Section 1. Results from Prior Support

The primary objective of the 1998-2004 proposal was to understand the influence of increased snowpack and atmospheric N deposition on ecosystem processes and landscape patterns, with increased emphasis on the biotic feedbacks and ecosystem responses to these changes. We also proposed to more fully exploit the long-term data sets available from the pre-LTER, LTER and non-LTER data collected in the greater Niwot Ridge area, and to include not only the alpine but the adjacent subalpine ecosystems as well. Our 2001 site review praised the productivity and quality of research at the NWT LTER and emphasized that we would significantly benefit from (1) regionalization of results and increased cross-site collaboration; (2) synthesis activities; and (3) a unifying conceptual model.

Reviewers are strongly encouraged to visit the NWT LTER homepage at http://culter.colorado.edu and use the expanded, electronic version of the full text of this proposal by clicking on '2004 proposal'. Space limitations demand that methodological details regarding collection, analysis, and frequencies of data be relegated to linked documents in the electronic version of this proposal, such as the Kiowa environmental chemistry laboratory procedure manual.

Publications: The quantity and quality of publications increased substantially since the prior funding period. Peer-reviewed publications increased by 41%, from 85 in 1992-1997 to 120 in 1998-2003. The total number of peer-reviewed publications, books and book chapters, and graduate dissertations/theses increased by 51%, from 123 in 1992-1997 to 186 in 1998-2003. We have also published manuscripts in *Nature* (Neff et al., 2002), *Science* (Schadt et al., 2003), and *Frontiers in Ecology and the Environment* (Townsend et al., 2003) for the first time.

Data Sets: On average, one or more of our data sets are accessed more than 600 times per week. Our homepage is currently accessed an average of 690 times per week by non-NWT LTER-associated computers. A search of our data sets by keyword or investigator is performed an average of 26 times every week by non-NWT LTER-associated computers. Independently, our TundraCam averages more than 5,000 hits per month (for more detailed information, see Section 5). An innovation in web-accessed data availability was the development of an interactive web site that allows information from an enhanced meteorological station and subnivean laboratory on Niwot Ridge to be accessed by all scientists and can be queried by time step, instrument type, and other parameters (Williams et al., 1999). Moreover, we now post climate data in real time on our NWT LTER web site from the D1 (3,739 m), Saddle (3,528 m), and C1 (3,022 m) meteorological stations.

Long-Term Measurements: Long-term monitoring at Niwot Ridge began in the 1950s with the installation of meteorological stations along an elevational gradient. Temporal analysis of four decades (1951-1996) of instrumented climate records show (1) decreasing autumn temperatures ($-0.043\ ^{o}C/yr$) but no significant annual cooling; (2) a decrease in incident summer solar radiation ($-1.04\ W/m^2/yr$) between 1965 and 1996; and (3) an annual precipitation increase of 11.0 mm/yr (Greenland and Losleben, 2001) (Figure 2.1a). Additional research has found: (1) an extreme cold temperature event from

1981-86 (Kittel et al., 2002); (2) different lapse rate changes at different elevations between 2,200 and 3,749 m (Pepin, 2000); (3) elevationally dependent differences in precipitation chemistry (Losleben and Pepin, 2000); and (4) decoupled climate conditions between upper and lower troposphere (Kittel et al., 2002; Williams et al., 1996a). The increase in annual precipitation and decrease in summer shortwave radiation are consistent with most model scenarios using doubled atmospheric CO_2 of increased annual precipitation and increased water vapor, but the lack of an annual temperature increase on Niwot Ridge is inconsistent with model predictions of increasing air temperature.

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 on Niwot Ridge, and also the subalpine Sugarloaf site at 2,524 m. Annual deposition of inorganic N in wetfall at the Niwot Ridge site showed a significant increase of 0.3 kg/ha/yr for the 1984-1996 interval (Figure 2.2) (Williams and Tonnessen, 2000). A sophisticated analysis of atmospheric deposition of pollutants throughout the entire Rocky Mountain Region from Canada to Mexico shows that nitrate and sulfate deposition increase from north to south, with hot spots of deposition in the Colorado Front Range (Nanus et al., 2003). Burns (2003a) shows that the increase of inorganic N in wetfall in the Front Range is partly driven by increases in the metropolitan population east of the Front Range.

Ice thickness measured in late March over a 20-year interval shows a statistically significant thinning of winter lake ice cover (2.0 cm/yr) that is best explained by increased winter precipitation (about 1% per year) and warmer water temperatures, leading to increased flows into the lake in fall and winter (Figure 2.1b) (Caine, 2002). Pre-LTER streamflow and water quality records have been supplemented by a much larger and ongoing effort at multiple sites in the Green Lakes catchment since 1982 (Williams and Tonnessen, 2000; Williams et al., 2002), with comparison of results to other sites in the Rockies (Baron and Caine, 2000; Meixner et al., 2000) and across North America (Soranno et al., 1999). New emphasis has been placed on the measurement of organic nutrients, including yields of C, N, and P (Hood et al., 2002), seasonal changes in the character and N content of organic matter (Hood et al., 2003a), and sources and chemical character of dissolved organic matter (Hood et al., 2003b; Williams et al., 2001).

Nitrate concentrations in stream waters have been increasing, apparently in response to these increases in atmospheric deposition of inorganic N (Williams et al., 1996b). Acid neutralizing capacity in these alpine lakes has decreased significantly at the rate of about 4 ueq/L/yr (Williams and Tonnessen, 2000), to the point that episodic acidification is now occurring during snowmelt runoff (Williams et al, 1996a). Recently collected sediment cores from several Front Range lakes, including Green Lake 4 (GL4), indicate long-term shifts in diatom populations that are consistent with increased atmospheric N deposition beginning in the mid-20th century (Wolfe et al., 2001; Wolfe et al., 2002; Waters et al., in press).

Plant species composition and abundance studies were initiated at Niwot Ridge in 1953, and these plots that have been periodically inventoried through 1996 (Korb and Ranker, 2001). These carefully preserved areas have been supplemented by plots established by

May in 1973, and a much larger number of plots established by M. Walker in 1987. Additional permanent plots were added by Bowman in 1990 and by Seastedt in 1993. Data for all plots are found on the LTER web site (http://culter.colorado.edu/Niwot/NiwotRidgeData/PlantProductionandPhenology.html; http://culter.colorado.edu/Niwot/NiwotRidgeData/PlantSpeciesComposition.html). Sites now include those that represent 'control' plots placed over a landscape grid, as well as plots specifically established to measure nitrogen additions (e.g., Bowman et al., 1993) and impact of enhanced snowpack (Seastedt and Vaccaro, 2001).

A snowfence 60 m long and 2.8 m high was erected in 1993 to study long-term effects of changing winter snow conditions on the integrated physical-biological processes of alpine tundra. The anoxic conditions produced by enhanced snow increased denitrification rates by an order of magnitude (Brooks and Williams, 1999). Initial findings suggested that decomposition rates increased because of enhanced snow (Williams et al., 1998), and this effort was subsequently expanded with litterbag studies (Bryant et al., 1998). At least one species, *Kobresia myosuroides*, had almost completely died out, but other species are increasing (Walker et al., 1999). Re-inventories of plant species richness and species composition have been obtained (e.g., Seastedt and Vaccaro, 2001) with the most recent collection in 2003. Those data are now being analyzed to estimate vegetation change that has occurred over the first 10 years of the experiment.

Process-Based Research Highlights: Experimental additions of N have caused changes in species composition from *Acomastylis* to *Dechampsia* in wet meadow communities (Bowman et al., 1995; Theodose and Bowman, 1997), and reductions in species richness (Seastedt and Vaccaro, 2001). Such shifts in species composition may lead to increased leaching of nitrate from soils to aquatic systems because the favored species often has greater rates of net nitrification (Bowman and Steltzer, 1998; Steltzer and Bowman, 1998). Additions of labeled N in the form of ammonium nitrate to snow showed that N uptake during snowmelt constituted over 12% of season-long uptake for a graminoid species, and averaged 7.4% for perennial forbs (Bilbrough et al., 2000). Nutrient addition studies generally support the hypothesis that long-term increases in atmospheric N deposition will likely shift terrestrial plant productivity in tundra ecosystems from N-limitation to P-limitation (Burns, 2003b). However, it remains unclear how changes in snow amount, duration, and timing interact with increases in N deposition to structure plant communities.

Our finding that microbial communities are active under snow has changed the estimated global rates of biogeochemical processes beneath seasonal snow packs. These results have prompted a re-evaluation of whether some seasonally snow-covered environments are sinks of atmospheric CO_2 (Fahnestock et al., 1999). In addition, under-snow microbial metabolism is an important biogeochemical N sink (Lipson et al., 1999). Unexpectedly, our results show that tundra soil microbial biomass reaches its annual peak under snow and not during the warmer summer months, and that fungi account for most of the biomass. Phylogenetic analysis of tundra soil fungi using microbiological and molecular techniques revealed a high diversity of fungi and three novel clades that constitute major new groups of fungi, divergent at the subphylum or class level (Figure 2.3) (Schadt et al., 2003).

These new insights into microbial function may partly explain our finding that nitrogen additions significantly accelerate decomposition of light soil carbon fractions (with decadal turnover times) while further stabilizing soil carbon compounds in heavier, mineral-associated fractions (with multi-decadal to century lifetimes). Our results using a combination of stable (^{13}C) and radiogenic (^{14}C) isotopes in combination with specific carbon biomarkers for undegraded plant lignin (2-methoxy-4-vinylphenol) and labile polysaccharide markers (e.g., 5-methyl-2-furanone) show that nitrogen additions significantly accelerate decomposition of light soil carbon fractions while there is increased productivity, leading to no statistically detectable change in total soil organic matter (SOM) carbon (Neff et al., 2002). This acceleration of decomposition of the light fraction of SOM could be the result of changes in microbial community composition. Our results suggest that current models of terrestrial carbon cycling do not contain the mechanisms needed to capture the complex relationship between nitrogen availability and soil carbon storage.

Alpine Tundra-Subalpine Forest Ecotone: Studies in the alpine tundra-subalpine forest ecotone have described how trees can impact both the soil environment beneath their canopy and the surrounding tundra by modifying the microclimate (Parker and Sanford, 1999; Seastedt and Adams, 2001; Shiels and Stanford, 2001; Liptzin and Seastedt, in progress; and Withing and Stanford, in progress). A completed formal analysis of the ecotone (Mujica, in prep) indicates that subunits of this zone may exhibit different, even opposite, responses to the same climate forcings. The extent to which disturbances, topography, and climate control the tundra-tree patterns and the consequences of these patterns on the biogeochemistry of the area, in conjunction with climate change concerns, has identified this area for continued and enhanced LTER studies.

Subalpine Forest: The Niwot Ridge Ameriflux site was established in 1999 and is located about 400 m from the long-term C1 meteorological site. The facility includes two tall flux towers (one that extends 15 meters above the 10-m canopy and one that extends 20 meters above the canopy), both of which are equipped with instrumentation capable of (1) measuring net ecosystem CO_2 flux by the eddy covariance method; and (2) quantifying the energy budget and evapotranspiration rate of the forest. The site is administered by Monson and primarily funded by the DOE Ameriflux program, with supplemental funding and logistical support from the NWT LTER. Initial results show that the energy budget closure was better than 84% on a half-hourly basis in both winter and summer, with slightly greater closure during the winter. These findings indicate that eddy covariance of ecosystem CO_2 flux, water, and energy are feasible in the rugged topography of mountain ecosystems (Turnipseed et al., 2002; Turnipseed et al., 2003).

Somewhat unexpectedly, the eddy covariance measurements showed a strong control of snow properties on net ecosystem exchange (NEE) of carbon (Figure 2.4a). The depth of the winter snowpack, its thermal characteristics, and its rate of melting strongly control the timing and magnitude of early season, and annual, NEE (Monson et al., 2002). Snowpack exerts a second important influence over annual NEE by affecting winter soil temperature and thus, winter soil respiration rate. Given that 50-65% of the C sequestered during the previous growing season is lost as wintertime respiration, wintertime snowpack and its effect on soil temperature exert a strong control over annual NEE rates (Figure 2.4b).

Network Participation and Cross-site Research: Since 2001, there has been considerable effort by the Niwot Group to expand their collaboration and interpret results beyond the NWT LTER. Specific examples include: (1) participating in LTER network activities, including hosting the Fall 2002 CC meeting; (2) obtaining cross-site LTER grants on dissolved organic matter (11 LTER sites, Williams PI) and SOM/nitrogen interactions (3 LTER sites, Townsend PI); (3) chairing LTER working groups on invasive species (Seastedt) and species response to N-deposition (Suding); (4) acting as lead convener on 6 workshops at the 2003 ASM; and (5) maintaining a leadership role in the International LTER program, including the recent selection of Bourgeron as one of two co-Chairs of the newly created US-LTER International Committee. Regional efforts are ongoing, such as the chapters that Seastedt and Bowman authored in Rocky Mountain Futures (Baron et al., 2002), and collaborative work with other research groups conducting alpine-subalpine research in the Rocky Mountains (Baron and Caine, 2000; Meixner et al., 2000). Moreover, NWT LTER personnel are exploring the effects of N deposition at national and international levels (Townsend et al., 2003; Fenn et al., 2003).

Synthesis and Unifying Conceptual Framework: The publication of “Structure and Function of an Alpine Ecosystem: Niwot Ridge, Colorado” (Bowman and Seastedt, 2001) is an important step toward a clear synthesis of ongoing research regarding the physical environment, plant ecology, and ecosystem structure and function of the NWT LTER. To our knowledge, this is the first comprehensive summary of alpine ecology in North America. While the focus is on Niwot Ridge, most chapter authors embrace a strong comparative approach whenever possible, allowing us to make statements regarding the generality of findings. This book was an important step toward a unifying conceptual framework for the NWT LTER.

A subset of the senior PIs of the NWT LTER authored a synthesis article that refocused and refined the unifying ecological theme for the site, and is appropriate for topographically rugged landscapes: the Landscape Continuum Model (LCM) (Seastedt et al., 2004). The model explicitly links terrestrial ecosystems to each other and to aquatic ecosystems (Figure 2.5). The heart of the model is that strong linkages are generated among landscape components as a result of transport processes caused by the extreme topography. These transport agents cause biogeochemical amplification and attenuation of processes not observed in most landscapes. Overall, the model links Billings’ (1973) mesotopographic alpine model with ideas developed in the Vannote et al. (1980) river continuum concept (RCC). The major difference between the RCC and our model is that the RCC is one-dimensional, containing just one transport agent (water), whereas we explicitly consider wind, water, and landslides as transport agents in a spatially complex system. Numerous testable hypotheses are generated from the model that form the core of our renewal proposal.

Section 2. Proposed Research

Introduction and Conceptual Framework

The panoramic splendor and complexity of high-elevation ecosystems have inspired and challenged humans for centuries. In our time, the perception that the mountains ‘are forever’ may provide solace to those seeking stability in a rapidly changing world. However, changes in the abundance and species composition of the native flora and fauna of these mountain ecosystems are potential bellwethers of global change. The flora and fauna of high-elevation ecosystems are on the edge of their environmental tolerance (Williams et al., 1998), and hence may be more sensitive to directional change in climate than downstream ecosystems (Williams et al., 2002). This sensitivity to small changes in climate is due to the propensity of these systems to amplify environmental changes within specific portions of this landscape. Here, we 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).

Our efforts to integrate the conceptual models of Billings (1973), Jenny (1941), and Burns and Tonkin (1982) on biogeochemical properties of high-elevation systems produced a model system for processes identified by Reiners and Driese (2001), and parallels with RCC of Vannote et al. (1980). Both high-elevation systems and RCC streams contain areas that receive potentially large energy and nutrient subsidies from ‘upstream’ sites. Both systems exhibit zones where the ratios of production and decomposition vary. Both systems mediate anthropogenic and natural environmental changes via biotic responses that both affect, and are affected by, transport processes.

The LCM provides the conceptual framework to understand high-elevation systems from a biogeochemical perspective, and sheds light on potential changes in these systems in response to directional change in precipitation and atmospheric chemistry. The model emphasizes landscape variation in the patterns of biogeochemical cycles, carbon fluxes, and net primary productivity (NPP), and makes predictions about growth strategies and nutrient characteristics of plants. The model easily integrates with similar concepts and principles required to understand within-community interactions, and provides a mechanistic interpretation for how different portions of the high-elevation landscape can be experiencing excesses and limitations of the same nutrient. The LCM explicitly links terrestrial processes to aquatic systems, and alpine ecosystems to subalpine ecosystems. Moreover, the LCM allows us to interpret our research results at regional and global scales.

The transfer of water, nutrients, and particulates from the mountaintops downward makes this uppermost zone a ‘source area’ for these materials. The combination of high precipitation, snowmelt runoff, limited soil and vegetation, and steep slopes results in large amounts of surface runoff, and export of solutes, nutrients, and sediment to downslope areas. High winds further augment the redeposition of minerals and organic materials downslope.

In the zone below the mountaintops, the wind-scoured dry meadows of the vegetated alpine regions, as well as the fellfields (rocky areas containing a low cover of vascular vegetation growing in protected areas), also are net sources of water, nutrients, and organic matter to lower elevation sites. Wind scour in the fellfield areas is so severe that soil formation occurs only in protected surface areas. The export of plant litter by wind scour implies that these sites have a net plant production to heterotrophic respiration ratio greater than one, similar to values observed in midreaches of rivers (Vannote et al., 1980).

The ‘subsidized’ moist and wet meadows of alpine tundra areas obtain water and nutrients from upland and upwind sources. The net flux of organic matter from these areas is poorly known. While portions of alpine tundra undoubtedly function as a sink for materials redeposited from uphill and upwind sources, much of the Colorado alpine is dominated by the wind-swept fellfields and dry meadows, and these areas function as a source of inorganic and organic materials to both aquatic systems and treeline areas.

In our uppermost alpine lakes, phytoplankton biomass increases steadily after ice-out and through the summer, suggesting that primary production contributes to nutrient transformations at that time. Further, the increase in biomass indicates that the net phytoplankton production to heterotrophic respiration ratio in the water column is greater than one. While we hypothesize that annual production will exceed respiration, the carbon balance of these systems remains a research question.

The lakes and wetlands near the alpine-subalpine interface can store and transform particulate material and solutes from upstream. The relatively longer ice-free period for these lakes may increase net primary production for the summer period and enhance the retention and transformation of nitrate through nutrient uptake. The alpine-subalpine interface, however, represents a transition to greater dominance of dissolved and particulate allochthonous organic matter in carbon cycling of these lakes. In these and downstream lakes and streams, the ratio of net primary production to respiration is believed to be less than one on a year-around basis (Figure 2.5).

We hypothesize that the maximum, landscape-scale impact of biota on materials occurs at treeline, where trees function as windbreaks, collecting snow, particulates, and nutrients. While the mechanisms responsible for the formation and location of treeline vary (Baker and Weisberg, 1995), snow depth is a major factor, particularly along the eastern side of the Continental Divide. Treeline areas may receive substantial subsidies of water, nutrients, and organic material from upwind and uphill sources, and net primary productivity becomes enhanced because of these subsidies (Monson et al., 2002).

From our studies and observations, a large number of testable predictions of the LCM are suggested. The most important of these include:

(1) Lakes near block fields and talus areas will receive the largest nutrient increases per unit area of catchment. Net primary production may exceed in situ respiration, and these lakes will show the greatest changes in species composition and production of all high-elevation ecosystems in response to increasing deposition of inorganic N.

(2) Windswept fellfield and dry meadow areas of alpine tundra will exhibit less change in plant productivity and species composition through time than more mesic areas capable of retaining atmospheric inputs. The reason is that they receive only a fraction of the precipitation and nutrients from atmospheric deposition that falls as snow in sheltered areas, and these sites also lose portions of the organic matter and nutrients contained in plant litter to wind scour.

(3) Treeline areas receive the largest subsidies of snow and particulates and benefit from the losses from fellfields and dry meadows. These systems should already consist of vegetation adapted to high nutrient availability. Forest production of subalpine ecosystems should be maximized at treeline, and these sites would be the first terrestrial areas to experience characteristics of N saturation (Williams and Tonnessen, 2000).

Niwot Ridge is the only multidisciplinary, long-term study site for high-elevation areas on the North American continent (Figure 2.6). As such, our site is an essential benchmark for regional, national, and global networks that measure biological changes and feedbacks and experimentally determine mechanisms for these relationships. Both high-elevation and high-latitude areas have been identified as being at risk from a variety of anthropogenic materials added to the atmosphere. The LCM suggests that high-elevation lakes and treeline may be the first locations to experience the impacts of these materials because of the amplification effects of transport processes. The following sections detail our strategy for evaluating the Landscape Continuum Model.

I. Atmosphere-Landscape Interactions

The LCM suggests that small changes in climate—energy, water, and chemicals—will be amplified in high-elevation environments. Thus, these high-elevation ecosystems may be source areas for the delivery of atmospheric pollutants such as N species and persistent organic pollutants to down-gradient ecosystems. Moreover, ecosystem processes such as net ecosystem exchange of CO_2 and nitrogen gases such as NH_3 may be important to down-gradient forested ecosystems. Both long-term measurements and new innovations in technology provide the opportunity to evaluate these questions.

A. Long-Term Measurements and Experiments (*Losleben, Caine, Williams*)

The Mountain Climate Program (MCP) headed by Losleben will continue to operate the many long-term measurement systems in place. These include four climate stations, with measurements beginning in 1951. One of these, D1, is the longest, continuously operating high-altitude climate station in North America (Figure 2.1a). The MCP also operates two sites in the National Atmospheric Deposition Program (Niwot and Sugarloaf), two in NOAA's CMDL Carbon and Halocarbon monitoring network (C1 and T van) (Figure

2.2), two in NOAA's surface ozone monitoring network (C1 and Saddle), and one site each in: the National Park Service National Ultraviolet Monitoring program administered by the University of Georgia, the National Resources Conservation Service Snotel network, NOAA's Climate Research Network, the National Weather Service’s cooperative precipitation network, and the Colorado Department of Transportation Automated Weather Observing System. New initiatives based on these long-term measurements include: (1) addition of soil moisture measurements to our long-term climate stations; (2) development and installation of a high speed wireless internet connection to the main CU campus; (3) further wireless connections of field data loggers to the internet; (4) comparison of surface temperatures to elevationally equivalent free air temperatures (only possible where steep topographic gradients exist); (5) evaluation of the importance of climatic extremes on ecosystem processes; and (6) determination of temporal trends in snowpack at NWT LTER and compared to the western US.

B. New Measurements and Experiments

B1. **Eddy Covariance Measurements: Carbon Dioxide, Water, and Energy** (*Blanken, Helmig, Williams, Losleben*). In sloping terrain characteristic of high-elevation catchments, the potential magnitude of the advective term to the total net ecosystem exchange might be large and, if properly accounted for, could yield new insight into C exchange in these regions (e.g., Schimel et al., 2002), especially because respired carbon from newly identified fungal species could be important (Schadt et al., 2003). The eddy covariance method of measuring CO_2 is preferred in complex terrain because it does not rely on assumptions of how eddy diffusivities vary with atmospheric stability, which is largely unknown for CO_2. However, concern about the use of eddy covariance methods in complex terrain exists because of the problem in accounting for the advective term.

We propose to measure the net ecosystem carbon exchange above alpine tundra (Saddle site, Figure 2.6) in complex terrain at Niwot Ridge while properly accounting for the influence of advection. Moreover, accounting for horizontal transport of energy fluxes will improve our ability to develop spatially distributed snow melt models, an important step toward linked terrestrial-aquatic biogeochemical models. Two eddy flux towers will be established on Niwot Ridge similar to the Ameriflux site at C1. The second tower will be placed upwind of the first tower within 15 degrees of the mean daytime prevailing wind direction. The advective term will be solved by applying Reynolds’ decomposition to incorporate the turbulent component in the horizontal advection terms due to changes in horizontal concentration and horizontal wind velocity, from Equation 4 in the detailed methods description on the web. This procedure will enable us to (1) quantify the importance of the advective flux of energy, water, and trace gases, understand under what conditions the advective components are large, and be able to identify site locations that minimize advective flux in complex terrain to simplify measurement requirements; (2) improve our ability to accurately measure the surface carbon and water budgets in topographically-complex terrain, complementing process-based based research on microbial dynamics and decomposition rates; (3) evaluate the importance of nocturnal ‘drainage’ flows of CO_2, both at our site and as an input to the down-gradient subalpine forest ecosystem; and (4) improve our ability to model snowmelt using a distributed energy balance approach and hence improve our ability to integrate terrestrial and aquatic ecosystems.

B2. **Eddy Covariance Measurements: Nitrogen Gases and Photochemical Reactions** (*Helmig, Losleben, Blanken*). Recent research in Polar Regions has yielded increasing evidence that scavenging of gases and particulates by precipitating snow can lead to a significant accumulation of chemicals atop and within surface snow. Solar irradiance can consequently trigger photochemical reactions that yield important trace gases including nitrogen species (NO, NO_2, HONO, alkyl nitrates), organic compounds (HCHO, HCOOH, CH_3COOH, CH_3Br, CH_3I, C_2H_4, C_3H_6), and hydrogen peroxide (Blake et al., 1998, 1999, 2000; Dibb et al., 1998, 1999a,b, 2002; Dibb and Arsenault, 2002; Honrath et al., 2002; Sumner and Shepson, 1999; Hutterli et al., 1999, 2002; Jones et al., 2001; Jacobi et al., 2002; Swanson et al., 1999, 2002, 2003). To date, most photochemical snowpack studies have been conducted in Polar Regions, and little is known about how well these data reflect temperate regions with alpine and seasonal snow conditions. Because of the generally higher atmospheric levels and higher deposition rates of particulate and gaseous nitrogen species in the densely populated Rocky Mountain States, it appears likely that similar processes do occur and may be of greater magnitude than in Polar Regions.

We propose to evaluate the processes that determine the partitioning of oxidized nitrogen gases and their surface-atmosphere fluxes, as well as their importance as ecosystem sinks and sources of oxidized nitrogen. This research builds on the NWT LTER research on microbial processes under snow (Schadt et al., 2003) and trace gas flux of N species through the snowpack (Brooks and Williams, 1999). Surface fluxes of NO, NO_2 and NO_y, and gradients of these gases in the snowpack, will be measured from the flux tower above with a series of inlets for the eddy correlation and snow pack measurements (detailed methods on web). We will be able to evaluate (1) whether an unknown but possibly significant fraction of deposited nitrate may be recycled and released to the atmosphere during the winter season; and (2) whether the mobility of the photochemically-formed, gaseous, oxidized nitrogen species may be much larger than that of nitrate scavenged in the snowpack. The snow-photochemical processes may yield a previously unaccounted for mechanism for providing and delivering oxidized nitrogen to ecosystem compartments.

B3. **Nitrogen Volatilization** (*Sievering*). We will complement the measurements of oxidized nitrogen gases by continuing our vertical gradient measurement of ammonia (NH_3) at the Saddle and extending these measurements to the C1 site (see Figure 2.6 for locations). We believe that as alpine tundra moves towards N saturation, the tundra will be a source of NH_3 emission, and the subalpine area should be a substantial sink for NH_3 (Rattray and Sievering, 2002; Tomaszewski et al., 2003). The gradient measurements will be conducted using two-point filter pack sampling (Sievering et al., 2001; Rattray and Sievering, 2002).

C. Synthesis, Regionalization, and Cross-Site Analysis

The LTER Mountain Climate Program continues to expand its relationship with the White Mountain Research Station in eastern California. This collaboration involves technical information exchanges and LTER equipment purchases to expand climate measurements. Losleben, Williams, and Bowman are participating in the developing Mountain Climate Consortium (CIRCMONT), which will provide an administrative vehicle to synthesize and interpret mountain climate information for the western United States. Losleben is a member of the LTER Extreme Events committee. The measurements of nitrogen gases will be compared to ongoing research projects on snow-photochemical and snowpack-atmosphere gas exchange processes at Summit, Greenland by Helmig, and will allow us to better decipher the role of the soil processes on gas exchange through the snowpack when compared to snow-cover with no soil. Perhaps most importantly, we will be able to regionalize our C, N, and water budgets by combining with similar results from the Ameriflux site at C1.

II. Mountaintop Landscapes

The LCM suggests that mountaintops are source areas of water, nutrients, and pollutants to downslope areas. The steep, rocky slopes that extend from the alpine ridgetops down to the valley floor have been infrequently studied as hydrological or biological systems because they were formerly assumed to be inert piles of rock and sand with little ability to modify biological or biogeochemical cycles. Unvegetated talus and block slopes have been shown to process N (Williams et. al. 1997; Bieber et al., 1998), but we know little about the N or C balance of these soils. Even barren patches of debris have been shown to contain wind-deposited organic matter and measurable microbial biomass (Ley et al., 2001). Because of the direct hydrological connection between these coarse debris areas and surface waters, they are probably a major source of nitrate and other nutrients to alpine streams, especially during the growing season (Campbell et al., 2000). For example, our measurements of streamwater quantity and quality show that the amount of inorganic N per unit catchment area exported downstream exceeds average wetfall inputs from the atmosphere near the mountaintops and then decreases downcanyon (Figure 2.7a). Moreover, as elevation decreases, there is an almost linear pattern of increasing concentrations of dissolved organic carbon and decreasing nitrate concentrations, suggesting retention and conversion of inorganic N to organic matter within aquatic communities (Figure 2.7b).

A. Long-Term Measurements and Experiments (*Caine, Williams, Mast*)

Precipitation Quantity and Quality: We will continue our long-term spatial measurements of snow quantity and quality in the upper Green Lakes Valley (Erickson et al., 2001; Williams et al., 2001; Erickson et al., in review). **Landscape Discharge**: We propose to resample streams draining these mountaintop areas for discharge, geochemical solutes, and nutrients. These sites include talus fields and block slopes identified in Williams et al. (1997) and Ley et al. (2004 (in press)), as well as glacial and rock glacier discharge (Caine, 2001). **Permafrost**: A new initiative is to evaluate changes in permafrost as a function of climate change by reoccupying the 14 sites first sampled in the 1960s (Ives, 1973) and instrumenting them with modern logging equipment.

Extensive surveys of basal temperature of winter snowpack (BTS), which have been important in mapping permafrost in the Swiss Alps for decades (Vondermuhll and Haeberli, 1990), will be conducted annually in Green Lakes Valley and on Niwot Ridge.

B. New Measurements and Experiments

B1. **Microbial Processes** (*Schmidt*, *Williams*). For N immobilization to occur in these soils, microbes must have an excess of available carbon, but one of the unsolved mysteries is the source (in the absence of plants) of carbon inputs. Preliminary studies in talus and block fields have shown a wide diversity of microorganisms (Ley et. al., 2002; Meyer et al., 2004) and suggest that dust deposition may be a dominant C source (Ley et. al., 2004 (in press)). However, our more recent preliminary research indicates that microbial photosynthesis may play a much more important role. Preliminary data suggest that 6% of the bacterial community consists of cyanobacteria, and other recent work indicates the presence of microbial eukaryotic photoautotrophs (Meyer et al., 2004). Also, our preliminary CO_2 flux data indicate that these unvegetated soils are fixing CO_2 (in the presence of light) at an average rate of 0.455 mol m^{-2} s^{-1} or 0.072 g CO_2 m^{-2} s^{-1} (Figure 2.8), which is 10-100 times higher than C inputs from dust as measured in recent studies (Ley et al., 2004 (in press)).

Our objective is to evaluate whether N cycling in plant-less high-elevation ‘soils’ will be driven by photosynthesis of novel, as yet un-cultured, microorganisms. We will monitor CO_2 fixation in talus soils using CO_2 flux using a PP Systems CIRAS-1 infrared gas analyzer (IRGA) with a CPY-2 transparent chamber. We will also measure N fixation and other inputs and outputs that will allow us to determine the N budget for these soils, using methods that we have previously employed in tundra soils (Fisk et al., 1998, 2001; Lipson et al., 1999). In concert with the above biogeochemical approaches, we will use molecular methods to fully characterize and quantify the seasonal dynamics of the C-fixing and N-fixing microorganisms in these soils.

B2. **Accumulation and Transport of Persistent Organic Pollutants (POPs)** (*Mast*, *Williams*, *Caine*). Melting of glaciers and snowfields has been shown to be a major source of organic pollutants to subalpine lakes (Blais et al., 2001). It is well documented that persistent organic pollutants are bioaccumulating in food webs in remote areas throughout the world. These compounds preferentially accumulate at northern latitudes due to cold condensation, a process which causes evaporation of POPs used at warmer temperate latitudes and subsequent condensation at colder northern latitudes (Simonich and Hites, 1995; Wania and Mackay, 1996). More recently, elevated concentrations of POPs in snow, sediment, fish tissue, and vegetation also have been documented in high-elevation ecosystems at temperate latitudes in Canada and Europe (Blais et al., 1998; Blais et al., 2003; Davidson et al., 2003; Grimalt et al., 2001). Because concentrations in these ecosystems may increase with increasing elevation, particularly for more volatile compounds, it is suggested that cold condensation and fractionation are also occurring in cold high-elevation areas (Blais et al. 1998; Davidson et al., 2003). Preliminary studies in nearby Rocky Mountain National Park have detected the presence of SOCs in snow and lake water (Mast et al., 2003; Simonich and Hageman, 2003).

We propose to evaluate whether colder temperatures at higher elevations enhance the deposition and accumulation of SOCs in temperate mountain areas. Snow, air, and vegetation samples will be collected and analyzed to evaluate how SOCs vary with elevation at NWT LTER. We will also measure SOC gradients in the snowpack using the instrumentation from Section I.B2. Streams draining different environments (subalpine, alpine, glacier discharge) will be sampled prior to and during the main snowmelt period for SOCs (detailed methods on web). We will be able to evaluate whether (1) high-elevation areas act as a source for SOC transport to downstream aquatic systems; and (2) snow and ice melt may contain atmospheric pollutants from decades ago when global use of SOCs was greater.

C. Synthesis, Regionalization, and Cross-Site Analysis

These measurements will allow us to directly evaluate whether mountaintops are source areas of nutrients and pollutants to downslope ecosystems. Our SOC measurements will contribute to the efforts of the NPS Western Airborne Assessment Project to determine the accumulation and impacts of POPs and other airborne toxins at six National Parks in the western United States. Moreover, Dr. Mast will assist us in a regionalization effort by comparing our results with the nearby Loch Vale research effort, a USGS WEBB site.

III. Tundra Ecosystems

Biota have the ability to attenuate or amplify fluxes of nutrients in the alpine, and to transform nutrients from reactive to inactive forms and vice-versa (Seastedt et al., 2004). Our LTER project has attempted to identify these patterns for plants (e.g., Bowman et al., 2003), consumers (e.g., Sherrod and Seastedt, 2001), and microbes (e.g., Schadt et al., 2003). Here, we identify projects designed to build upon the long-term studies that elucidate the role of biota in the biogeochemistry of the region. As with previous LTER activities, these projects will function as benchmarks for more intensive work that will be conducted using opportunities and resources found outside of the core LTER program.

Microbial decomposition of litter and soil organic matter (SOM) is one of the most basic ecosystem processes, matched only by terrestrial productivity as a primary controller of structure and function in ecosystems around the world (e.g., Schlesinger, 1977; Melillo et al., 1982). The alpine is no exception, as the dynamics of its substantial SOM pools exert significant controls over multiple key features of the tundra landscape, including community composition (Bowman and Steltzer, 1998; Bowman, 2000; Seastedt and Vaccaro, 2001), the delivery of nutrients and energy to aquatic systems (Brooks et al., 1999), and the storage and/or release of increasing N inputs (Williams et al., 1996a). For example, studies from Niwot Ridge have shown that a substantial fraction of added N is quickly stored in soils (Holland et al., unpublished data), that organic matter turnover responds to increased N inputs (Neff et al. 2002), and that these changes play a role in plant dynamics and community composition (Bowman and Steltzer, 1998; Bowman, 2000; Seastedt and Vaccaro, 2001). In addition, studies of dissolved organic matter dynamics illustrate how plant microbe competition for soil resources is controlled in part by organic matter chemistry (Lipson et al., 1999; Raab et al., 1999; Ley and Schmidt, 2002), and how specific soil fractions and compounds can be transferred to aquatic ecosystems (Brooks et al., 1999; Hood et al., 2003). For example, a decade of N fertilization shows a decline in the ^{14}C abundance in the light (density-separated) fraction of soils from Niwot Ridge, Colorado (Figure 2.9). Both lignin and polysaccharide plant biomarkers show 90+% declines following fertilization. These results (Neff et al., 2002) illustrate the significant chemical and isotopic changes that can occur in soils despite lack of an observable change in bulk SOM pool sizes.

We propose to conduct new research on P cycling to complement our existing work on N cycling. Moreover, such research will provide the basis for an ecological stoichiometry approach to linking terrestrial and aquatic ecosystems. Nitrogen and phosphorous are the most common nutrients limiting growth of plants in terrestrial ecosystems (Vitousek and Howarth, 1991; Chapin et al., 2002; Aerts and Chapin, 2000). However, in areas that receive continuous input of anthropogenic deposition such as the Colorado Front Range (3-5 kg N ha^{-1} yr^{-1}) (Williams and Tonnessen, 2000; Burns, 2003a), N limitation should be progressively alleviated, eventually creating a situation in which the availability of P is more important than that of N in regulating carbon balance and community composition. For example, Williams et al. (1996a) found that foliar N:P ratios in bristlecone pine increase with increasing elevation, indicating that atmospheric deposition of N may be causing a change from N limitation to P limitation in the alpine environment.

A. Long-Term Measurements and Experiments (*Bowman*, *Suding*, *Seastedt*)

We will supplement our long-term plots (see Section 1) with long-term experimental manipulations.

A1. **Fertilization Experiments** (*Bowman, Seastedt, Suding*). Complementing our long-term vegetation monitoring will be long-term manipulations of N and P availability, temperature, and snow cover, to assess how these components of environmental change influence species composition and diversity in the alpine (Arft et al., 1999; Walker et al., 1999; Seastedt and Vaccaro, 2001). Together, these data sets will determine how vegetation is changing, how predictive experiments are of the change that is occurring, and whether these vegetation changes are associated with concurrent changes in adjacent aquatic and terrestrial systems.

A2. **Species Manipulation** (*Suding, Bowman*). While diversity change across productivity gradients is quantified almost entirely by changes in the distribution and abundance of taxonomic richness (i.e., number of species), system functioning and ecological feedbacks may be more closely tied to changes in functional richness and dominance. Hence, one approach towards understanding diversity changes in response to environmental changes is to examine the types of species that are lost and those that increase in dominance following experimental manipulations of resources. While shifts in vegetation can cause species loss and changes in diversity, they also can change ecosystem processes such as N retention, carbon storage, and decomposition rates, and influence nutrient transfer between terrestrial and aquatic systems. For example, experimental additions of N in alpine tundra have caused a shift from species with low rates of N cycling and high rates of N retention to high rates of N cycling and low rates of N retention (Figure 2.10).

These modifications can influence biotic interactions and enhance community diversity (Suding et al., 2004). Simulation models suggest that enhanced resource availability due to N deposition and/or climate warming may break the existing balance among species effects and diversity (Clark et al., 2004). This change is predicted to lead to the dominance of a single species and a cascade of species losses. Moreover, the species predicted to increase in abundance are those with rapid N cycling rates and lower nutrient efficiencies, and thus, decreased nutrient retention and increased N loss to the aquatic systems may result. To experimentally address how this predicted vegetation shift will influence ecosystem processes and nutrient transfers between systems, a long-term project involving the removal of species and manipulation of nutrient availabilities across seven sites on Niwot Ridge was initiated in 2000 using funds from the Mellon Foundation. These long-term experiments will help us to better understand the functional diversity at Niwot Ridge, how these individual characteristics scale to larger-scale processes, and how feedbacks among scales and systems influence function.

A3. **Consumers** (*Seastedt*). We have identified alpine gophers as ecosystem engineers capable of significantly altering plant species composition and soil biogeochemical characteristics (Sherrod and Seastedt, 2001; Sherrod et al. (in review)). No ongoing experiments involving consumers are proposed for the ‘04-‘10 study interval. However, we do plan an inventory effort to assess long-term changes of consumers. Beever et al. (2003) indicated that environmental change affects were implicated in the extirpation of local populations of the high-elevation small mammal, the pika (*Ochotona princeps*) in areas west of the Front Range. Historical data on the abundance of these species obtained in the 1980s (summarized in Armstrong et al., 2001) provide us with a mechanism to see if Niwot populations have shown similar trends. Initial surveys were conducted in summer 2003, and we will repeat this activity in summer 2004. Dr. Barry Rosenbaum, Colorado College, is responsible for this effort. Based on these findings, we will determine whether additional small mammal surveys are appropriate during the ‘04-‘10 interval and, if so, we will seek external funding for this effort.

B. New Measurements and Experiments

B1. **Plant-Soil Feedbacks** (*Bowman, Suding*). The composition of vegetation influences soil microbial activity with unknown feedbacks to plant N availability and other resources (Bowman et al., 2004 (in press)). While C:N ratios are correlated with mineralization and nitrification rates, the lability of the C appears to override this generalized relationship (Steltzer, 1999). Although often considered inhibitory to herbivory and microbial activity, some phenolic compounds are important growth substrates for soil microbes, primarily fungi (Fierer et al., 2001; Schmidt et al., 2000). Plants high in low molecular weight phenolics appear to stimulate microbial immobilization of N, thus lowering net N mineralization. The role of litter in this plant-soil feedback is unclear, as microbial activity during the winter in many alpine soils is quite high (Lipson et al., 1999; Schadt et al., 2003), and most phenolics in the litter may be consumed before the vegetative growing season starts. Additional research is underway to elucidate the temporal dynamics the plant-soil feedbacks, which appears to be an important plant modification of resource availability, influencing biotic interactions and ultimately diversity of alpine communities (Suding et al., 2004).

B2. **Microbial Dynamics** (*Schmidt*). The recent discovery of novel microbes in snowmelt saturated soils at Niwot Ridge (Schadt et al., 2003) suggests that we may be poised to increase our understanding of denitrification from a microbial standpoint. Numerous novel microbial groups have been identified in soil (Hugenholtz et al., 1998), but studies correlating relative abundance with in situ biogeochemical processes are absent (Kent and Triplett, 2002). However, techniques for measuring relative abundance and culturing have recently improved for application to soil (Christensen et al., 1999; Janssen et al., 2002; Pernthaler et al., 2002; Sait et al., 2002). Thus, in situ studies of novel soil lineages are feasible, but are especially well suited to ecosystems with a long history of ecological and microbiological investigation, facilitating correlative work.

Our overarching goal is to explore the relationship between the presence of novel, uncultivated microbes associated with under-snow and snowmelt saturated soil and the biogeochemical implications of seasonal soil anoxia on Niwot Ridge. We propose to determine the covariance of diversity and abundance with soil characteristics (including soil redox) in tundra and forest across season and soil depth. Specific objectives include (1) discovering the phylogeny for novel sequences sampled; (2) quantifying the abundance of specific novel lineages; and (3) determining the covariance of phylogeny or abundance with environmental parameters including oxygen profiles and soil redox. Five 20 cm deep soil cores will be collected from wet and dry meadow tundra and forest sites for each season: summer, winter, and during spring snowmelt, and divided into surface (0-3 cm) and subsurface samples. Phylogenetic trees will be constructed and significant shifts in diversity across environments will be detected according to the methods of Martin (2002) as applied by Schadt et al. (2003).

We will complement these field measurements by isolating novel soil microbes from anoxic soil using innovative culturing methods focused on anaerobic and micro-aerobic conditions. Soil slurry incubations will be in sealed vials with anaerobic headspace in the dark at 0-3ºC, and abundance measurements will be conducted. The culturing experiments will explore a wide variety of conditions within the context of cold, dark, anaerobic or micro-aerobic incubations. This will involve several novel approaches including the use of: (1) 96-well culture arrays (in which two conditions such as inoculum, medium, nutrient, or soil extract concentrations are simultaneously varied) incubated in an anaerobic chamber; (2) independently sealed vials such that headspace gas concentrations can also vary; (3) techniques in which concentration gradients of carbon and/or energy sources develop within a semi-solid matrix such as those used for isolating microaerophilic Fe(II) or H_2S oxidizers; and (4) diffusion chambers in which inoculated growth medium is remains in diffusional contact with soil (Kaeberlein et al., 2002). We will test a range of organic and inorganic electron donors and acceptors, as well as various carbon and other nutrient sources.

B3. **Soil Organic Matter (SOM), Dissolved Organic Matter (DOM), and Plant/Microbial Dynamics** (*Townsend, Neff, Lehman*). The Niwot Ridge LTER has been a pioneer in the use of new techniques to understand soil processes, ranging from microbial community composition (Schadt et al., 2003), to decomposition processes (Neff et al., 2002), to terrestrial-aquatic linkages (Hood et al., 2003b). However, as described earlier in this proposal, interactions between climate, topography, and a diverse biota in the alpine lead to a complex landscape across which responses to a changing environment are not uniform. Thus, advancing our understanding of alpine soil processes requires that we extend many of these new approaches to the landscape scale, in ways that account for the major gradients present in the alpine.

We propose a unique set of soil chemical and isotopic analyses devoted to understanding: (1) the effects of gradients in water and nutrient availability on the chemical structure, stability, and turnover of SOM; (2) the related effects on DOM chemistry, turnover, and transport; and (3) the relationship between soil biochemistry and plant/microbe community dynamics. Our goal is to broaden our conceptual understanding of SOM and DOM dynamics by combining new analytical techniques with studies along carefully chosen ecological gradients. We will use pyrolysis mass spectrometry and ^{14}C accelerator mass spectrometry (AMS) techniques to explore the chemistry and isotopic content of SOM and DOM in a range of soil and vegetation types that represent a spectrum of environments for C and N stabilization and transport, and which are characterized by differing plant and microbial communities. In addition, by using biomarker-based studies of SOM, we can begin to separate out the influence of groups of microorganisms or plants on the production of specific compounds in soil organic matter. This research will be used to explore several gaps in our understanding, including: (1) the effects of both climate and nutrient availability on rates of SOM turnover and stabilization; (2) the role of DOM in soil organic matter formation; and (3) the potential for DON to function as both a plant nutrient source and ecosystem nutrient loss (Neff et al., 2003).

B4. **Biogeochemistry and Availability of Phosphorous** (*Townsend*, *Seastedt*, *Bowman*, *Litaor*). Numerous fertilization experiments conducted in the alpine tundra ecosystem have demonstrated the importance of N and P availability on plant primary productivity, abundance, and species diversity (Bowman et al., 1993; Bowman, 1994; Theodose and Bowman, 1997; Seastedt and Vaccaro, 2001). Despite the apparent importance of P availability in influencing alpine plant communities and ecosystem structure and function, relatively little is known of the actual biogeochemical processes that govern P cycling and availability in alpine soils, especially in a continuum landscape context. For example, Bowman et al. (2003) found no significant correlation between foliar N:P ratio and soil N and P supply for 3 alpine herbaceous plants with widespread distributions, as well as no significant differences in the rates of P supply with landscape position. On the other hand, Litaor et al (in review) found strong correlation between antecedent soil moisture, texture, SOM, non-labile and labile P pools, and P availability across an alpine topographic/snow gradient, but found that the high level of available P in certain landscape positions provides a growing advantage to only selected alpine plants and is not a good indicator of the spatial distribution of total aboveground biomass.

The main goal of this study is to ascertain the biogeochemical factors that control the level of available P. We will employ the alpine continuum slope approach tested by Litaor et al. (2002), which includes all the major alpine plant associations described by Walker et al. (1993), along with snowfence manipulations of snow depth, duration, and timing (Williams et al., 1998). The available P will be fully quantified using the three classic factors of available P, including intensity, quantity, and capacity. We will utilize a Pi strip method described by Chardon et al. (1996). This method uses Fe hydroxide-impregnated paper strips as a sink for phosphate ions, which account for only the net transfer of phosphate ions from the soil particles to the soil solution. We will modify the Pi strip method by attaching the paper strips to a passive capillary sampler made of flat fiberglass wick to better simulate the suction pressure exert by root uptake. The results of the Pi method will be compared to the ion exchange resin probes (Qian and Schoenau, 2002) and the isotope exchange kinetic technique (IEK) as a reference method (Aigner et al., 2002).

C. Synthesis, Regionalization, and Cross-Site Analysis

Regionalization of the fertilization experiments will be accomplished by conducting new fertilization experiments with support from the National Park Service and in cooperation with Tonnessen in Rocky Mountain National Park and Glacier National Park. These experiments will allow us to address the influence of variations in background N deposition rates and climate differences on the response of Rocky Mountain alpine vegetation to N inputs. Bowman will conduct similar fertilization experiments in the Tatra Mountains of central Europe with funding from ILTER. A cross-site synthesis effort led by Niwot LTER (Suding) is being conducted to address how changes in resource availability influence both taxonomic and functional diversity over a range of 8 LTER sites. Results to date from 32 N fertilization experiments across 8 LTER sites and 2 non-LTER sites show significant differences among functional traits (Figure 2.11).

IV. Treeline

Trees have been attempting to recolonize high-elevation and high-latitude environments since the end of the Pleistocene Era. The LCM predicts that the maximum, landscape-scale impact of biota on materials occurs at treeline, where trees function as windbreaks, collecting snow, particulates, and nutrients. Niwot Ridge has been the site for numerous studies on krummholz and treeline since the 1970s (e.g., Marr 1977; Holtmeier and Broll 1992; Pauker and Seastedt 1996; Parker and Sanford 1999; Seastedt and Adams 2001; Shiels and Stanford 2001; Liptzin and Seastedt, in progress; and Withing and Stanford, in progress). Our results suggest that the interaction of materials transport with trees has a large effect on the biogeochemistry of the alpine-subalpine ecotone (ASE) (Figure 2.12A).

We have documented that the ASE, as noted for other areas (e.g. Baker and Weisberg, 1995), does not exhibit a uniform configuration in terms of the patchiness of trees at the ecotone. Mujica-Crapanzano et al. (in prep) demonstrates the existence of three rather unique configurations of ecotones formed by the relative strengths of disturbance, topography, and climate. The extent to which these three different ASE types affect current and future biogeochemical processes is of interest, as are the “self-organizing” questions regarding the role of present structural attributes of ecosystems in organizing future structural attributes (Figure 2.12B). Accordingly, tree demographic studies in these different ASEs become an interesting and appropriate LTER activity. Our preliminary data suggest that the transition from alpine tundra to forest produces a monotonic decline in local species richness. If so, this finding is in contrast with the anticipation that the highest richness would be found at the alpine-forest interface. A study attempting to provide a causal relationship between this pattern and the species richness pattern observed in the alpine is a new and high priority activity for our group.

A. <u>Long-Term Measurements and Experiments</u>

We will continue the measurement program initiated in 1998. During the course of this study, 13,553 trees were mapped onto 7 permanent (GPS-marked) transects and 21 permanent (GPS-marked) plots. Initial analysis shows that at the local scale (ecotone versus closed forest), tree and shrub richness in the ecotone was associated with low elevation and low terrain variability, and a gradient in wind index variability separated graminoid richness (higher values) from forb richness (lower values).

B. <u>New Measurements and Experiments</u>

B1. **Maximization of Environmental Drivers at Treeline** (*Seastedt, Sanford, Bourgeron, Williams*). We propose to evaluate the prediction of the LCM that snow amount, nutrient loading, and particulate loading are maximized at treeline relative to nearby alpine source areas and down-gradient forested areas. We will conduct the following measurements along replicated transects, starting above treeline and continuing into the subalpine forest using methods developed specifically for the NWT LTER: (1) snowpack surveys including water, nutrient, and particulate content; (2) year-round wetfall and dryfall N deposition measurements; (3) construction of permanent plots for vegetation and soil analyses; and (4) specific, selected N measurements, including C:N ratios of soil and denitrification studies.

B2. **Landscape Patterns and Seasonality of C, N, P Across Treeline** (*Sanford, Seastedt, Bourgeron*). Preliminary sampling across the alpine subalpine forest ecotone suggests that the stoichiometric pattern of soils is surprising and should be examined in more detail (Figure 2.12A). On a local scale, trees influence total C, N, and P in fairly consistent patterns across the ecotone, with more C and N under trees (Figure 2.12A-a,b), but with less P adjacent to tree stems (Figure 2.12A-c). Moving from the alpine to the forest, C and N decline overall, while the pattern for total P is more complex, with an overall decline across the ASE and a peak in patch forest (located just above the zone of continuous (closed canopy) subalpine forest). At first glance, it appears that C and N are decoupled from P in these soils; however, labile C, N, and P often have little dependency on total soil pools (at least in the short term). Ongoing measurements show that labile P varies significantly across the ASE, with most labile P in the patch forest (Figure 2.12A).

We propose to sample surface soils across the ASE on a monthly basis to measure patterns for C, N, and P. In addition, because labile forms of N and P have the most influence on community structure, we will measure plant-available N and P on a monthly basis across the ecotone. Until recently, seasonal patterns of labile P have not been commonly measured; however, alpine soil sampling during the growing season at Niwot (Hanne, 2001) and monthly measurements elsewhere (Sanford et al., 2003) indicate that labile P may fluctuate as much as or more than NO_3 and NH_4. Our sampling intensity will increase to biweekly from April 1-June 30, when snowmelt has been shown to have a large influence on N dynamics in the alpine.

C. Synthesis, Regionalization, and Cross-Site Analysis

Understanding factors that influence treeline and treeline change remains an international focus (Korner, 1998). Bourgeron is a co-chair of the newly created US-LTER International and is the lead on interpreting these results in a regional and international context.

V. Aquatic Ecosystems

The LCM provides a framework for understanding how the effects of changes in climate and/or anthropogenic inputs will propagate through aquatic ecosystems. In particular, alpine lakes may be more responsive to environmental change than terrestrial ecosystems because (1) ecosystem processes are strongly dependent on climatic conditions, e.g. duration of ice and snow cover, and timing and extent of spring snowmelt (Hinder et al., 1999); and (2) algal communities and grazing zooplankton have much shorter generation times than plants and herbivores in the terrestrial ecosystem and because algal species distribution can be strongly influenced by many water quality parameters. Our study of a sediment core dated using ^{210}Pb in GL 4 (Figure 2.13) has shown that beginning in the 1940s, there were significant changes in the biogeochemistry and ecology of the lake that are associated with N enrichment, including shifts in the dominant diatom species, increases in benthic diatoms, and accumulation of organic matter and chlorophyll a degradation products (Waters, 1999; Waters et al., in press).

A. Long-Term Measurements and Experiments (*Caine, Williams, McKnight*)

We will continue our historical sampling of aquatic parameters, including lake ice thickness and ice-out date and stream waters, for quantity and quality on a transect along the hydrologic axis of Green Lakes Valley from the Continental Divide through the subalpine forest (Williams and Caine, 2001). We will use standard limnological methods (Wetzel and Likens, 2000) to measure summer algal species abundance and distribution, along with chlorophyll a, nutrient concentrations, particulate C, N and P, and ancillary measurements.

B. New Measurements and Experiments

B1. **Nutrient Bioassay Experiments** (*McKnight, Williams*). Lakes in an alpine/subalpine valley can be thought of as ‘chemostats’ connected in series, where phytoplankton and nutrients are transported to downstream lakes by stream segments and the flushing rates change seasonally, being greatest during snowmelt (McKnight et al., 1988; Kolesar et al., 2002). Our nutrient enrichment experiments in Green Lake 4 have shown that the phytoplankton are consistently limited by P throughout the summer, and that the algal species distribution shifts in response to P enrichment (Gardner, 2003). Along the downstream cascade, changes in the terrestrial ecosystems cause changes in the chemical characteristics of runoff entering a stream/lake segment. For example, Hood et al. (2003b) showed that the DOM quality changed from being predominantly microbially-derived in the alpine lake to being terrestrially-derived in the lowest subalpine lake in Green Lakes Valley. Following our landscape continuum concept, we expect the relative ratios of N and P to change downstream. We will conduct nutrient enrichment experiments in four connected lakes in Green Lakes Valley (2 alpine and 2 subalpine), following the methods successfully employed by Gardner (2003). We will use a factorial design for N, and P amendments and will monitor changes in chlorophyll a, nutrient concentrations, C, N and P content of particulate matter, and algal species distribution, as well as changes in DOM, while also monitoring these parameters in the lakes. For one of the alpine and subalpine lakes, we will include amendments with DOM to evaluate the possible role to photochemical release of N and P from DOM.

B2. **Mesocosm Experiments** (*McKnight*). The increase in biomass of the phytoplankton and the benthic algal communities implies either an increasing supply of P, or an efficient in-lake recycling of P to support greater growth. Mesocosms will be constructed in duplicate pairs with the bottom open to the benthos, where one pair will be amended with P directly and another pair will be amended with ‘dust equivalent’ of leachable P, following protocols in Gardner (2003). A second experiment will manipulate the organic carbon in the mesocosm sediments to evaluate the importance of P recycling and sediment weathering in providing P to the lake ecosystem. These experiments are significant because they will reveal the potential role of aeolian and fluvial transport of sediment in enhancing algal growth in response to the known anthropogenic changes associated with increased N loading and climate change.

B3. **Terrestrial-Aquatic Linkages** (*Williams, McKnight, Caine*). Terrestrial-aquatic linkages of water and nutrients as a function of temporal and spatial scales are among the least-understood processes in ecosystem science. We intend to improve our understanding of these linkages by integrated sampling of hydrometric, geochemical, nutrient, and isotopic parameters in all possible hydrologic reservoirs at high temporal and spatial frequencies. We will then analyze these datasets using end-member mixing analysis (EMMA). Unlike the more traditional techniques of hydrograph separation using single or paired tracers, EMMA uses conservative tracers that are common to all potential end-members (Christophersen and Hooper, 1992). Initial application of EMMA at GL4 provides proof-of-concept for the use of EMMA, as well as some surprising results: (1) we can recreate concentrations of conservative tracers such as calcium reasonably well; (2) groundwater is much more important than we thought; (3) talus and block fields and not soils are an important source of both water and nitrate; and (4) in the late summer, the nitrate released from talus is removed before it reaches the stream, suggesting nitrate may be lost by denitrification in saturated wetlands and riparian areas (Figure 2.14).

We will complement our long-term stream and lake sampling by sampling all potential hydrologic reservoirs, including streams and lakes, discharge from glaciers, rock glaciers, talus and block fields, soil lysimeters, and new groundwater wells. All samples will be analyzed for major solutes, stable water isotopes, and dissolved and particulate forms of C, N, and P. Subsets of the samples will be analyzed for radiogenic water and sulfur, chemical fractionation, fluorescence, SUVA, and stable isotopes of C and N of dissolved organic matter (Hood et al., 2003, in review). Subsidies of nutrients to downstream sites will be evaluated using the protocols above and by comparing similar measurements from the Como Creek forested control (Hood et al., 2003a).

C. Synthesis, Regionalization, and Cross-Site Analysis

Williams is the PI and McKnight a Co-I on a cross-site initiative from eleven LTER sites: "Dissolved organic nitrogen intersite comparison (DONIC)." McKnight is a co-organizer on a new LTER workshop on the biogeochemistry of dissolved organic matter in aquatic environments, with 7 LTER sites participating.

VI. Subalpine Forests

We view the presence of complex terrain and associated flow complexities at the Niwot Ridge site as an opportunity to better understand how to make good measurements of NEE in mountainous topography. Using primary funds from the DOE (NIGEC and TCP Programs) and NSF (Biocomplexity Program), with supplemental funding from the NWT LTER, we have maintained the Niwot Ridge Ameriflux site since 1999. We will continue our primary mission to (1) measure the amount of annual C sequestration by the surrounding subalpine forest; (2) assess the validity of making C flux measurements in complex terrain; and (3) understand the primary controls over seasonal and interannual variability on the rate of C sequestration. Moreover, potential atmospheric transport of N to the subalpine forest (especially NH_3) introduces a source of new N that may stimulate tree growth. We are interested in (1) the accurate assessment of N deposition; (2) N deposition exchange with the forest canopy as well as the soil and roots; and (3) the impacts of elevated N deposition on forest ecosystem function and C sequestration.

A. Long-Term Measurements and Experiments (*Monson, Helmig, Schmidt, Williams*)

We plan to continue studying the effects of complex flows on estimates of NEE by screening all datasets for the frequency and magnitudes of anomalies where the energy balance does not show closure. Once the Saddle towers are in place, we will conduct comparative analyses that will provide unprecedented insight into the temporal dynamics of complex flows and their relationship to interannual climate dynamics. These results will improve models of variation in NEE for ecosystems in complex terrain. We will work more closely with NWT LTER personnel to understand the importance of snow

(Williams, Helmig) and microbial (Schmidt) activity on the processes that determine C sequestration (Figure 2.4).

B. New Measurements and Experiments

B1. **Advective CO_2 Flux** (*Monson, Blanken*). Most recently, we have focused on the potential for mesoscale flow complexities and their effect on local canopy-scale flux measurements. One example is streamline separation in the presence of lee side waves that cause the formation of recirculating flow, or ‘rotor winds,’ which occur during periods of strong to moderate westerly winds when lee side waves can form near the tower site. These complex flows can cause non-stationarity in calculating wind and flux statistics. During those periods with observable drainage flows, we calculated an average advective CO_2 flux of 2-5 mmol m^{-2} s^{-1}. This is about half of the magnitude of nighttime respiration measured with eddy covariance (Monson et al., 2002). Combining our eddy correlation measurements with those at the Niwot Saddle will provide the opportunity to address the question of advection at the mesoscale.

B2. **Nitrogen Balance of the Subalpine Forest** (*Sievering*). Our main initial goal was to estimate, reasonably well, the N budget at the C1 site. A key aspect of this budgeting effort was to accurately determine canopy N uptake (CNU) during the growing season (Tomaszewski et al., 2003). The CNU contribution to new growth was found to be almost half as much as the soil/root contribution (Figure 2.15A). This assumes that 100% of the canopy N uptake is taken up by new growth foliage.

We propose to continue the research on estimating the N balance at C1, with an emphasis on obtaining CNU and relating CNU variations to NEE routinely observed at the Ameriflux tower (Sievering et al., 2003b). This has been ongoing since 2000 under DOE funding, and can be continued at minimal cost. Fluorometry measurements will be used to determine the proportion of photons that are utilized in photosynthesis (P), heat dissipation (D), and plant stress (S). The CIRAS-II photosynthesis system will be used in conjunction with fluorometry to determine the absolute magnitude of P, D, and S in tundra plants and tundra-forest ecotone plants, for comparison with these same measurements obtained in the subalpine forest during the 2003 and 2004 growing seasons. As mentioned in the Land-Atmosphere section, we will make measurements of NH_3 flux using gradient measurements.

C. Synthesis, Regionalization, and Cross-Site Analysis

Much of the proposed research explicitly links measurements made in alpine ecosystems to the subalpine forest. Monson was the host of an NSF-NEON planning workshop in 2002 and is currently a member of an ad hoc NEON National Coordinating Committee chaired by Bruce Hayden. An LTER new research initiatives mini-grant (Sievering is the PI) is providing resources to produce a field study plan on “N deposition at Forests: C Sequestration and Ecosystem Function.” A representative from each of nine LTERs/ILTERs is in the process of coordinating the multi-site plan.

Synthesis: The Alpine and Subalpine as an Integrated System

There are no extant models that couple water and nutrient fluxes between terrestrial and aquatic ecosystems in seasonally snow-covered ecosystems, nor address alpine-subalpine linkages. There are a suite of models that incorporate our best understanding to date of the biogeochemistry of C, N, P, and sulfur, such as CENTURY, Pnet, and BIOME-BGC, but they are not well-connected to surface water flux and snowmelt. Similarly, there are a number of snowmelt and hydrological models for mountain terrain (e.g., SRM), but none are coupled to biogeochemical models. We will use the Landscape Continuum Model as an integrative tool for synthesis activities at the NWT LTER while continuing to develop linked terrestrial-aquatic models. The LCM provides a conceptual approach with testable hypotheses to integrate terrestrial and aquatic processes across habitats and taxa. Additional and complementary approaches to integration and synthesis follow.

Denitrification from Plot to Watershed Scale: Little is known about the importance of denitrification in biogeochemical cycling of high-elevation catchments. Denitrification in anaerobic soils is a major component of the global N cycle, nearly balancing terrestrial N inputs from biological fixation (Galloway, 1998). However, a combination of logistical difficulties and the paucity of studies combining microbial processes with biogeochemical cycling have limited our knowledge of how denitrification rates may respond to increases in N deposition in high-elevation catchments. Our results to date suggest that denitrification may be a major pathway for N cycling in high-elevation areas. In particular, during snowmelt, the combination of microbial respiration, deep snow cover, and a supply of nitrate from over-winter mineralization and snowmelt release, along with low pH and anoxic conditions, may provide ideal circumstances to elevate denitrification rates. We will use the sampling platforms for trace gas measurements in combination with our microbial and SOM activities to measure denitrification rates at a point, and couple those fluxes with process-level understanding on the biological and physical controls of denitrification. We will work towards developing an automated GC/ECD system that measures N_2O flux directly and continuously from our trace gas platform. This plot-level knowledge will be extended to the watershed scale using a combination of mass-balance measurements of nitrogen, EMMA (Figure 2.14), and process-based modeling, detailed below.

Ecological Stoichiometry: Measurement of C, N, and P in the majority of our samples—soil, water, organic matter—at multiple spatial scales and landscape types will provide a means of integrating and synthesizing our research activities. It has been difficult to integrate terrestrial-aquatic linkages across diverse taxa and habitats to create a more generalized understanding of tropic interactions. Such integration has been facilitated by the recent development of the theory of ecological stoichiometry, the study of the balance of energy and multiple chemical elements in ecological interactions (Sterner and Elser, 2002). For example, compilations of available data make it clear that terrestrial autotrophs have drastically higher C:P and C:N ratios than lake phytoplankton, but do not differ in N:P ratio (Elser et al., 2003). Therefore, we can investigate whether P limitation may be more frequent for organisms in landscapes receiving elevated amounts of atmospheric N in wetfall. Our stoichiometric measurements thus provide a means of integrating our research as well as investigating the effects of N deposition along an elevational gradient.

Integrated Watershed Modeling: For the first two years of the renewal, Williams will work with the USGS to develop a hydrologic model that explicitly incorporates a spatially distributed snowmelt model and hydrologic flowpaths that are appropriate for seasonally snow-covered basins. To date, we have adapted the existing MMS model as follows: PRMS for precipitation input, the National Weather Service Hydro17 model for snowmelt, and TOPMODEL for hydrologic routing. However, initial simulations show that discharge is not properly modeled due to the lack of a spatially distributed snowmelt model (Liu et al., 2002). We will modify our initial attempts at adapting MMS by incorporating (1) measurements and modeling of the spatial distribution of snow (Erickson et al., 2001, in review); (2) spatially distributing energy fluxes using ISNOBALL (Marks et al., 1999); (3) adapting the snowmelt model SNTHERM (Jordan, 1991); and (4) improving our measurements of subsurface water quantity and quality by installing four groundwater monitoring wells in Green Lakes Valley and two at the Saddle site. This model development is an important step toward an integrated and coupled terrestrial-aquatic model. In year 3, we propose to begin coupling our adapted MMS model to the biogeochemical model developed by Meixner and Bales (2003). To illustrate, they report that their C and N simulation model could not accurately depict nitrate export patterns in the subalpine Emerald Lake watershed until denitrification was properly modeled using the results of Del Grosso et al. (2000). At that time, we will recruit Meixner to be the lead on our integrated modeling activities.

Carbonshed Approach. Our NWT LTER research on coupled CO_2 fluxes in upslope alpine ecosystems and downslope subalpine forests will directly contribute to the measurements and modeling efforts of the recently funded NSF-Biocomplexity award to Monson and others to study carbon flux in mountain catchments of the western US. Collaboration with other research scientists through the Biocomplexity award provides the opportunity to develop a ‘carbonshed’ approach for the study of the ecosystem carbon balance of montane landscapes throughout North America (Schimel et al., 2002). We define a carbonshed within the same context as a watershed, a mountainous tract in which the slopes and valleys cause complex topographic patterns which directly influence the drainage and accumulation of CO_2, as well as patterns in the redistribution of energy and water, which indirectly influence the exchange of CO_2 across the landscape. We make the case that the carbonshed scale is crucial for linking local, ecosystem-level CO_2 fluxes to regional, landscape-level CO_2 fluxes. Linking our eddy covariance measurements of CO_2 fluxes with our N measurements provides an important step toward regionalization and international understanding of carbon cycling at the NWT LTER (Figure 2.15B). Moreover, Monson and others are currently writing a white paper that proposes the Niwot area as an ‘intensive site’ for the North American Carbon Plan.

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, a Co-PI on this proposal. Faculty outside of INSTAAR were recruited to the program, including Dr. Tim Seastedt, the administrative PI on the 1992 renewal proposal. 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 3.1). 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.

We emphasize that the science component of the 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 1998 to 2003, LTER Co-PIs have generated extramural funding of $13,000,000 on LTER-related projects. Compared to $3,500,000 in LTER base funds, outside funding yields a return of almost 4 dollars for every LTER dollar. We have also attempted to maximize support of graduate student research at NWT by leveraging extramural support from other state and federal programs. From 1998 to 2003, the $376,000 in graduate student support from the LTER funds was augmented by an additional $1,100,000 in graduate student support from other funding sources, a return of nearly 3 dollars for every LTER dollar.

The Mountain Research Station remains a major component of the NWT LTER program. Directed by Dr. William Bowman, the MRS is responsible for the logistics of 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 manages the LTER analytical laboratory (the Kiowa Lab), as well as offices for the lab coordinator, field technician, and climatologist. The MRS also maintains the Tundra Laboratory and organizes travel from the field station to the tundra sites. Completion of a family-friendly, winterized housing facility at the MRS in March 2004 is expected to enhance the use of the site by non-CU scientists and facilitate LTER workshops.

In addition to training several undergraduates annually as part of the LTER-REU supplement, LTER researchers comprise much of the faculty involved in a CU Department of Ecology and Evolutionary Biology REU summer research program. 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 the 1998 management model to be appropriate for our site, with the following changes. First, continuity of leadership must be ensured. Dr. Tim Seastedt, the fourth PI in the NWT LTER program, has transitioned his role as administrative PI to Dr. Mark Williams for the 2004 renewal; Dr. Williams was a signatory Co-PI on the 1998 renewal. To ensure continuity in management decisions and corporate knowledge, we have created a new position: Assistant Administrative PI. Dr. Seastedt will assume this position through 2007. This arrangement provides Dr. Williams with the knowledge accumulated by Dr. Seastedt over the last 12 years. This management structure will be incorporated into future NWT LTER renewal efforts. Secondly, we will hold monthly meetings as of spring 2004. Because Co-PIs are often committed to many projects, the meetings will be required of staff personnel but optional for Co-PIs, and will feature a short science presentation by a Co-PI or graduate student to entice attendance.

For the 2004 renewal, the NWT LTER has taken responsibility for the mountain climate program (MCP). Mark Losleben has been the mountain climatologist since 1980 and currently reports to the director of the MRS. As of 2004, he reports to the PI of the NWT LTER program. His salary is 50% LTER and 40% INSTAAR, with 10% from NOAA to help with their Climate Diagnostics and Monitoring Laboratory.

Outside Collaboration: We have encouraged regionalization of the NWT LTER by including appropriate Federal partners as Co-PIs in our renewal proposal. Dr. Alisa Mast is a geochemist with the US Geological Survey (USGS) and a participant in the nearby Loch Vale experiment watershed, one of five USGS WEBB (Water, Energy, and Biogeochemical Budgets) watersheds. Dr. Kathy Tonnessen is the National Park Service (NPS) scientist responsible for overseeing science projects in national parks spanning the Rocky Mountains. The inclusion of Mast and Tonnessen as Co-PIs presents the opportunity for USGS and NPS personnel to work at Niwot Ridge as well as for NWT scientists to collaborate with research scientists throughout the Rocky Mountain region.

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 the NWT LTER and mentoring new undergraduates. Finally, we actively recruited women to be Co-PIs on this proposal.

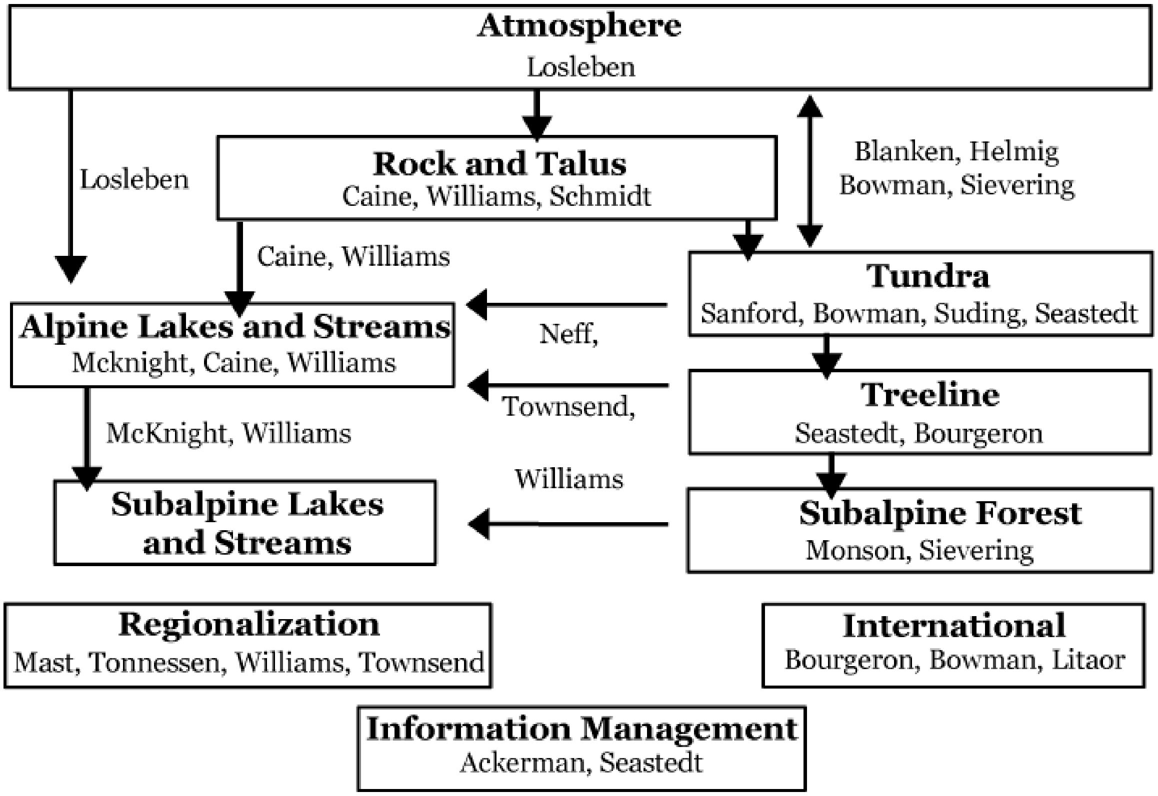


Figure 3.1. Site management following the Landscape Continuum Model with designated personnel research interests.

Section 4. Information Management (IM)

The Niwot Ridge LTER centralized IM system is entering its twelfth year. The objectives of this system have been to ensure the quality, security, and integrity of NWT LTER data, as well as to facilitate access to these data. Our formal Data Management Policy is online at: http://culter.colorado.edu/Niwot/Niwot_Ridge_LTER_datmanpolicy.html. These objectives have been met through the implementation of several strategies, described in more detail in Ingersoll et al. (1997).

Data Storage: Data are stored electronically on a Sun Ultra 60 (Culter) that is housed, along with all paper and historical archives, at INSTAAR. This workstation also serves as the Web server. Raw data, as well as all other data regardless of the degree of reduction, are stored with adequate metadata (defined here as all of the information such as materials, methods, parameter units, etc. that are necessary for the proper interpretation of a data set). This metadata is currently being expanded to meet the requirements of Ecological Metadata Language (EML).

Data are organized into three general types, distinguished by source and degree of possible manipulation: (1) data generated by equipment such as data loggers, which are the least subject to human error or manipulation; (2) manually recorded data provided via hard-copy field or laboratory forms that are entered by IM personnel; and (3) electronic data that have not been downloaded directly from an electronic instrument (e.g., MS Excel files), and may have been subject to some reduction or manipulation by non-IM personnel. These three types of data are each archived according to specific procedures, and are stored in separate locations on the central workstation.

Incentives for Investigators to Submit Data to the LTER Database: IM personnel become involved in new projects as early as possible. We arrange a meeting between the information manager and investigator or data collector at the beginning of each academic year. These meetings are essential to the creation and maintenance of adequate metadata, and allow time for the creation of hard copy data forms. Undergraduate students enter manually recorded field data from the data forms in the IM laboratory using a commercial DOS-based data entry program, EasyEntry. Accuracy of entry is ensured through range checks, table look-ups, and re-key verification. These programs, along with all procedures for entering data, are documented on a real-time basis in our manuals. Turn-around time from hard copy submittal to digital format is usually under one week.

Having a central data entry lab greatly reduces the time between collection and entry, allowing for more timely improvements in experimental design, data recording forms, and recovery of poorly or erroneously recorded data. Centralized data entry also relieves the investigator of what can often be a tedious and time-consuming task, and this can be a tempting incentive for contributing to the LTER database.

Data Security and Integrity: The security and integrity of the data is of utmost importance in the centralized information management system. We perform daily tape backups of the user and data partitions of our workstation, and weekly backups of the entire system. The user and data drives of the PC used for data entry are also backed up weekly. Another important data security measure is the use of Unix file and directory permissions, and sccs (source code control system). Unix group permissions prevent unauthorized users from editing or deleting data files. The sccs, originally designed for the integrity of programming source code, allows only a single authorized user to make edits at a time, while it records the date, time, user, and all modifications. This is an alternative to file versioning, creating a comprehensive electronic history for every file, and allowing users to return the file to a previous version.

Perl, awk, shell scripts, and Visual Basic programs are also used to ensure data integrity. We use these tools to write specific programs for each data set that automate any processing or reformatting. These programs allow for consistent processing as well as increased security, and their permissions can also be set so that only authorized personnel may access them. These programs, along with all procedures for processing the data, are documented on a real time basis in our manuals. It is important to note that all modifications are made to copies of the data files, and that all files remain archived in their original format.

Once the data are in the format desired by the investigator, they are joined with the appropriate metadata in end-user files. If an end-user file already exists for that data set, the new data are appended to the appropriate section, and additions are recorded in the log section of the metadata header. Storage of these files in ASCII format facilitates migration across variable computing platforms. These files use a consistent structure of tags demarcating their various components, a modification of the structure presented in Conley and Brunt (1991). This structure is described online at: http://culter.colorado.edu/Niwot/Niwot_Ridge_LTER_datafiles.html. These files are then available to all NWT LTER investigators without restriction via their account on Culter. When the data files are updated, corresponding metadata in the SQL Server database are updated at the same time.

Data Availability: Public access to NWT LTER data and other information is available via our World Wide Web server. Data sets are searchable through web forms located at: http://culter.colorado.edu/Niwot/Niwot_Ridge_LTER_datmansearch.html. The data provided by these servers are generated directly from the end-user files on Culter, so they are automatically updated as the data set is created or appended. The majority of our data sets are available without restriction, but some investigators have concerns about the proprietary rights of their data sets. Therefore, only the metadata are publicly available for previously unpublished data sets that are still considered proprietary by their primary investigator. Currently, more than 110 data sets are freely available, while just 30 are still considered proprietary. We also have a second retrieval system for the data collected from the Subnivean laboratory with over 100 channels of data collected at 10-minute time steps. The web forms allow for querying data at 10-minute, hourly, and daily time steps after the field technician has viewed and quality-checked the data.

A current site bibliography is maintained in InMagic format. The bibliography is searchable by author, keyword, title, and year, via our web page at: http://culter.colorado.edu/Niwot/Niwot_Ridge_LTER_bibliography.html. Perl scripts have been written to convert InMagic format into EndNote export format if necessary.

Current and New Initiatives:

Wireless technology: We are installing wireless connections at eight field sites. The wireless connections are made using spread spectrum, frequency-hopping technology in the 900 MHz range. This technology is particularly well suited to mountainous terrain, where true line of sight virtually never exists (Figure 4.1). Wireless connection to the Niwot Ridge and Green Lakes Valley field sites will enable two-way, interactive communication with data loggers over the Internet. This feature has the potential to save many hours of effort and travel time for maintenance, plus real time data accessibility to researchers and the public via our web page. We also propose replacing the current T1 line with a wireless system that utilizes this same frequency-hopping technology, but in the 5 GHz range, which permits higher data throughput speeds compared to the 900 MHz frequencies. This system will require two repeaters between the endpoints of the MRS and the main CU campus. Preliminary tests have confirmed that this routing will perform well and meet our needs. The near real time data from three of these automated stations, C1, Saddle, and D1, are graphically displayed on the LTER web page at http://culter.colorado.edu/.

Visual Basic forms: We are rewriting our data entry forms using Visual Basic so that they are compatible with forms used by the field investigator, while simultaneously providing the security of data entry safety through such features as range checks and table look-ups. This improvement should result in more use of IM personnel by field investigators.

Relational Database: We have been developing a relational database that currently houses existing metadata from the flat file datasets and imports data received from the data loggers on our wireless system. A prototype web form to access data logger data can be viewed at http://culter.colorado.edu/exec/Database/database_query.pl. The current flat file system will work in concert with the relational system until all of the bugs are worked out of the new database.

Metadata: We have been working with the LNO to generate eXtensible Style Language Transformations (XSLT). The use of a XSLT will allow us to convert metadata exported by the relational database into well-formed EML documents. Our native XML documents are output by a SQL Server relational database that has been populated with existing metadata from our ASCII data files.

GIS: All GIS layers have been converted to a common projection. We are in the process of taking high-resolution (< 0.6 m) GPS measurements of every study plot and field site. The spatial data is currently being imported into a geodatabase. A prototype online Internet map server (ArcIMS) is being beta-tested so that investigators can easily make project-specific maps or find locations of previous or on-going research projects, as well as make decisions for future plot locales. (http://dbkong.colorado.edu/Website/NiwotRidgeMap/)

MD5 Checksum: As requested by the mid-term review team, a MD5 checksum has been added to the data file directory on Culter.

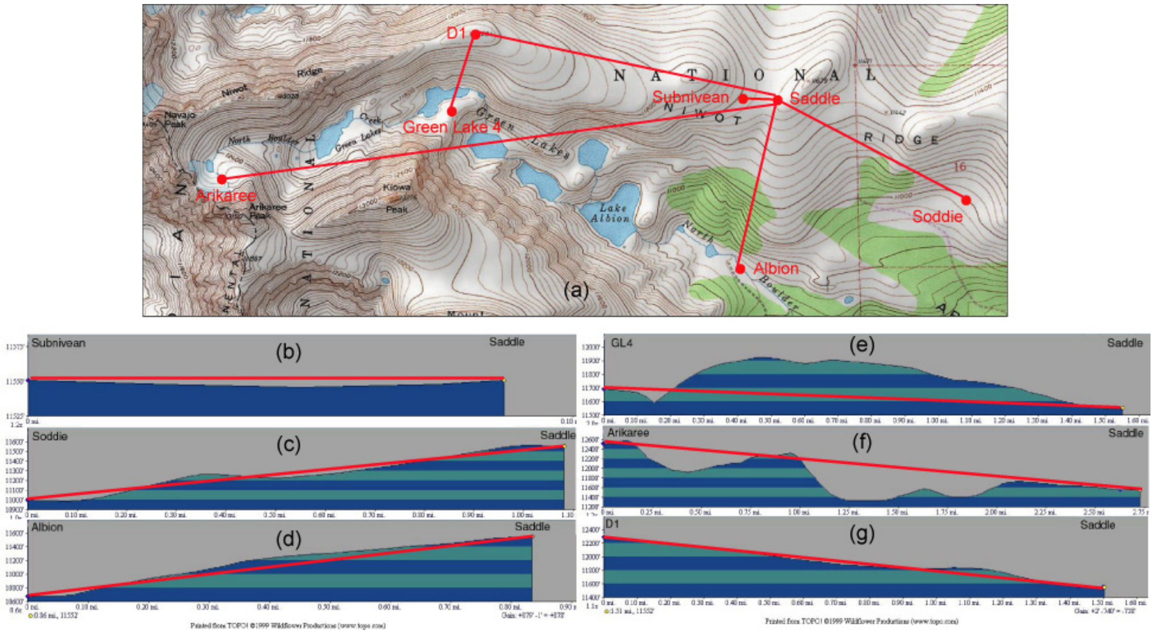


Figure 4.1. Location of 6 wireless field sites and their point of connection to the Internet, the Tundra Lab, located at the Saddle site. Elevation profiles show the difficulties in obtaining line of sight communication to remote field sites.

Section 5. Outreach Efforts

TundraCam: The alpine and subalpine 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* web cam located at the NWT LTER at an elevation of 11,600 feet (http://instaar.colorado.edu/tundracamII/). This camera can be controlled by anyone; a robotic arm and special software allow the camera to be panned and zoomed from a web browser. The TundraCam has been very successful, receiving about 5,000 hits per month and approximately 750,000 downloaded images per year.

K-12 Outreach Program: Since 1998, the 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 the MRS. Starting in the summer of 2001, we included a group of middle school students from a program for children with troubled family situations. We are currently developing a program with the "I Have a Dream" program in Boulder.

"Alpine Ecology and Experiential Learning Summer Course": This is a CU-Boulder course targeted at education students and practicing K-12 teachers; about half of the 5-15 students each year are in-service teachers. The course is taught by NWT LTER scientists (e.g. Diane McKnight, Susan Sherrod, and Hector Galbraith) and by Dr. Jane Larson, an expert in science education from the College of Education at CU. *Teacher training*: A major use of outreach funds has been and will continue to be for stipends to support the participation of current elementary school teachers in this program. We actively encourage participation by providing stipends to seven K-12 teachers each summer. *Computer support*: Using supplementary LTER funds, we provide computers to the teachers who participated in the class, allowing access to the NWT LTER database and use of other materials employed in the training classes. For example, the teachers can access TundraCam images (described above). *Open House*: 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. As a result of this activity, one middle school student conducted a science fair project with a NWT LTER graduate student and won an award at the state competition.

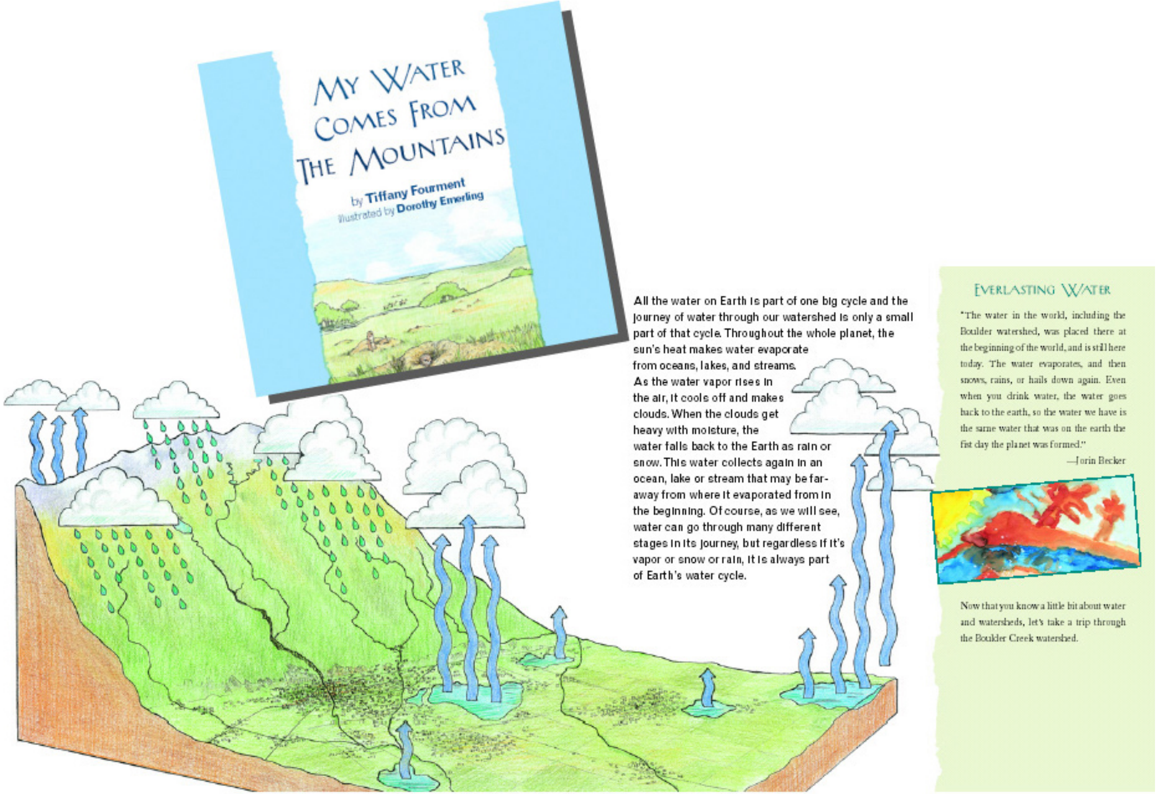
Children's book: "My Water Comes from Silver Lake", by Tiffany Fourment and illustrated by Dorothy Emerling, published by Roberts Rinehart, February 2004 (Figure 5.1). Another accomplishment of the NWT LTER K-12 program has been the publication of this children's book describing the ecology of the Green Lakes valley and the hydrologic cycle that supplies water from the valley to the City of Boulder. Tiffany is a former student from the MRS summer course who had her third grade class paint brilliant water colors to illustrate their impressions of the NWT LTER field site. Several of these illustrations were enlarged, framed, and now grace the halls of the national NSF building in Arlington, VA. We will distribute classroom sets of this book to elementary classrooms in the Boulder Valley and St. Vrain school districts through collaboration with the Boulder Water Department and a local stakeholder group called the Boulder Creek Watershed Initiative. The success of this effort has led to a new book project with Roberts Rinehart Publishing about the McMurdo Dry Valley LTER site in Antarctica.

Virtual Field Trip to Niwot Ridge: With support from CU, the NWT LTER has developed a virtual field trip to Niwot Ridge. The field trip prototype is posted on the Internet at http://culter.colorado.edu/Field_trip. The virtual field trip provides background information, and then 3 field trips: (1) mammals; (2) plants; and (3) and the effect of nitrogen on biodiversity.

Science Library Video: Led by Dr. Diane McKnight, NWT LTER scientists provided technical support and coordinated local arrangements for production of a video series on biomes of the world for Schlessinger Science Library. NWT LTER scientists and elementary and middle school students participating in our outreach effort last year were filmed. This footage was used extensively in three tapes: Biomes of the World in Action: Tundra; Biomes of the World in Action: Coniferous Forest; and Forest Ecosystems for Children. These videos are sold to K-8 educators and audiences worldwide.

New Directions: We have committed an additional $10K from the LTER renewal budget to outreach as seed monies to develop several new and vital outreach efforts.

- *Assessment*. Develop an assessment plan for the Alpine Ecology and Experiential Learning class. Because assessment has been a key weakness of our outreach program, we will collaborate with a CU Department of Education specialist in the area of educational assessment. The specialist will help design an information gathering program, perform an assessment analysis, and provide feedback on how to improve our efforts to meet educational standards.
- *Outreach web site*. Create a set of integrated web pages to better publicize our outreach and education, as well as assist with assessment of the outreach program.
    - *"Current Outreach" pages*: A searchable mini-database of current outreach efforts and availability of NWT LTER speakers.
    - *"For Teachers" pages*: This site will be primarily for K-12 instructors, but will also include selected materials used in our introductory college courses. For example, we have already begun developing "Alpine Ecology Curricula" pages using field trip guides developed by in-service elementary teachers taking the MRS class described above. To facilitate access and dissemination, we will list the site with large educational clearinghouses like DLESE (Digital library for Earth Science Education) and ERIC (Educational Resources Information Center).
- *College education program*: Expand our undergraduate education program based on the model provided by a new NSF grant: "CU-LTER Scholars Program in Biology and Applied Math for Undergraduates, $99,927, 9/03-8/05"; Drs. Seastedt, Williams, and McKnight are Co-PIs along with PI Michael Grant, Associate Vice-Chancellor for Education at CU.



MY WATER COMES FROM THE MOUNTAINS

by Tiffany Fourment

Illustrated by Dorothy Emerling

All the water on Earth is part of one big cycle and the journey of water through our watershed is only a small part of that cycle. Throughout the whole planet, the sun's heat makes water evaporate from oceans, lakes, and streams. As the water vapor rises in the air, it cools off and makes clouds. When the clouds get heavy with moisture, the water falls back to the Earth as rain or snow. This water collects again in an ocean, lake or stream that may be far-away from where it evaporated from in the beginning. Of course, as we will see, water can go through many different stages in its journey, but regardless if it's vapor or snow or rain, it is always part of Earth's water cycle.

EVERLASTING WATER

"The water in the world, including the Boulder watershed, was placed there at the beginning of the world, and is still here today. The water evaporates, and then snows, rains, or hails down again. Even when you drink water, the water goes back to the earth, so the water we have is the same water that was on the earth the fist day the planet was formed."

—Jorin Becker

Now that you know a little bit about water and watersheds, let's take a trip through the Boulder Creek watershed.

Figure 5.1. An outgrowth of Diane McKnight's K-12 LTER outreach program is the publication of *My Water Comes from the Mountains* written by Tiffany Fourment and illustrated by Dorothy Emerling (Roberts Rinehart Publishers, Rowman and Littlefield Publishing Group) in February, 2004. This children's book describes the ecology of the Green Lakes valley and the hydrologic cycle that supplies water from the valley to the City of Boulder using both professional illustrations and brilliant watercolors painted by third graders to illustrate their impressions of the NWT LTER field site. Several of these illustrations were enlarged, framed, and now grace the halls of the national NSF building in Arlington, VA.