the pulse-press disturbance model, such as forestry management for insect infestation.

When it comes to socio-economic evaluations, evidence also suggests that visitors place a high value on alpine recreation experiences (Keske and Loomis 2008; Loomis and Keske 2009). However, the potential economic benefits of recreation must be further balanced with the carrying capacity of the soils and the impact of human behavior on the disturbance regime. Humans also place value on indirect land uses such as clean air and clean water, and non-use values such as the existence of pristine or undisturbed areas. This project will measure the indirect values and non-use values of the COFR study area to evaluate the economic and ecological trade-offs between resource use and non-use. Values that humans place on ecosystem services such as carbon storage and aesthetic views will be measured through the use of a non-market valuation study using choice modeling (Louviere et al. 2000) and contingent valuation methodology (Hanemann 1984)

SYNTHESIS AND INTEGRATION:

Taking a step back, our overarching questions are:

1. How can we synthesize and integrate our understanding of hydrological, ecological, and socio-economic processes into a predictive understanding of our key ecosystem services at the catchment scale and then use that understanding at the regional scale?

2. How do we detect and quantify ecological tipping points that may occur in response to changes in climate, land use, and invasive species, which play out over decades?

Our approach is based on a multiscaled sampling strategy, using systematically deployed ground-based sensors, experimental manipulations, remote sensing of snow and other variables, as well as socio-economic analyses, and emphasizes consistent data standards. Such standardization promotes integration of our local site behavior with regional and national programs such as NEON, which allows us to address ecological processes at regional to continental scales and to observe transport processes (e.g. dust, N) that couple ecosystems across regional to continental scales.

The elements of our synthesis and integration include a) continued development of a new conceptual framework to test the ways in which a stoichiometric perspective may better predict N accumulation along the hydrologic continuum both within and beyond the NWT region; b) contributions to and validation of ecohydrological models of terrestrial water and nutrient cycling and export to aquatic systems; and c) integration with other research programs over regional scales.

Stoichiometric model. Here, we propose to build on a new conceptual framework and global meta-analysis developed by NWT personnel (Taylor and Townsend 2010) to test the ways in which a stoichiometric perspective may better predict N accumulation along the hydrologic continuum both within and beyond the NWT region. We argue that this framework, described briefly below, will not only shed new light on nutrient dynamics at NWT, but also that our LTER site presents an excellent test bed for evaluating the broader utility of stoichiometric models of nutrient accumulation. Taylor and Townsend (2010) developed the conceptual model based upon the tenets of ecological stoichiometry (e.g., Sterner and Elser 2002) to explain the coherence of C-nitrate relationships across systems, and the tendency for nitrate to accumulate only in systems that display low organic-C:nitrate ratios. Their conceptual model suggests that when such ratios match or exceed the C:N requirements of many microbial heterotrophs, inorganic N is rapidly immobilized into biomass and thus nitrate concentrations remain lower. Though space constraints prevent a full description here, the analyses done by Taylor and Townsend (2010) suggest that heterotrophic anabolism exerts a major control over nitrate accumulation in a diverse array of ecosystems, and that two other key processes that can affect nitrate concentrations – nitrification and denitrification – only rise in relative importance at low C:N ratios.

We will test and further develop this stoichiometric model of nutrient accumulation in several ways. Analysis of past data on C and N species (along with other nutrients) along flowpaths from surface soils to streams and lakes – along with continued collection of such data (as detailed elsewhere in this proposal) – will provide insight into the general stoichiometric patterns in the NWT landscape, and the conditions in which they may break down (e.g., strong snowmelt, unvegetated portions of watersheds, etc.) (Figure12). We will augment the lake, stream and soil solution chemistry analyses above with targeted sampling of long term N and P fertilizer plots in the tundra (e.g., Bowman et al. 2006), and of both intact and recently MPB-killed portions of the subalpine forest (Xiong et al. submitted). For the latter, NSF-SGER support has allowed us to instrument forested areas with both surface lysimeters and deep wells so that MPB-driven alterations in water chemistry can be assessed. Such data are important in their own right, but will also contribute directly (as a type of manipulation) to understanding controls over inorganic N accumulation in water (see Figure 12 for an example). We will work to incorporate stoichiometrically-driven predictors of N accumulation into the watershed scale modeling described elsewhere in this proposal. Beyond alteration of the model structure itself, such work will require targeted sets of lab and mesocosm-based experiments that identify a) the range of C:N values for microbial populations along the NWT hydrologic continuum, b) the ways in which those values change following C or N additions, and c) the ways in which bacterial growth efficiency changes following similar factorial resource additions. Determining the latter two factors – plasticity in C:N ratios and growth efficiency – allows the conceptual framework described in Taylor and Townsend (2010) to be reworked as a set of equations that can predict the relative contributions of microbial anabolism, nitrification and denitrification to measured concentrations of nitrate in soil solution, stream or lake water.

Ecohydrologic Modeling – SNOWPACK-Biome-BGC. Distributed ecohydrologic models provide the ability to derive spatiotemporal dynamics of root zone soil moisture, saturated zone levels, and various processes such as soil biogeochemical cycling, canopy evapotranspiration, and carbon cycling. Here we synthesize and integrate the various landscape components detailed above into Biome-BGC. We choose this model because it was used in the Vegetation/Ecosystem Modeling an Analysis Project (VEMAP) (Schimel et al. 2002; Kittel et al. 2004) to simulate high-altitude forests in the western United States. Further, model testing and validation from tower data have been conducted as part of an integrated, real-time MODIS and ecosystem model evaluation experiment conducted across the AmeriFlux network (Baldocchi et al. 2001). Within the model, snowfall is accumulated at the surface as snow water equivalent (SWE) depth. Snow cover sublimation and melt are computed from daily net solar (direct + diffuse) radiation and a modified thermal degree-day approach, while snowmelt is routed directly to a soil water pool.

The crude representation of the snowpack in Biome-BGC will be replaced with a new physically based snow module. The basis of the snowpack reconstruction model lies in the utility of Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover depletion curves for relating snow covered area to SWE. The fractional MODIS snow-covered area product will be acquired from the National Snow and Ice Data Center in Boulder, CO. We will then use a reconstruction modeling approach, which relies on remotely sensed snow cover data and energy balance modeling, to reconstruct the spatial and temporal distribution of SWE and rates of snowmelt (Molotch and Bales 2005; 2006; Molotch et al. 2004). Energy fluxes are directly transformed into water mass to derive estimates of sublimation and snowmelt. It is our intention to use Bayesian recursive estimation (filtering) techniques, including the related techniques of BaRE (Thiemann et al. 2001) and Ensemble Kalman Filtering (EnKF), as the basis for assimilating remotely sensed data into Biome-BGC for updating of the parameters. We will then evaluate snowpack controls on NEE at the watershed scale by coupling these estimates of snow accumulation and snowmelt to distributed runs of Biome-BGC. From this modeling approach, we will evaluate estimates of NEE using cross-validation data from our core observing sites. Comparisons of model performance between our enhanced version of Biome-BGC and the standard version of Biome-BGC will be used to identify the utility of our approach.

Regionalization. We are leveraging several additional programs to integrate and synthesize our results from the NWT LTER over a larger region (Figure 1). The alpine area of the NWT LTER is one of three headwater catchments that comprise the Boulder Creek Critical Zone Observatory (BC-CZO). Altitudinal gradients are among the most powerful 'natural experiments' for testing ecological and evolutionary responses of biota to geophysical influences, such as differences in air temperature (Körner 2007). Partnering with the BC-CZO allows us to evaluate the LCM in along a large altitudinal gradient: Green Lakes Valley (3,500 m), Como Creek (2,900 m), Gordon Gulch (2,400 m), and Betasso (1,830 m) catchments (Figures 1, 4). Initial results show that headwater catchments along this elevation gradient process nutrients differently (Parman et al. 2009), thus calling into question the universality of the LCM, but that snowmelt is still the primary source of streamflow (Cowie et al. 2009). A key component of the NWT LTER/BC-CZO partnership is the development of compatible hardware, software, and data standards to facilitate the integration and synthesis of information across the two programs.

NWT LTER is also partnering with NEON to establish a transect across the mountains from the Great Plains to the Colorado Plateau to address source-receptor relationships between land use change, climate change, and human activities on movement of dust, nutrients, and water, across a region we call the Prairie, Peak, Plateau (P3) region of the U.S. West (Baron et al. 2009) (Figure 1). NWT LTER is the core site for NEON domain 13 and the SGS LTER is the core site for the adjacent climate domain 10, effectively bounding the Colorado Front Range. The NEON transect is critical to understanding the changes wrought by soil disturbance, dust deposition, and agricultural and urban nitrogen emissions – from eutrophication and acidification of soils and lakes, to impacts on snow and Western water supply. As part of this regional focus on atmospheric deposition, the Neff lab is working to develop a regional understanding of dust deposition patterns and history using sites in the San Juan Mountains of Southern Colorado, NWT LTER and in the Wind River Range in Wyoming. This study is paired with and co-supported by an NSF grant to examine ecological responses to dust and nutrient deposition using lake sediment cores and diatom analysis (NSF DEB 0948823). One specific focus of this examination will be to examine patterns of biological response to nutrient deposition with the goal of understanding how aquatic responses to the history of N deposition at NWT compare to the changes in aquatic ecosystems elsewhere in the region.

Model Linkages and Forecasting Future Ecosystem Services. These syntheses and integration activities allow us to look forward – beyond the next decade and into the next century. For example, in the subalpine forest we have collected ten years of tower flux data which provide a perspective on the spatially-integrated forest stand and its response to climate across a range of scales, from diurnal, through seasonal, to interannual (Figure 14). In looking forward to the next ten years, we have designed a research plan that allows us to maintain this whole-forest perspective while also zeroing down to the level of individual species. This type of approach will allow us to anticipate changes in the flux of water, C and N due to the regional mountain pine beetle epidemic, changes in climate, and other perturbations, for example.

We will then explore ecohydrological feedbacks over the NWT LTER through the next century by running the distributed version of the SNOWPACK-Biome-BGC model with transient simulations of climate through 2100. The climate change scenarios will follow the protocols developed by Lazar and Williams (2008) for high-elevation mountain areas of the western U.S. For example, we will evaluate the 2030, 2050, and 2100 estimates of carbon flux to the measured conditions over the last decade and the model simulations. We will also compare our simulations against longer-term retrospective analyses (e.g., VEMAP; Schimel et al. 2002). In this regard, we can extend improved physical knowledge obtained from the NWT LTER research to projections of ecosystem sensitivity to climate change. Better models of ecosystem sensitivity can, in turn, be applied to our outlook for the respective health of high-elevation ecosystem services into the future – many of which (e.g., freshwater, climate regulation, etc.) are currently taken for granted and/or assumed to be systematically resilient. The notion of tipping points – as well as established knowledge of high-elevation areas' sensitivity to human-induced change – calls those assumptions into question, however, and brings a sense of urgency to our efforts to model future climate change scenarios.

Our approach to developing improved models of ecosystem services is to use scenarios to populate an impact matrix, and the scenario-planning process to capture the trade-offs between human benefits, such as financial gains, and environmental quality. By quantifying trade-offs among ecosystem services and their interactions with selected dimensions of human well-being, we can determine the risks that must be undertaken in various scenarios. Decisions to mitigate the risks of possible changes in ecosystem services depend on the capacity to predict the consequences of mitigation action (Carpenter et al. 2009). Specifically, we will seek to enhance our capacity to identify the outcomes of current activities and global change, and to compute probabilities for the different outcomes (Chapin et al. 2009). To achieve this, we will apply well-established and well-known risk management problems from the financial literature to environmental models (Hoag 2009). This accomplishes two goals. First, it easily captures the financial side of ecosystem services. Second, it puts the non-financial aspects in a comparable realm, as both can be compared using similar units of measurement.

One model for describing trade-offs is an "impact matrix" (Hoag et al. 2005). An impact matrix visually captures the trade-offs between human benefits, such as financial gains, and environmental quality. The variables presented in the matrix—and the trade-offs that will be measured—will change, and will likely depend upon the uncertainty studies conducted in a prior phase.

A complementary approach for measuring trade-offs is scenario planning. Scenario planning (van der Heidjen 1996, Kahane 2004) is a creative exercise that is particularly well-suited to

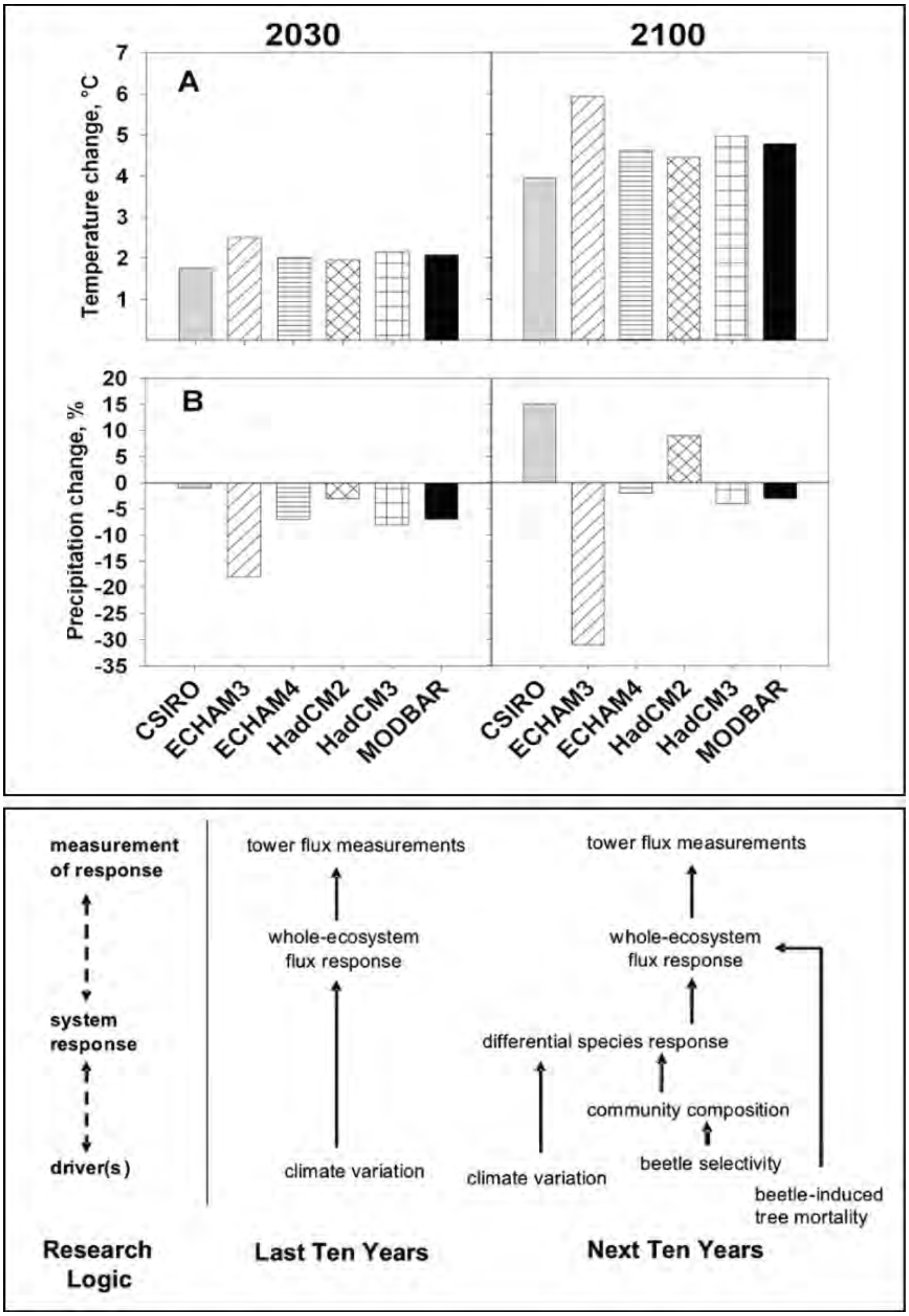

Figure 14. **Upper panel**. Estimated changes in temperature for NWT LTER in 2030 and 2100 (relative to 1990) using the A1B scenario (adapted from Lazar and Williams, 2008). Under this scenario, the average model warming is 2 ºC with a range of 1.8 to 2.5 ºC by 2030. By 2100 the average annual temperature increases by 4.8 ºC with a range of 4 to 6 ºC. **Lower panel.** The mountain beetle epidemic is altering ecosystem-atmosphere fluxes of CO_2, water and energy to forested regions of the western US. We are likely to have the rare opportunity to observe these interactions in an intact forest ecosystem across decadal time scales. We have presented a diagrammatic representation of where we want to take the research over the next ten years, relative to measurements the past ten years.

considering complex systems, fundamental uncertainties, and conflicting values. Scenario planning will be used to describe and quantify (where possible) the causal chain by which one or more ecosystem services and their intrinsic values are delivered. Of particular interest to this project will be the shape of the curves relating various levels of activity to the corresponding levels of delivery for key ecosystem services (Scholes and Maltitz 2007). This analysis will provide the basis for the analysis of resilience of these ecosystem services (e.g., the decline of the ability of the landscape to regulate fire in the wildland-urban interface; Spyratos et al. 2007; Bourgeron et al. 2009).

SUMMARY

We believe that changes in drivers such as climate change, N deposition, and dust deposition may be 'tipping' high-elevation ecosystems into new states not experienced in recent Earth history. To meet this challenge, our proposed research for the 2011-2016 funding cycle integrates past strengths with the need to expand our synthesis and integration at watershed to regional scales. This presents conceptual and practical challenges for which we have developed observational, experimental, and synthesis initiatives that incorporate both new and proven empirical and modeling approaches to integrate complex information at the scale of the Colorado Front Range (Figure 15).

The success of our proposal rests on the composition of our research team and the management of the project (Section 3), the accomplishments and approach to information management (Section 4) that ensure that different groups of collaborating investigators can develop a comprehensive knowledge of local-to-regional systems, and a strong outreach program that communicates our successes and that of the LTER network to the K-12 educational community and the general public. We are confident that the NWT LTER has the potential to be a leader in mountain research and expect our results will be of considerable interest to policy makers, planners, and the business community of the Colorado Front Range and other mountain areas of the Western US and internationally.

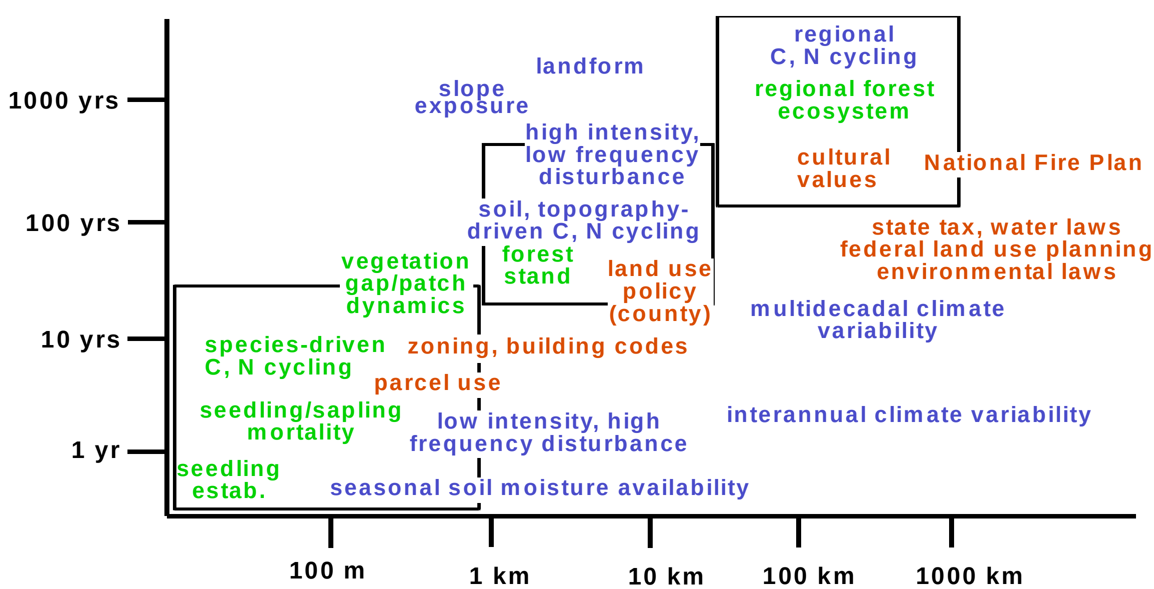

Figure 15. Colorado Front Range social-ecological hierarchy.

Section 3. Management of the Niwot Ridge-Green Lakes Valley (NWT) LTER

History: Part of the first cohort of LTER sites, the NWT LTER began in 1980 as a University of Colorado (CU) Institute of Arctic and Alpine Research (INSTAAR) multi-investigator ecosystem program. The LTER consisted of a consortium of PIs, each managing his/her own programs. This model was deemed unsuccessful, and an improvement and reorganization of the program commenced in 1990 under the leadership of Dr. Nel Caine, who is now retired from CU-Boulder but remains actively involved with NWT LTER. Faculty outside of INSTAAR were recruited to the program, including Dr. Tim Seastedt, the administrative PI on the 1992 and 1998 renewal proposals. An Information Manager for the NWT LTER was hired, and additional core staff (lab coordinator and field technician) were added in 1992.

Current: Since 1998, the NWT LTER program has been directed by the PI, who is responsible for developing the annual budget and coordinating the infrastructure and science programs. The signatory Co-PIs support the PI on administrative activities both locally and for the LTER network. All Co-PIs are involved in science writing, the overall science program, and program development (Figure 16). Science coordination is accomplished via e-mail, LTER meetings at INSTAAR, faculty and graduate student seminars, and an annual full-day workshop held in late August at the Mountain Research Station (MRS). The graduate students involved in NWT studies, a group larger than that comprised of PIs, are an important intellectual and social linkage for the group.

NWT LTER is fortunate in that the majority of our senior scientists are at CU-Boulder; the only subcontract is to Professor Katie Suding at UC-Berkeley, a former post-doc at NWT LTER. We emphasize that the science component of NWT LTER is clearly a group effort. The LTER program focuses on those projects and studies that can be accomplished using (1) the core staff of LTER field, laboratory, and information management personnel; and (2) a partially-supported investigator and graduate research program. Intensive science efforts require extramural support beyond that provided by the LTER; therefore, our group uses LTER funding to address a framework of core questions, but also uses these data to leverage additional support to enhance particular research efforts. From 2004 to 2010, LTER senior personnel have generated extramural funding of about $20,000,000 on LTER-related projects, a return of almost 5 dollars for every LTER dollar. We have also leveraged NWT LTER participation in two large new environmental observatories: (1) the Boulder Creek Critical Zones Observatory for which the NWT LTER is one of three test basins; and (2) NEON, where NWT LTER is the core site for the Southern Rocky Mountains-Colorado Plateau (domain 13).

The Mountain Research Station remains a major component of the NWT LTER program. Directed by Bowman (Co-I on this proposal), the MRS provides logistical support for the LTER program. The MRS coordinates (1) our involvement in the Niwot Ridge Man and Biosphere site, the special-use permit by which we operate on the Forest Service lands used for most terrestrial research; and (2) research in the Green Lakes Valley, which is owned by the City of Boulder and requires very restrictive special-use permits. The MRS houses the offices for the field technician and climatologist, maintains the Tundra

Laboratory at 11,500’, and organizes travel from the field station to the tundra sites. Completion of the family-friendly Moores-Collins Lodge in 2005 provides year-round use of the MRS for families, courses, retreats, and conferences. The lodge is self-sufficient, with the capacity to house 32 people in 8 sleeping rooms, and contains a kitchen, bathrooms/showers, a meeting/eating room, and lounges. In addition to training several undergraduates annually as part of the LTER-REU supplement, LTER researchers comprise much of the faculty involved in a site-based REU summer research program at the MRS (Bowman PI). These students are housed at the MRS and work on their own projects alongside graduate students and faculty. This program has been remarkably productive, with many of these students lead-authoring or co-authoring research efforts published in journals worldwide.

Changes: Experience has shown that the 1998 management model is appropriate for our site, with the following changes. First, continuity of leadership has been ensured; Williams was the PI for the 2004 renewal and has the same role for this proposal. Williams will transition off as PI for the mid-term site visit so that the new PI will have three years of experience with the LTER network before writing the renewal. We have formed an internal executive committee that is composed of the Co-Is on this renewal to provide feedback to and oversight of the lead PI. The executive committee met weekly for two months in fall 2009 to craft the outline and overarching objectives of this proposal. For this round of founding, we will form an external steering committee to facilitate synthesis and integration of NWT LTER with other regional programs, including the PI of the Boulder Creek CZO, USGS lead for the Loch Vale WEBB program, the USFS lead for their GLEES program, and the project scientist for domain 13 of NEON.

Postdoc mentoring: Post-docs on this proposal will receive individual and group mentoring. Williams as PI will have ultimate responsibility for the mentoring program. NWT LTER scientists whose discipline the post-doc most closely matches will have day-to-day mentoring responsibilities, e.g., Schmidt will mentor Mladenov. Our mentoring plan consists of three parts: a) self-assessment by the postdoctoral scholar; b) scheduling regular meetings; c) conducting a final evaluation.

Diversity: We have several strategies for enhancing diversity at the NWT LTER. One is to lead by example. Mark Williams, the PI on this renewal, is a Hispanic and a first-generation college graduate. Also, we participate in the Summer Multicultural Access to Research Training (SMART) program, allowing under-represented undergraduates to conduct summer research in science and engineering. Several members of the SMART program are now graduate students working at NWT LTER and mentoring new undergraduates. Finally, we actively recruited women to be senior scientists and postdocs on this proposal.

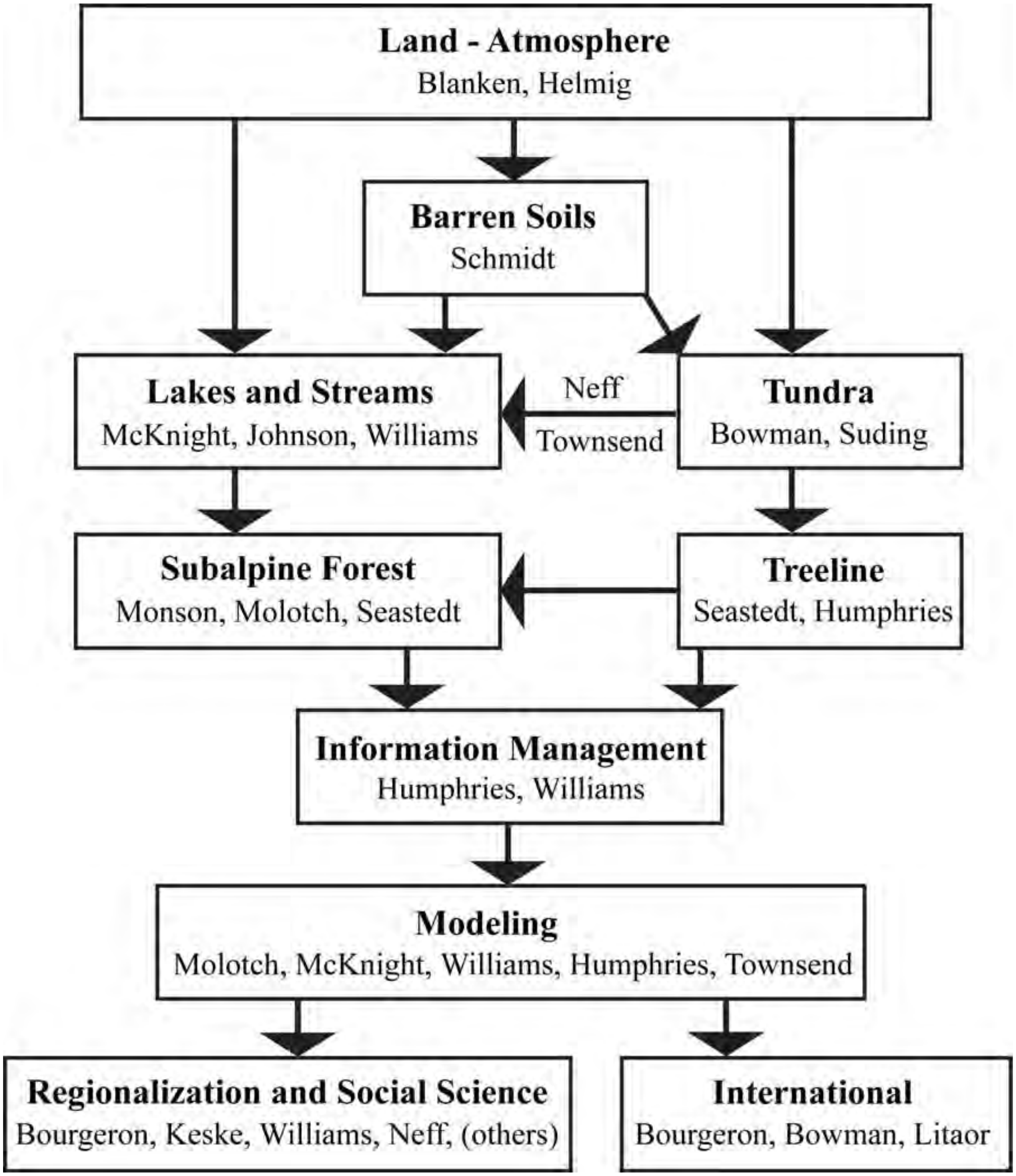

Figure 16. Site management plan.

Section 4. Information Management (IM)

The primary goals of the Information Management program are to ensure the quality, security, and integrity of data collected at NWT LTER. All current IM procedures are consistent with the revised IM Network Guidelines. The formal Data Management polity can be viewed at: http://culter.colorado.edu/NWT/data/datman_policy.html.

Data. Non-spatial data is viewed as comprised of one of three "types": 1) electronically provided data collected by equipment; 2) data provided on hard-copy field forms or charts; or 3) electronically provided data not directly downloaded from electronic equipment. Data sets are archived according to the type of data. Data files are organized and stored as ASCII text files containing both metadata headers (where metadata is defined as all information such as materials, methods, parameter units, etc. that are necessary for proper interpretation of a data set) and the data. Our primary data dissemination method is web-based. Finalized data sets are made available and are searchable via the NWT LTER data search page (http://culter.colorado.edu/NWT/data/datmansearch.html). Data sets are stored online. For some data sets, the metadata note the existence of finer temporal resolution data that are not available online, but may be obtained from the data manager. Datasets are updated as often as possible; continuously collected datasets have an update lag time of 1 month to a maximum of 2 years; e.g., Kiowa wet chemistry lab data takes approximately a year for sample analysis and conducting QA/QC procedures. Basic tracking of data downloads currently takes place by web access to the "data access agreement" page. 151 non-spatial and 59 spatial data sets are available online. An additional 19 data sets have been received by IM but not yet posted; of these, 13 require further processing and 6 are ready to post.

Metadata. Metadata headers are mirrored in a relational database that allows for automated EML generation. As ASCII data files are updated, a Perl script updates the metadata information in the relational database. We currently have high-level EML being generated for all available tabular data and some vector GIS data. Raster data EML generation is in development. Our current standing in the EML hierarchy is level 3, with elements of levels 4 and 5. Five additional elements are necessary for existing tabular data to reach level 5 EML (<intellectualRights>, <project>, <methods>, <constraint>, and <qualityControl>). New data sets meet level 5 criteria; the lead PI has not allocated resources to move other data sets to level 5 to date. NWT EML is harvested daily by the KNB EML harvester, where any updates are archived.

Hardware. The main file server that serves as the archival location for data is a Sun Microsystems SunFire V250 with 270GB of storage space. This machine also acts as the primary web server for the NWT LTER project. In addition to the UNIX server, we have a Dell PowerEdge 2600 Windows server, which downloads all meteorological data collected via wireless radios. The Dell is our relational database server, running Microsoft SQL Server 2005; it also handles generation of EML metadata. A ReadyNAS NV+ server acts as our FTP server, delivering all spatial data and associated metadata.

Security. Data is protected with UNIX permissions and group designations to prevent unauthorized manipulation of data files. Source-code versioning protocols are used to retrieve earlier versions when necessary. Incremental backups are performed nightly and full backups are performed every 60 days for our UNIX server; backup tapes are stored offsite. Within the next 1-2 months, we will replace the tape-based backup system with a ReadyNAS NV+ desktop server, which will be housed offsite and will be used for incremental and full backups of the UNIX server. Our PC server is backed up weekly to tape.

Management. NWT LTER supports a full-time position dedicated to IM. Additionally, the information manager has a stand-alone account that receives $17,000 in discretionary funds each year, reflecting NWT's commitment to investing in data management. In 2008, Todd Ackerman, information manager since 2001, transitioned to half-time and Hope Humphries was hired as his half-time replacement. In August, Ackerman resigned and Humphries became the full-time manager. A strong link between the manager and PIs exists through regular meetings with the lead PI, and through interaction at NWT meetings. The manager becomes involved in research projects as early as possible by meeting with the PIs. Annually submitted Mountain Research Station (MRS) Research Applications help to alert the manager to new projects and any changes that may occur in existing ones. Incentives for PIs to submit their data include independent archiving to a computer that is regularly backed up, script writing for data processing, and the ability to point other researchers to their data for quick access.

IM data entry tasks include scanning and keying field forms using Visual Basic forms developed by IM staff. These data are moved to the SunFire V250, processed with scripts, and then archived. Visual Basic data entry forms are customized to mirror field data forms exactly, thus reducing errors and entry time. The forms employ lookup tables as well as a re-key function to decrease entry mistakes. Field forms, charts, maps, photographs, and paper documents are all stored in the IM lab housed at INSTAAR. Programs and procedures are documented in real-time in our living documentation.

Currently all NIS modules have NWT participation. Ackerman has represented NWT at every IMC meeting since 2001, as well as the two ASMs since then. He served on the IMexec committee and the LTER GIS Committee. He led the Unit Dictionary Working Group with SBC and BES managers and organized training for LTER managers with the SGS manager. In January, 2007, he participated in the post-ASM workshop on derived datasets. Humphries attended IMC meetings in 2008 and 2009, participated in a training workshop held in Albuquerque in May 2008, and was NWT's IM representative at the 2009 ASM.

Publications. All current and in-press publications are listed in the Publications section of the website: http://culter.colorado.edu/NWT/publications/publications.html and are searchable by author, keyword, title, and year. The site bibliography is maintained in InMagic format.

Website. The website has been completely redesigned since the last renewal, taking into account suggestions from the information management community and local PIs. The new design provides easier access to data, publications, and information regarding NWT LTER. Hourly real-time meteorological data has been more prominently featured on the main home page, and continues to be a valuable source of information for local researchers as well as the general public. The climate data display now includes data from the Albion townsite, Green Lake 4, and Arikaree stations in addition to the D1, Saddle, and C1 stations.

The TundraCam has been a popular NWT LTER web destination, and the website was redesigned in 2007 to further its role as a significant outreach tool (http://instaar.colorado.edu/tundracam/index.php). During the period 2004-2006, the TundraCam averaged more than 12,000 visits per month compared to 5,000 visits per month in 1998-2003. However, due to technical problems with the camera, visits dropped to 5,000 per month in 2008 and 1,000 per month in 2009. TundraCam problems since 2007 have included 2 camera failures and internet access problems. Currently, the camera overloads when made available to the public; consequently, only still images are now displayed. Further testing of the system to attempt to resolve the problem is underway.

A website has been developed to accompany the "My Water Comes from the Mountains" children's book to display information about the book and, importantly, artwork contributed by each individual student from various schools in the Rocky Mountain region (http://culter.colorado.edu/MyWater). A website has been initiated for the Rocky Mountain Lake Algae outreach effort that contains images, taxonomic information, and data for hundreds of algae taxa, mostly from lakes in the NWT LTER site, but also from nearby Rocky Mountain National Park (http://culter.colorado.edu/lake-algae/). The Alpine Microbial Observatory (AMO) website complements NWT LTER microbial research (http://amo.colorado.edu). When the AMO grant (DEB 0455606) expires in 2010, NWT will host and integrate the AMO website and database.

Communications. Currently 10 meteorological sites are serviced by frequency-hopping radios. Three sites have recently been enhanced with High Throughput radios which support Ethernet as well as serial communications. Ethernet communications at the Soddie lab enable remote control and management of the computer which interfaces with the instrumentation. The radios allow for troubleshooting problems quickly. Previously, such problems could have gone weeks without notice. The installation of the radios has saved time and energy for researchers and MRS personnel, adding the ability to perform minor tasks such as changing data logger programs or rebooting upon system failure. A wireless connection from MRS to Boulder, replacing the previous T1 connectivity, has been completed. This system consists of a fiber-optic line from MRS to the TundraLab, and a wireless connection from the TundraLab to the world with a bandwidth of 3mbs.

Spatial Data. Spatial data sets are searchable and can be downloaded from an FTP site accessed via our web page (http://culter.colorado.edu/exec/Database/gis_layer_query.cgi). A 1m Lidar DEM data layer covering the Green Lakes Valley and Saddle site was obtained through the NSF-sponsored National Center for Airborne Laser Mapping (NCALM). One-meter resolution subwatershed boundaries were generated for the study site using the elevation data, an improvement over the previous 10 m resolution. A major accomplishment was the release, in the fall of 2009, of a set of high-resolution orthophoto mosaics and accompanying DEMs and accessory map layers for NWT, including twelve "timeslices" encompassing the past seven decades (Figure 17a). These map layers are available from our FTP site. Figure 17b-c demonstrates the potential usefulness of the imagery for change detection. A new fine-scale land cover map is currently under development by Humphries, and will be used to determine the current spatial distribution of vegetation, document phenological changes over time for the National Phenology Network, examine treeline and shrub movement, and conduct biogeochemical modeling.

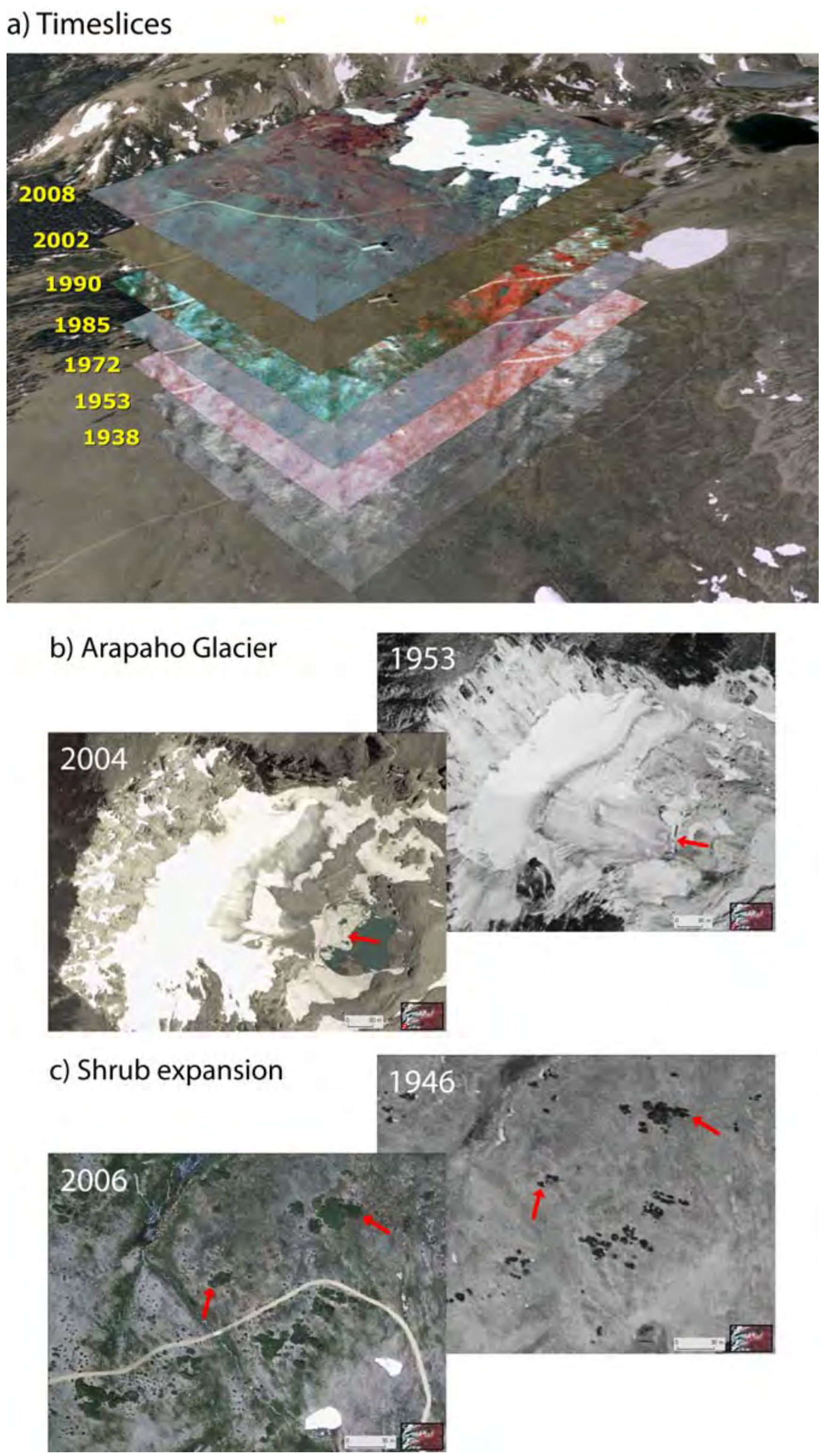

Figure 17. Illustration of use of orthoimagery for change detection. **a)** Orthoimagery timeslices. **b)-c)** Arrows indicate areas of change between time periods. **b)** Arapaho Glacier in 1953 and 2004; **c)** Shrub expansion from 1946 to 2006.

Section 5. Outreach Efforts

K-12 Outreach Program. The theme of the NWT LTER K-12 outreach program is the connection between alpine ecosystems and communities of the Rocky Mountain Front Range. Since 1998, NWT LTER has had an outreach program to elementary and middle school students in the Boulder/Denver area through a collaborative effort with Science Discovery, a local program based at CU, Bixby School in Boulder, and Wild Bear Science School in Nederland, a small mountain town located near MRS. To reach middle school students more directly, for the past several years INSTAAR has held an event in which 200-500 middle school students come to INSTAAR for a half-day of lab tours and a science lecture. NWT LTER scientists demonstrate field methods for measuring stream flow, sampling water quality, and collecting aquatic biota at nearby Boulder Creek.

LTER Schoolyard Book Series. We continue to take a lead role in developing this children's book series. We edited and published a DVD for the LTER network on how to incorporate LTER science into K-12 education: "***Scientific children's literature: Perspectives for planning the Schoolyard Book Series of NSF's Long term Ecological Research Network***", edited by Diane McKnight and Monica Elser. The DVD is based on a 2005 workshop held in Boulder, CO: "***LTER Workshop on Scientific Children's Literature***", with support from NSF (DEB 0423662). McKnight serves as the Chair of the Editorial Committee for the series, which provides guidance to scientists and educators at other sites as their book projects are developed. We published two new versions of the children's book "***My Water Comes from the Mountains***" in 2009 that were distributed to more than 2,000 3rd and 4th graders in SW Colorado (Figure 18). Our goal for this renewal is to develop a Spanish language edition, "***Mi Agua Viene de las Montanas***," and an associated Spanish-language Teacher's Guide for use in bilingual schools throughout the western US.

Teachers Guide and Materials Packet. In 2006, we published "***MY H2O: My Water Comes from the Mountains Teacher's Curriculum Guide and Kit***"; with funding support from: US EPA, sLTER, University of Colorado-Boulder Outreach Committee, the City of Boulder, and the Watershed Approach to Stream Health (WASH) Project. The Teacher's Guide adds accompanying lessons, incorporation of water-wise sustainability in the classroom and community, and improvement of environmental education teaching skills with exemplary projects and practical edification. Each section includes a thorough explanation of 7-8 interactive projects, along with corresponding background information, suggested approaches, and the book's parallel page number(s) for supplementary purposes. In addition to the Teacher's Guide, a complementary Materials Pack supplements the Guide and recommended activities by containing all required supplies and instruction tools to implement each activity.

Presidential Awards for Excellence in Mathematics and Science Teaching Recognition Program. In January 2010, the book series was highlighted at an event at NSF honoring 87 award-winning elementary teachers from around the US. McKnight participated in breakout sessions on School Yard Ecology with Todd Crowl and other

NSF program officers, gave a presentation about using narrative to promote active science learning for elementary students, and provided handouts (Figure 18).

TundraCam. The alpine and subalpine zones are places of spectacular beauty, and are therefore places of high visitor potential. However, the rigors of high elevation, steep topography, and lack of road access preclude the use of our site by a large number of visitors. A partial solution to this dilemma of visitation versus protection was to install a "TundraCam", a *live* and *interactive* webcam located at the NWT LTER site at an elevation of 11,600 feet. We upgraded our web page, and during the period 2004-2006, our TundraCam averaged more than 12,000 visits per month compared to 5,000 visits per month in 1998-2003 (http://instaar.colorado.edu/tundracam/). However, due to technical problems with the camera, visits dropped to 5,000 per month in 2008 and 1,000 per month in 2009. A goal of this renewal is to fix these technical problems.

The "Rocky Mountain Lake Algae" Website (RMLA) is a new outreach effort that answers basic questions like "What are algae"? This effort builds on the success of our undergraduate education program supported by the NSF grant: "CU-LTER Scholars Program in Biology and Applied Math for Undergraduates, $99,927, 9/03-8/07". With supplemental funds we initiated a website that contains images, taxonomic information, and data for hundreds of algae taxa, mostly from lakes in the NWT LTER site, but also from nearby Rocky Mountain National Park: http://culter.colorado.edu/lake-algae/. Remaining work that will be completed in the first two years of this renewal, before a formal launch of the website, includes uploading taxonomic information, writing the K-12 version of the main text, cleaning up some existing data, and putting existing references into the database. A new camera will help this process; the FlowCAM (by Fluid Imaging Technologies) automates the process of characterizing and enumerating algae and other particles by employing flow-through imaging software that photographs and records different algal communities and allows the user to build a database of distinct organisms (EAR 0930048; 2009).

NWT LTER Supports ECOARTS. NWT LTER helped support and participated in a unique outreach activity that combined performance art with science. EcoArts is a collaboration of 22 science, environmental, arts, indigenous, and other organizations in 3 cities to increase awareness of climate change and sustainable living. Each performer brings his/her own unique artistic sensibilities to "Balancing Acts" – and all of them are not what one might expect. For example, Michelle Ellsworth describes her collaboration with biogeochemist Jason Neff, visual artist Priscilla Cohan, and composer Michael Theodore as "a dense and efficient performance piece about 'the situation' that employs choreography, chatting, and lubricated ball bearings to explore the complexities and interconnectedness/co-dependence of sex, blame, and science."

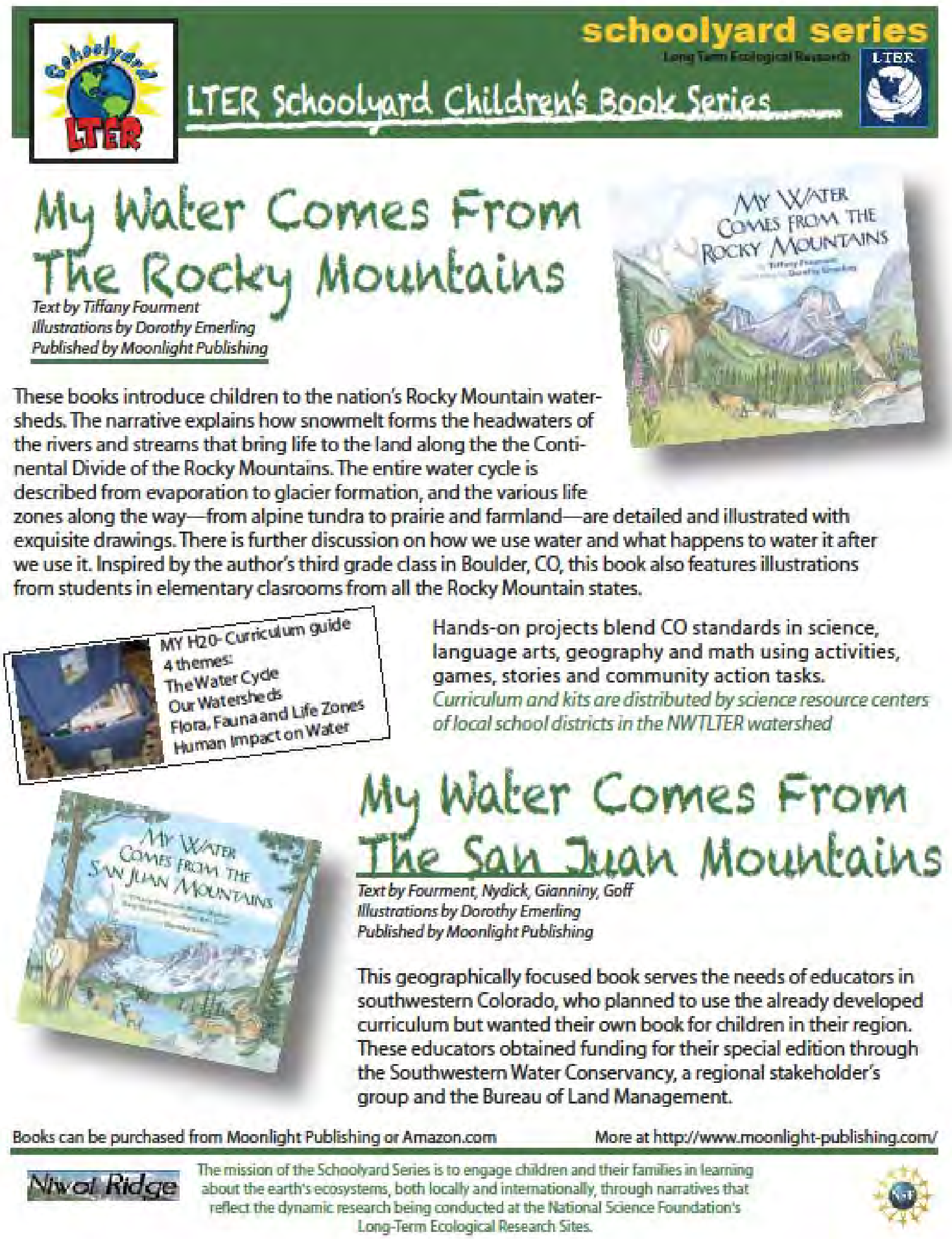

Figure 18. Handout for the School Yard Ecology breakout session at the January 2010 "***Presidential Awards for Excellence in Mathematics and Science Teaching Recognition Program*",** which features the children's book "***My Water Comes from the Mountain***s" and the 2009 regional version "***My Water Comes from the San Juan Mountains***."