Long-term experimental manipulation of winter snow regime and summer temperature in arctic and alpine tundra

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Abstract:

Three 60 m long, 2.8 m high snowfences have been erected to study long-term effects of changing winter snow conditions on arctic and alpine tundra. This paper describes the experimental design and short-term effects. Open-top fiberglass warming chambers are placed along the experimental snow gradients and in controls areas outside the fences; each warming plot is paired with an unwarmed plot. The purpose of the experiment is to examine short- and long-term changes to the integrated physical-biological systems under simultaneous changes of winter snow regime and summer temperature, as part of the Long-Term Ecological Research network and the International Tundra Experiment. The sites were at Niwot Ridge, Colorado, a temperate high altitude site in the Colorado Rockies, and Toolik Lake, Alaska, a high-latitude site. Initial results indicate that although experimental designs are essentially identical at the arctic and alpine sites, experimental effects are different. The drift at Niwot Ridge lasts much longer than do the Toolik Lake drifts, so that the Niwot Ridge fence affects both summer and winter conditions, whereas the Toolik Lake fence affects primarily winter conditions. The temperature experiment also differs in effect between the sites. Although the average temperature increase at the two sites is similar (daily increase 1.5 °C at Toolik and 1.9 °C at Niwot Ridge), at Toolik Lake there is only minor diurnal variation, whereas at Niwot Ridge the daytime increases are extreme on sunny days (as much as 7–10 °C), and minimum nighttime temperatures in the chambers are often slightly cooler than ambient (by about 1 °C). The experimental drifts resulted in wintertime increases in temperature and CO2 flux. Temperatures under the deep drifts were much more consistent and warmer than in control areas, and at Niwot Ridge remained very close to 0 °C all winter. These increased temperatures were likely responsible for observed increases in system carbon loss. Initial changes to the aboveground biotic system included an increase in growth in response to both snow and warming, despite a reduced growing season. This is expected to be a transient response that will eventually be replaced by reduced growth. At least one species, Kobresia myosuroides, had almost completely died at Niwot Ridge three years after fence construction, whereas other species were increasing. We expect in both the short- and long-term to see the strongest effects of snow at the Niwot Ridge site, and stronger effects of temperature at Toolik Lake. Copyright © 1999 John Wiley & Sons, Ltd.

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INTRODUCTION

Predicting the effects of complex changes in summer and winter climate on ecosystems represents a challenge from both scientific and practical standpoints. The problems are particularly acute in ecosystems where winter climate exerts a strong control on overall system function. Arctic and alpine landscapes in particular require integrated studies of physical and biological systems because of strong feedbacks and controls (Oechel et al., 1997). We present an integrated experimental study of the effects of increased winter snow and increased summer temperature at one alpine and two arctic sites.

The landscape-scale distribution of snow is perhaps the single most important mesoscale variable controlling biological systems in arctic and alpine ecosystems (Walker et al., 1993). Although global circulation models show great variability in potential climate in arctic and alpine systems in coming decades, it is clear that warming will be enhanced at high latitudes, and that hydrologic processes may be intensified in all systems (Houghton et al., 1996; Maxwell, 1992, 1997). Arctic and alpine systems are useful for comparative study because they share a dominance of winter processes, cold summer temperatures, and have similar species and vegetation. Snow is a major control of many patterns and processes in both systems. Yet they also have important differences that should strongly influence their responses, most of them driven by differences in solar radiation patterns and topography. Arctic ecosystems are strongly linked to temperature, particularly in their biology and patterns of species distribution and diversity. Thus, they may respond most strongly to changes in temperature. Although snow is an important control over species and community distribution, the influences of snow in arctic ecosystems may be tied most closely to winter processes, because the melt patterns are such that there is no more than a few weeks difference between early and late-melting sites. Alpine ecosystems, on the other hand, are likely to be very sensitive to changes in snow regime. The snowmelt period extends throughout the summer in these systems, and in certain topographic locations snow may be permanent in some years. The influence of alpine tundra to regional biogeochemical and hydrologic extends far beyond its limited area. The temperate alpine and subalpine region of North America supplies most western water and much of that used in the plains region as well. The North American continental climate is strongly influenced by this region (Greenland and Swift, 1990; Manabe and Broccoli, 1990).

We are using large snow fences and small portable open-top chambers to examine the effects of altered snow regimes and air temperatures in arctic and alpine tundra. In this paper, we describe the experimental design and short-term changes to physical and biological components of the system in response to the experiment. The experiment is intended to last for a much longer time period than the standard three to five year ecology experiment (Walker et al., 1993). The long term of the experiment is essential, because tundra vegetation communities do not equilibrate quickly. Changes to below ground resources and substrate require long adjustment periods, and a series of transient plant communities without apparent natural equilibrium analogues may occur in the interim. The experiment is part of the NSF-sponsored Long-Term Ecology Research (LTER) project on Niwot Ridge, CO, and the International Tundra Experiment (ITEX) at Toolik Lake, AK. The Toolik Lake site is also part of the LTER site network. Previous studies have examined tundra response to increased snowpack over a similar time period (e.g. Webber et al., 1976), but this is the first experiment to combine the ITEX warming simultaneously with a snow increase. The study integrates processes within the physical system (soil and air temperature, season length, snow chemistry and composition), the below ground biotic system (decomposition, trace gas fluxes), and the above ground biotic system (phenology, growth, greenness, and community composition).

METHODS

Study areas and experimental design

In the summers of 1993 and 1994, we erected three snowfences at Niwot Ridge, Colorado, and Toolik Lake, Alaska for the purpose of manipulating snowpack (Figures 1 and 2). The Niwot Ridge site (40°03’N, 105°36’W) is a broad tundra upland ridge at 4085 m a.s.l. elevation. Toolik Lake (68°37’N, 149°32’W), in the
Figure 1. Locations of Niwot Ridge and Toolik Lake snow-warming experiments

Figure 2. The Toolik Lake dry-site snow fence and open-topped chambers (OTCs). OTCs are 40 cm high, 1 m across, and are constructed of translucent fiberglass. They raise summer air temperatures about 2 to 5 °C (Marion et al., 1997). OTCs are placed over experimental plots as soon as 50% of the plot becomes snow-free; they are removed in late August or early September
northern foothills of the Brooks Range at about 700 m a.s.l. elevation, is a gently rolling site with predominantly tussock tundra vegetation (Walker et al., 1994a). The fences are all 2-8 m tall and 60 m long and create leeward drifts approximately 60 m long (Figure 3). Areas further than 60 m from the fence receive less than ambient amounts of snow. At Niwot, we placed one fence in an ecotone separating a moist meadow from a dry meadow. At Toolik Lake, we located one fence in a dry tundra site and the other in a moist tussock-tundra site. Fences are either removed or laid down during the summer so as not to affect ambient summer wind regimes. The Niwot Ridge fence is on a north-south axis, because predominant winds are from the west, and the Toolik Lake fences are on east-west axes, because the predominant winter winds and storms are from the Brooks Range to the south.

The experimental design is factorial. Plots are subjected to increased winter snow (+S), increased summer temperature (+T), and both simultaneously (+S+T); full controls (ambient snow and temperature) are designated as +0. Summer air temperatures are elevated using small greenhouses, 1 m² open top chambers (OTCs) that passively warm the tundra (Marion et al., 1993, 1997) (Figure 2). The OTCs are also used at 24 circumpolar and alpine sites in replicated experiments and are of the standard International Tundra Experiment (ITEX) design (Henry and Molau, 1997). Control plots are located in areas adjacent to the fences.

Permanent plots were established within the snow fence grids and in locations outside of the influence of the snow fences (Figure 4). Several types of plots were established, including: (1) undisturbed OTC and non-OTC plots along the snow gradient for examining tundra plant phenology, growth, and community composition, (2) OTC and non-OTC plots along the snow gradient for disruptive or destructive sampling (soil chemistry, mineralization and decomposition, soil and leaf moisture, temperature), (3) CO₂ and CH₄ flux plots along the snow gradient only, and (4) normalized difference vegetation index (NDVI) plots along the snow gradient only. Vegetation maps were prepared at all the fences to portray the pre-experiment vegetation patterns (Figure 5). The total experimental design includes the response of species along the gradient of snow regimes, including decreased snow at distances beyond about 60 m.

Because our primary purpose here is to present the experimental design, details of methods are presented in the figure captions. Measurements of the physical system include depth, extent, and density of snowpack, soil and air temperature, and snow chemistry and composition. Snow measurements are made at a grid behind the experimental fences and at fixed landscape points outside the experimental areas. Site-scale climate monitoring is provided by the Niwot Ridge and Arctic LTER programs operating at each of the sites.

Soil measurements include rates of decomposition and of CO₂ flux. Baseline measurements of major soil properties — organic matter, pH, texture, water-holding capacity, bulk density, depth of O and A horizons — were taken in order to be compared with data much later in the experiment. Because we do not expect major physical soil properties to change noticeably in the first few years of the experiment, they are not addressed here.

NDVI = (NIR - R)/(NIR + R), where NIR is the spectral reflectance in the near-infrared, where light scattering from the canopy dominates, and R is the reflectance in the red, chlorophyll-absorbing portion of the spectrum.
Like the soils, measurements of the vegetation system include both short- and long-term components, and we focus here on the short-term components. Measurements for which we expect to see short-term responses include a series of variables that can be categorized as either phenology or growth variables. Phenologic measurements capture timing of critical biological events, and growth measurements are analogues for biomass and allocation. These measurements follow earlier work on natural variation in phenology and growth in response to interannual climatic variability (Walker et al., 1994b, 1995b). Measurements are standardized according to ITEX guidelines (Molau and Mølgaard, 1996). Unfortunately, there are no species abundant enough at both sites to provide a direct comparison, but nonetheless we can look at and compare overall patterns for the three fences. The phenology and growth data from both sites have also been used in a meta-analysis of 17 ITEX sites worldwide (Arft et al., 1999).

We are also using measurements of NDVI to supplement the direct measures of phenology and growth and to serve as a non-destructive measure of green biomass. It is useful for examining phenological development, and serves as an analogue for leaf area index and biomass of tundra landscapes (Shippert et al., 1995; Walker et al., 1995a).

We expect the short-term variations in phenology and biomass to ultimately result in significant shifts in community composition. To document these changes, we are also taking extensive long-term...
Figure 5. Vegetation map of the Niwot Ridge snow fence site. Associations are according to Komárková (1979) as mapped by Walker (Walker et al., 1993). Scale is provided by the fence, which is 60 m in length. Note the ecotone between dry and mesic tundra along the fence. The increased snow cover provided by the fence should cause a shift in conditions more similar to those currently found on the windward side.
community-scale measurements of vegetation as well as measurements of community biomass. These data will be used to look at longer-term changes over five to ten year time periods and thus are not presented here.

RESULTS

Physical system

There were two main effects of snow on soil temperature: (1) higher average temperatures, and (2) more spatially and temporally consistent temperatures. Deep snow accumulation behind the fences causes large increases in winter soil temperature at all sites. Soil surface temperatures in the deepest part of the drifts at Toolik Lake and Niwot Ridge are about 15 °C warmer on average than adjacent controls (Figure 6). Although shallow snow areas have occasional warming periods related to periodic storms, they are short lived. Temperatures under the deep part of the Toolik Lake drift remained near freezing in 1994, declining to a minimum of about −7 °C in early May. At Niwot Ridge, soil temperatures at −15 cm under deep snow did not decline below freezing all winter, in contrast to the pre-fence conditions where mid-winter temperatures were in the −10 to −12 °C range (Figure 7). The presence of snow led to a much more consistent set of conditions through the winter, so that the pattern of temperatures prior to the fence was largely influenced by time (of year), and after the fence by spatial position relative to the fence.

The OTCs had somewhat different effects at the two sites, which has also been recognized in other studies of their effects across a broad spectrum of sites (Marion et al., 1997). Mid-day summer air temperatures in the OTCs are more strongly elevated at Niwot Ridge than at Toolik Lake, probably due to much higher mid-day solar radiation at the lower latitude site (Figure 8). The mean daily increase at Niwot Ridge is 1.9 °C, compared to 1.5 °C at Toolik Lake. Diurnal fluctuations are also greater at Niwot Ridge, with cooler nighttime temperatures and warmer daytime temperatures. Soil temperatures are not elevated at the arctic

![Figure 6. Soil surface temperatures beneath the Toolik Lake dry-site fence and control plots, winter 1994–1995. Temperatures were recorded every 48 minutes using Hobo temperature logging devices (Onset Computer Corporation, Pocasset, MA). A very similar pattern was found at Niwot Ridge](image-url)
Figure 7. Niwot Ridge –15 cm soil temperatures before (1992–93) and after (1993–94) fence construction. Temperatures were measured approximately every three weeks on a 10 m grid on both leeward and windward sides of the fence.

site, but are elevated about 1–2°C on average at the alpine site. These differences in mean increase and in diurnal distribution of change mean that the chambers have a potentially greater effect at Niwot Ridge. Toolik Lake is more subject to long periods of cloudy weather, which will also tend to dampen the chamber effect.

Organic and mineral inputs from the snowpack potentially influence the nutrient availability in these sites, but in different ways. Snow composition varies markedly between Toolik Lake and Niwot Ridge (Figure 9). Most notable are the large differences in sediment and organic matter inputs; the Niwot Ridge snow contained very little organic material, and mineral inputs at Toolik Lake were nearly twice that at Niwot Ridge. The very high organic matter accumulation in the Toolik Lake snow occurs primarily in early winter, before substantial snowfall covers the region. It represents a large input of leaves and organic debris stripped from nearby snowfree areas in early winter and deposited in the artificial drift. The much deeper alpine snowpack and relative scarcity of deciduous shrubs results in less organic matter in the alpine snow drift. Snow pH at Toolik Lake is higher than at Niwot Ridge due to carbonate-rich loess blown from nearby river systems.

The high concentrations of mineral and organic debris found directly behind the fences also occur in natural tundra snowbeds, although at somewhat lower concentrations (personal observation). The densities of the snow fence drifts were comparable to the snow outside of the drift areas. This suggests that the best areas for examining the ecosystem effects of enhanced snow cover are in the areas farther downwind from the
early-winter drift formation (beyond 25 m from the fences). In these regions snow cover is enhanced, but based on our observations there is no artificial increase in organic material.

**Belowground biotic system**

Decomposition patterns at the two sites varied significantly in their response to snow. Placement of litterbags with respect to the experimental snow gradient had a very significant effect on decay after two years in the field at Niwot Ridge but absolutely no detectable effect at Toolik Lake (Figure 10). These results are somewhat difficult to reconcile with other soil measurements. Our interpretation is that the change in microclimatic conditions in the alpine resulting from enhanced snow appears biologically much more significant at Niwot Ridge than at Toolik Lake. Presumably, the observed differences relate to the length of time the substrates remain non-frozen and available as a resource for microbes and invertebrates. Temperature effects on decomposition have not yet been assessed.

The differences in rate of decay between the sites can be attributed to substrate-quality differences. *Acomastylis rossii* contains large quantities of polyphenols, which are lost during the early stages of decomposition (Dearing, 1997), and this species therefore has a relatively rapid decomposition rate during the first
Figure 9. Snow pH, mineral sediment, and organic matter in the deepest part of the three drifts. Snow samples were collected in spring at maximum and annual depths. Samples represent a complete snow column.

Figure 10. Mean and standard error of percent of initial mass remaining after two years of decay at the Toolik Lake moist site and at Niwot Ridge, in the deepest part of the drift and under ambient snow conditions. Litterbags containing senescent foliage were placed in deep and ambient snow conditions at the two sites. Alpine avens (Aconostylis rossii) foliage litter was used at Niwot Ridge, and foliage litter of dwarf birch (Betula nana) was used at the Toolik Lake moist site. Both species are dominants at their respective sites. Decay rates of both of these species have been studied in their respective environments (Hobbs, 1996; O’Lear and Seastedt, 1994), so we have a baseline for comparison. Procedures used in the litterbag experiments are detailed in O’Lear and Seastedt (1994).

Year of decay. Betula nana has a smaller percentage of labile compounds and therefore exhibits a substantially lower rate of decomposition. Although this difference explains the overall greater rate of decay at Niwot Ridge, it does not explain the lack of a snow effect at Toolik Lake.

The snowfences cause an increase in winter CO₂ flux on a scale similar to that found in natural snowdrifts (Figure 11a). At Niwot Ridge, CO₂ fluxes were measured before and after the installation of the snow fence and integrated over the full season in 1993 and 1994. Increases were detected under the deeper snow in the snow-fence drift as compared to pre-fence measures. Fluxes under the enhanced snowpack fit into the
observed variation found in a natural drift of similar magnitude. The difference between the 1993 pre-fence site and the 1994 low-snow control site demonstrates the natural variation in similar sites between years with different snowfall (Brooks et al., 1996).

At Toolik Lake, the dry site showed a two-fold difference between deep snow and controls, whereas there was little difference at the moist site (Figure 11b). Winter CO₂ flux in natural communities is strongly controlled by depth of the winter snowpack (Fahnestock et al., 1998), and during spring, as the subnivian soils warm, the fluxes increase several fold.

**Aboveground biotic system**

There were immediate responses of the phenology and growth of vegetation to the experiment; temperature and snow had predictably different effects. The main short-term effect of increased snow cover is a shortened growing season. The growing season in the deepest part of the drift at Niwot Ridge was reduced to 51 days, or about 30% of the pre-fence growing season (Figure 12). Snowmelt in the Arctic was much faster and resulted in only about a two to three week delay in season start. The large difference between the two sites is due primarily to the much lower nighttime temperatures at the temperate alpine site compared to 24 hours of daylight in the Arctic.

Figure 11. Winter CO₂ efflux at the Niwot Ridge (a) and Toolik Lake (b) sites. At Niwot Ridge, the flux of C is significantly less in the naturally shallow snow area than in the experimental and natural drifts and the pre-fence drift. Although the mean flux increased in the drift area following fence construction, differences are not significant. There were no pre-fence measurements of flux at Toolik Lake, where both fences increased CO₂ flux, but only at the dry site was the increase statistically significant. Measurements at Niwot Ridge were taken over a full year before (1993) and after (1994) fence construction, and are therefore presented on an annual basis. At Toolik Lake, CO₂ fluxes were measured in base traps which were placed before snow fall in 1994 and collected as soon as the traps became snow-free the following spring. Measurements are integrated into a daily average for that period.

Figure 12. Meltout dates for the three fences in 1995. These are the dates on which all experimental plots were free of snow.
Toolik

Dryas octopetala

Niwot

Acomastylis rossii

Bistorta bistrortoides

Figure 13. Phenology of Dryas octopetala in experimental manipulations and controls at the Toolik Lake dry site and of Acomastylis rossii and Bistorta bistrortoides on Niwot Ridge. Note the compressed phenology in the snow treatment plots. Phenological diagrams were constructed from data which recorded the first and last occurrence of major phenological events within the study plots: release from snow, appearance of leaves (which in these species is the first appearance of the plants), flowering buds, opening of buds, anthesis, seed dispersal, and leaf senescence, which signals the end of the season.

Phenological diagrams for Acomastylis rossii and Bistorta bistrortoides at Niwot Ridge and for Dryas octopetala at Toolik Lake indicate that, at least in this early period of the experiment, plants respond to increased snow with a compressed growing season (Figure 13). These two species are able to complete a full growth and reproductive cycle under these conditions, they just do it in a shorter span of time. By the end of the season there were as few as nine days separating the phenology of plants in the deep part of the drift from those in the control area. Temperature had a somewhat complementary effect of snow by lengthening the growth season on the autumn end. Both of these effects will likely have important influences on species composition and community function in the long-term. Although most arctic and alpine plants should be able to survive the rare shortened year, a series of short years will result in a depletion of belowground reserves.

The effects of changing growth season length are already evident at Niwot Ridge for Kobresia myosuroides, the dominant plant there prior to fence construction. After three years, most of it has been killed in the deep drift areas, most likely because it cannot translocate sufficient amounts of carbohydrates to belowground reserves before the end of the growing season (Willard and Marr, 1970; Bell and Bliss, 1979). Compression in
the early season might therefore lead to reduced growth in a particular year, and extension in the late season
can lead to failure to properly harden and store nutrients and carbohydrates before winter. Several other
changes in species composition have been noted in the alpine site, but so far none have been noted in the
arctic site. The site differences are likely due primarily to the phenological differences related to snow melt
date.

NDVI measurements at Niwot Ridge corroborate the end-of-season lengthening seen in the individual
species. In September 1994, NDVI in the snow-fence area was considerably higher than control areas on
either side of the fence, indicating a much greener area behind the fence with delayed senescence (Figure 14).
Similar measurements of NDVI at Toolik Lane showed no differences in greenness at the end of the season,
although some differences are evident early on due to the delayed season start.

Both Acomastylis rossii and Bistorta bistortoides on Niwot Ridge responded to the experiment with
increased growth (Figure 15), but specific responses varied with species and variables measured. Maximum
height and maximum leaf length of B. bistortoides in the +S+T treatment were higher than in other
treatments, and plant height in particular was increased. A. rossii responded most strongly to the +T
treatment; its growth was less in the +S+T treatment, possibly due to the much later growing season start.
Examining the overall pattern of response, both species generally respond positively to temperature, and in
some cases there is a synergistic effect of temperature and snow, but in no case did the snow-only treatment
lead to a significant increase in growth.

DISCUSSION AND CONCLUSIONS

Because snow and temperature together define much of the landscape-scale pattern of arctic and alpine
ecosystems, changes in these regimes should have major influences on these ecosystems. Our results indicate
that interactions between snow and temperature are important to account for and may affect ecosystems in
somewhat surprising ways.

The snowfences had very different influences on the growing season in the arctic vs. the alpine. Despite
identical drift size and nearly identical snow water equivalent, the arctic drift melted out over 1-5 months
before the alpine drift, a consequence of the different solar insolation regimes in the two regions. In a growing
season of only about 90–100 days, this is a major difference indicating that increased snowfall could have
more significant ecosystem consequences in the alpine than in the Arctic. The growth and phenology responses, including the death of the dominant species *Kobresia myosuroides* at the Niwot Ridge site, support this. Webber et al. (1976) also noted a fairly rapid decline and demise of *K. myosuroides* in their study of experimentally increased snowpack in the San Juan Mountains of southwestern Colorado. The measurement of NDVI at both sites also suggests that changes to phenology have been most noticeable in the alpine.

On the other hand, the Arctic generally has less snowfall than alpine areas, and small changes in arctic winter snowpack could have greater impacts on arctic soil temperatures than in the alpine. Increased winter soil temperature in both areas will have major impacts to a wide variety of ecosystem functions including winter plant activity, decomposition, flux of trace gases, and subnivian animal activity (Walker et al., 1999). Furthermore, arctic winter soil temperatures are critical to permafrost temperatures (Zhang, 1993), and enhanced winter snow cover could lead eventually to a melting of the permafrost particularly in areas with permafrost temperatures near 0 °C. At regional scales, snow may interact with other variables to change the entire system state, affecting vegetation, soil chemistry and nutrients, permafrost depth, and trace gas flux (Walker et al., 1998, 1999).

Effects on decomposition and carbon flux show the strong importance of snow in particular on these processes. The addition of snow causes an immediate increase in CO₂ loss, which is indicative of complex
changes in the soil microbial system. Williams et al. (1998) found that increasing snow in alpine ecosystems will also result in increased N mineralization, increase in N₂O flux, and increase in net nitrification. Our data indicate the importance of snow in trapping mineral and organic debris, leading to a major redistribution of these materials on the landscape, and therefore having a key role in soil development and landscape-scale soil patterns (Burns and Tonkin, 1982).

The results presented here are short-term responses in an experiment meant to last at least for decades. Many of the transient responses related to increased rates of nutrient cycling and loss and plant growth will not likely be sustained, but the rates at which each will change to a new quasi-equilibrium are unknown (e.g. Webber et al., 1976). The phenology and growth data serve as a surrogate for demonstrating the complexity of interaction between the physical and biological components of this experiment and the switch between short and long-term processes. Growth of most measured species increased with both temperature and snow, even though snow caused a greatly shortened growing season. Although this result seems at first contradictory, Walker et al. (1995a) noted the same response in natural populations following an El Niño year with deep snowpack and delayed melt. They speculated that the increase was due to two things: (1) additional snow leads to additional growth season moisture, an important limiting factor in the alpine tundra late in the growing season, and (2) the delayed melt causes the growth to be pushed into a warmer period. This can only be a short-term response, however. These alpine species depend primarily on stored resources from the previous year for growth in the current year (Mooney and Billings, 1960; Walker et al., 1994b, 1995b). They then use these resources to fix more carbon and take up more nitrogen, which is again stored over the winter. Species’ ability to adapt to changing phenological conditions in the long term will depend greatly upon their relative use of stored versus currently available nutrients.

One of the key things that we will be able to accomplish with this long-term experiment will be to understand the different rates at which certain processes and species switch from transient to long-term. Initial changes in nutrient cycling, for example, will likely not be maintained as the nutrient and microbial pools gradually adjust to the changing conditions. The ability of the system to maintain ‘extra’ carbon made available through a pulse of mineralization will depend upon the specific capacities of the plant species and microbes, or in their ability to quickly increase biomass and therefore conserve system nutrients. Interspecific competition for nutrients will lead to changing composition of both plant and microbial communities. Over the longer-term, these will feed back into changes in soil organic matter pools, causing more profound changes to the overall ecosystem state.

This is the first long-term, large-scale manipulation of snow and temperature simultaneously, and by working in both arctic and alpine ecosystems we gain a much broader understanding of the complex system functions involved. With this integrated, experimental approach, we hope to gain a much better understanding of how these ecosystems are likely to change in the coming decades to centuries.

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