50TH EASTERN SNOW CONFERENCE
61ST WESTERN SNOW CONFERENCE
Quebec City 1993

Hierarchic Studies of Snow-Ecosystem Interactions
A 100-Year Snow-Alteration Experiment

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ABSTRACT

The Niwot Long-Term Ecological Research (LTER) project is examining the long-term ecological effects of altered snowpack regimes. Key components of the studies include: (1) hierarchic analysis of the relationship between natural snowpack patterns and geobotanical features, and (2) a snow-fence experiment. A 3-m high snow fence will be built in the summer of 1993. Baseline soil-temperature and snow-depth studies were initiated during the unusually wet winter of 1992-93 (183% of normal precipitation at the D-1 climate station on Niwot Ridge). Minimum winter soil temperatures (15-cm depth) were about -10°C.

INTRODUCTION

Alpine ecosystems are thought to be particularly sensitive to climate change. Research at the Niwot Long-Term Ecological Research (LTER) site in the Indian Peaks of the Colorado Front Range is focusing on the consequences of changed temperature and precipitation regimes. We are particularly interested in the effects of altered snowpack because of the known importance of snow to the distribution of alpine plant and animal communities. The distribution of snow patches and windblown areas, duration of the snow-free period, and position of melt water drainages strongly affect the patterns of alpine plant communities (Billings, 1988; Bliss, 1985).

Two of the goals of the Niwot LTER project are to understand how current snowpack distributions affect patterns of vegetation and primary production from species to regional scales, and how altered snowpack regimes will change the existing ecosystems. There are two primary components to the study (Walker et al. 1993): (1) hierarchic analysis of species, plant communities, and regional patterns of plant production using a geographic information system (GIS); and (2) experimental manipulation of snow depths using large snow-fences. This paper presents the main results from the hierarchic vegetation studies and some of the early results of the baseline investigations for the snow-fence experiment.

HIERARCHIC STUDIES OF SNOW-ECOSYSTEM RELATIONSHIPS

Regional-scale studies

Image analysis of remotely sensed data provides an efficient means to examine shifts in patterns of primary production associated with climate change in large regions, such as the entire City of Boulder Watershed or the Front Range (10^6 to 10^8 km^2, Fig. 1). We propose that biomass production is broadly controlled by environmental gradients associated with elevation, and also influenced by smaller scale topographic influences that control snow distribution patterns. Currently we are using SPOT[1] satellite images to examine patterns of greenness along

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[1] *Systeme Probatoire l'Observation de la Terre*-1 satellite: High-resolution visible (HRV) with two modes of sensing, (a) "panchromatic" black and white with 10-m resolution over the range 0.51 - 0.73 µm, and (b) multispectral with 20-m resolution in 3 channels (0.50 - 0.59, 0.61 - 0.68, and 0.79 - 0.89 µm).

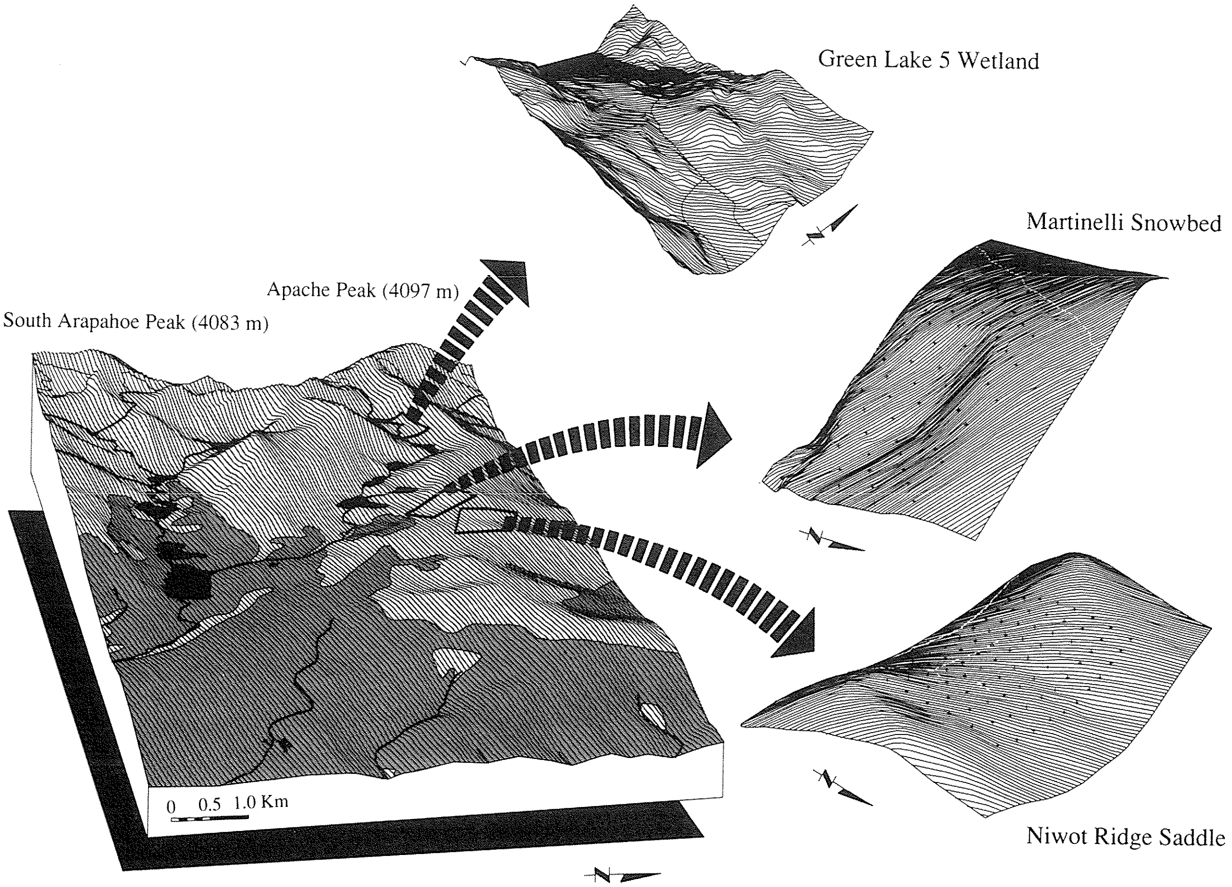

Figure 1. Hierarchy of digital terrain models for the alpine HGIS. The DTM on the left covers the City of Boulder watershed at the headwaters of North Boulder Creek. The three small DTMs enclose the intensive research sites for the Niwot LTER project. The points on the Saddle and Martinelli snowbed demarcate research grids. During the 1992-93 winter, snow depths were measured on the Saddle grid (350 x 500-m, 88 points spaced at 50-m intervals) at about 3-week intervals. Results of the monitoring in the Saddle Grid are shown in Figure 3. (From Walker et al . 1993.)

elevation gradients. Our early studies indicate that the fine-scale patterns associated with snow distribution at plot and landscape scales do have an influence on regional patterns of primary production (Walker et al., 1993). The normalized difference vegetation index (NDVI[2]), which is often used as an index of green biomass, generally shows a strong negative correlation with elevation in the Front Range. This is logical because of colder temperatures and longer periods of snow cover at higher elevations. However, this relationship is also affected by strong winds. West-facing slopes east of the Continental Divide show no relationship between elevation and NDVI, an indication of the strong control of wind on production at all elevations. Based on these preliminary findings, we can expect distinctive responses of the NDVI-elevation relationship to different climate regimes that could be used to build quantitative relationships between NDVI and climatic gradients.

Landscape-scale studies

At the landscape scale (10^2 m^2 to 10^6 m^2), we expect that shifts in snowpack regimes due to either climate change or experimental alteration of snowpack regimes should cause changes to vegetation-community boundaries that are predictable from present-day vegetation-snow relationships. We are examining the patterns of vegetation

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[2] NDVI = (NIR - R)/(NIR + R), where NIR is the spectral reflectance in the near-infrared (0.725 to 1.1 μm), where light scattering from the canopy dominates, and R is the reflectance in the red chlorophyll-absorbing portion of the spectrum (0.58 to 0.68 μm). The index is related to the amount of illuminated chlorophyll in the plant canopy and is often used as an index of green biomass or leaf area.

communities, primary production, and small-mammal distribution associated with hill-slope toposequences, and snow gradients from wind-blown sites to deep snow patches. Our main study site is the Niwot Ridge Saddle Grid (Fig. 1), where we prepared a detailed vegetation map at 1:500 scale and analyzed the vegetation patterns in relation to mean maximum snow depth, slope and aspect (Halfpenny et al., 1984; Walker et al., 1993). Snow controls the distribution of the dominant alpine species at the plant-community level. For example, the primary vegetation types on west-facing slopes are either fellfield associations (*Trifolietum dasyphylli* and *Sileno-Paronychietum*) or dry sedge meadow associations (*Selaginello densae-Kobresietum myosuroidis*) (Komárková, 1979). In contrast, east-facing slopes have a predominance of deep snow accumulation areas and snowbed associations. Plant communities associated with either windblown sites or snow patches cover a total of 78.6 percent of the Saddle Grid and 77.9 percent of the alpine area on Niwot Ridge mapped by Komárková and Webber (1978), an indication of importance of wind and snow cover in this alpine landscape (Walker et al., 1993).

Plot-scale studies

At plot-level scales (10^{-2} to 10^{2} m^2), our main hypothesis is that plant species will react to changes in snowpack in a manner that is predictable from their present-day distribution along snow-depth gradients. We are interested in the plant-species dynamics associated with snow distribution. Snowpack influences the length of the growing season, winter and summer soil temperatures, soil moisture, plant moisture stress, and the impact of herbivores such as pocket gophers (*Thomomys talpoides*), all of which affect species distribution patterns. To monitor natural changes in species composition, we are using a grid of 88 permanent plots that span the snow gradient from windblown sites to areas with over 6 m of maximum winter snowpack. We are using permanently registered point quadrats as described in (Walker et al., 1993). We are using the same method to examine the effects of experimentally altered snow regimes.

Snow-fence design

We will build the fence in summer of 1993. The fence will be made of a composite Centaur® polymer/ wire rail of the type used for livestock fencing. The fence will be 2.4 m tall and 60 m long and is designed to create a 3-m deep snow drift on the leeward side of the fence and 1.5-m deep drift on the windward side. The leeward drift will extend approximately 60 m downwind of the fence, and the windward drift will extend 30 m from the fence. It will be necessary to remove the fence during the summer to prevent changes in the summer wind regime at the site, so the fence is designed for rapid annual erection and removal. The experimental area is situated along an ecotone between areas of shallow and moderate late-season snowpack. The snow drift will impact a series of alpine soils and plant communities (Fig. 2). The primary communities that will be experimentally altered are: (1) dry sedge meadow (*Kobresietum myosuroidis*), (2) moist forb meadow (*Acomastyletum rossii*), and (3) a moist shrubland (*Salicetum planifoliae*).

Baseline snow and ground-temperature studies

During the winter of 1992-1993, we periodically monitored snow-depths and ground-temperatures in a grid that covers the projected area of the snow-fence drift (Fig. 3). Maximum winter snow depths varied from 20-30 cm in the dry meadow to 100-130 cm in the shrubland. Early in the winter, snow accumulated mainly in microtopograpic depressions and patches of low-growing willows; whereas later in the winter, large snow drifts associated with the mesotopography of the West Knoll (120 m of relief) overwhelmed many of the microtopographic depressions on the west side of the snow-fence grid. We also monitored snow depths at the 88 grid points of the 350 x 500-m Saddle Grid that encloses the snow-fence experimental area (Fig. 4). The West Knoll drift developed during the winter and eventually affected the snow-fence experimental area during the spring. Other investigators in the LTER project monitored the density and chemistry of the snowpack of the Saddle Grid.

Our baseline temperature studies demonstrated the importance of snow cover on soil surface temperatures at the soil surface (Fig. 5a) and in the plant rooting zone (15-cm depth, Fig. 5b). Minimum rooting-zone temperatures in the dry meadow (shallow snow) were about -10°C; whereas minimum temperatures in the western portion of the willow community was about -5°C. In summer of 1993, baseline measurements of soil properties and vegetation composition will be measured in 50 permanent plots along the projected snow depth gradient. The winter (Nov-Apr) of 1992-93 was the wettest on record with over 183% of the normal precipitation at the D-1 site (Table 1). April was the wettest month on record (1951-1993) with 271 mm of precipitation.

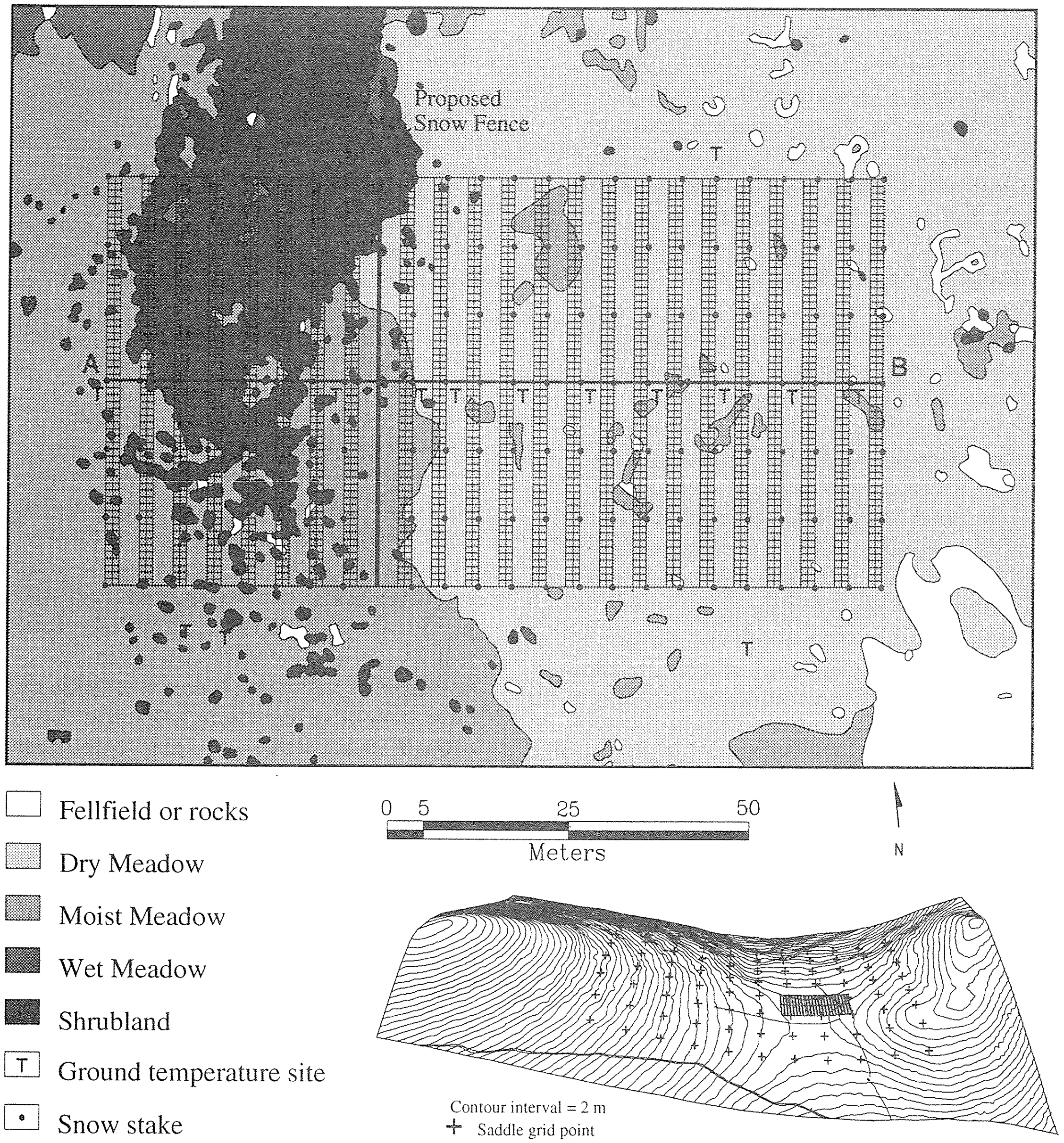

Figure 2. Layout of snow-fence experimental area on a vegetation map of the site. The area enclosed by the experiment is 60 x 125 m. The fence will be built on an ecotone between a moist Acomastylis rossii *community, a wet* Salix planifolia *shrubland, and a dry* Kobresia myosuroides *community. The linear grids of 1x1-m experimental plots are separated by 3-m corridors that provide access to the plots. The plots will be used to monitor changes to plant-species composition, biomass, spectral reflectance, soil characteristics, insects, and small mammals. During the winter of 1992-93, snow depths were monitored at the points marked (•), and soil temperatures were monitored at the points marked (T).*

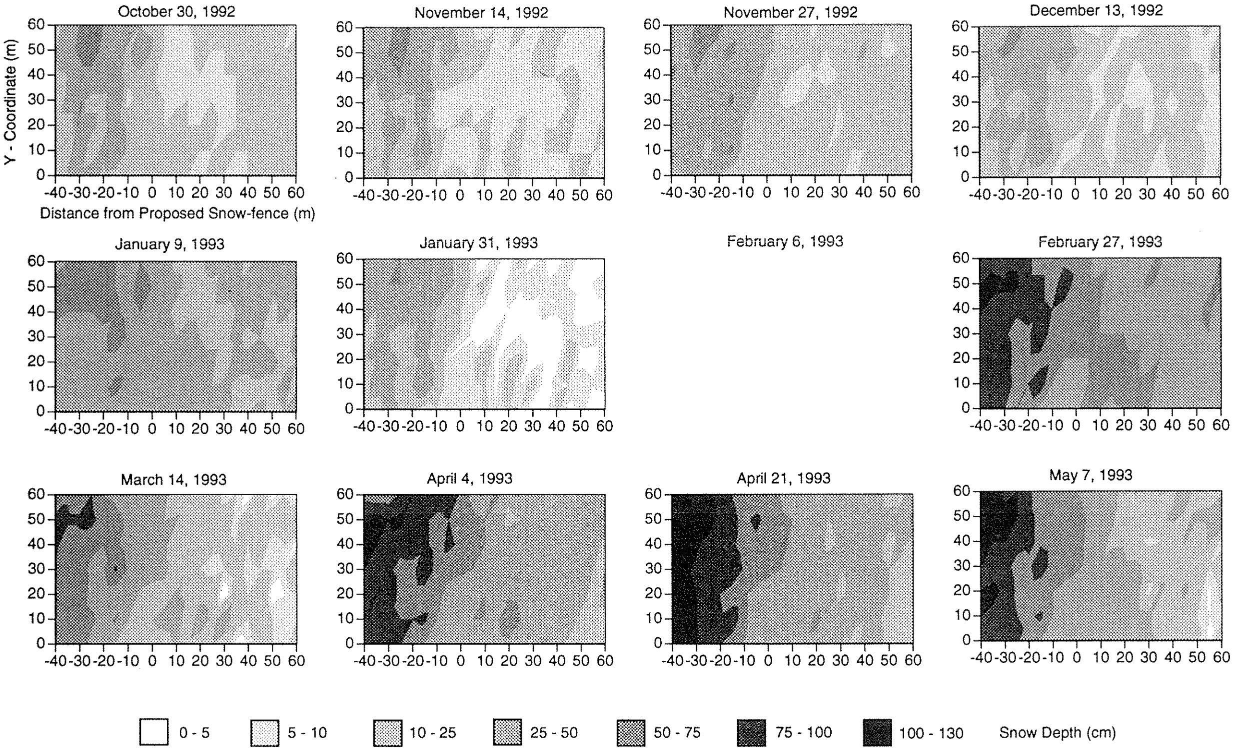

Figure 3. Snow depths within the snow-fence grid (60 x 100 m) from October 30, 1992 to May, 1993. A grid of 140 snow stakes is used for monitoring winter snow depths in the snow-fence experimental area (Figure 2). The stakes consist of 0.75" id PVC pipe that fit over a vertical piece of 0.5" rebar. The deeper snow occurred in the Acomastylis *and* Salix *communities (-40 to 5 m along the transect), and generally shallow snow occurred in the* Kobresia *meadow (5 to 60 m). Dates of deeper snow (Nov 27, Jan 9, Feb 27, and Apr 4) alternated with deflation of the snowpack by wind in the intervening periods. During the early winter (Oct 30 to Jan 31) the deepest snow was found in the* Salix *community where willows trapped the snow. Later in the winter (Apr 21), a large snowdrift associated with the west side of the Saddle overwhelmed the western portion of the grid (see Fig. 4).*

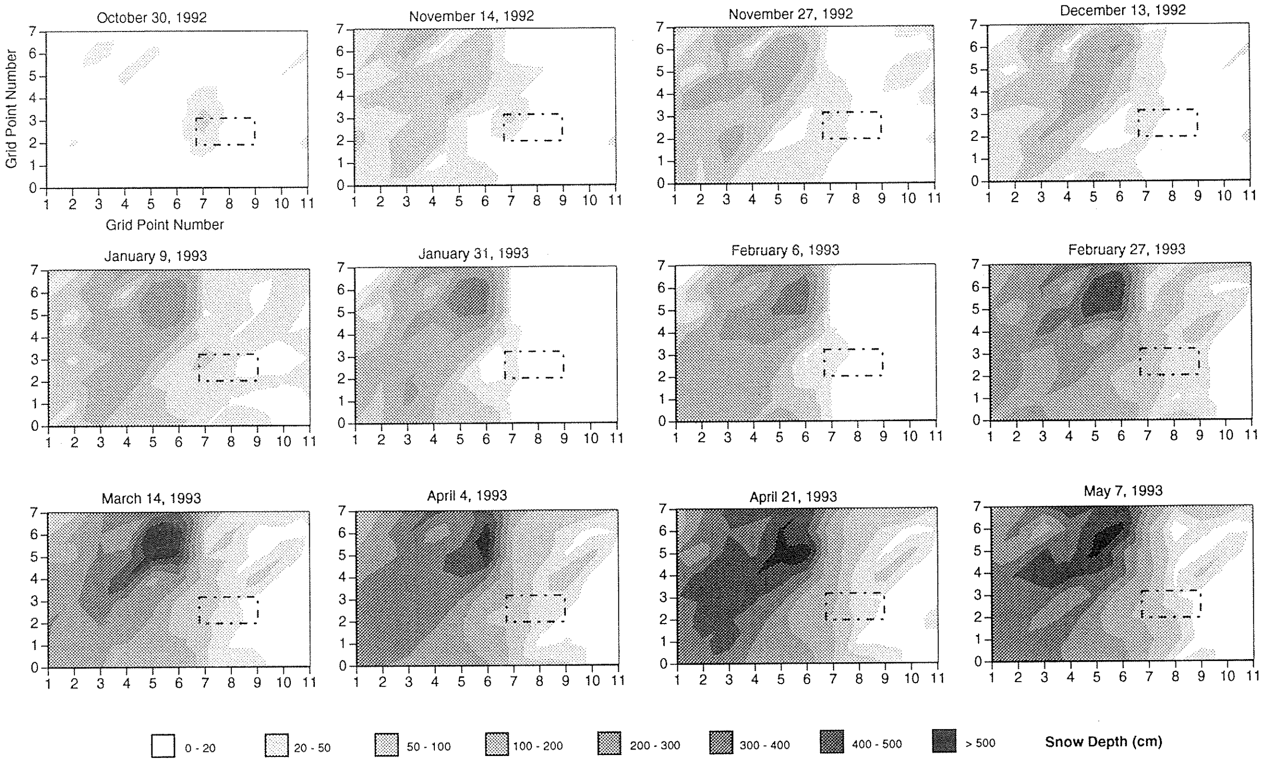

Figure 4. Snow-depth baseline study in the Saddle Grid (350 x 500 m). Snow accumulation in the early winter (October 30 to November 27) occurred in willow areas (central portion of the grid) and in depressions associated with stone-banked terraces (upper left portion of the grid). Later in the season, the mesotopography of the Niwot Saddle determined the drift patterns. Winds are predominately from the west (left), and snow accumulates on east-facing aspects and in a large depression in the upper central portion of the grid. The east side of the grid is predominantly west-facing and has shallow snow or is blown free of snow throughout the winter. Strong winds on Niwot Ridge cause periods of snow deflation over much of the grid with deposition in the deep snow-accumulation areas. Wind-deflation is evident on December 13, January 31, February 6, March 14, and May 7. The dashed rectangle shows the position of the snow-fence experimental area.

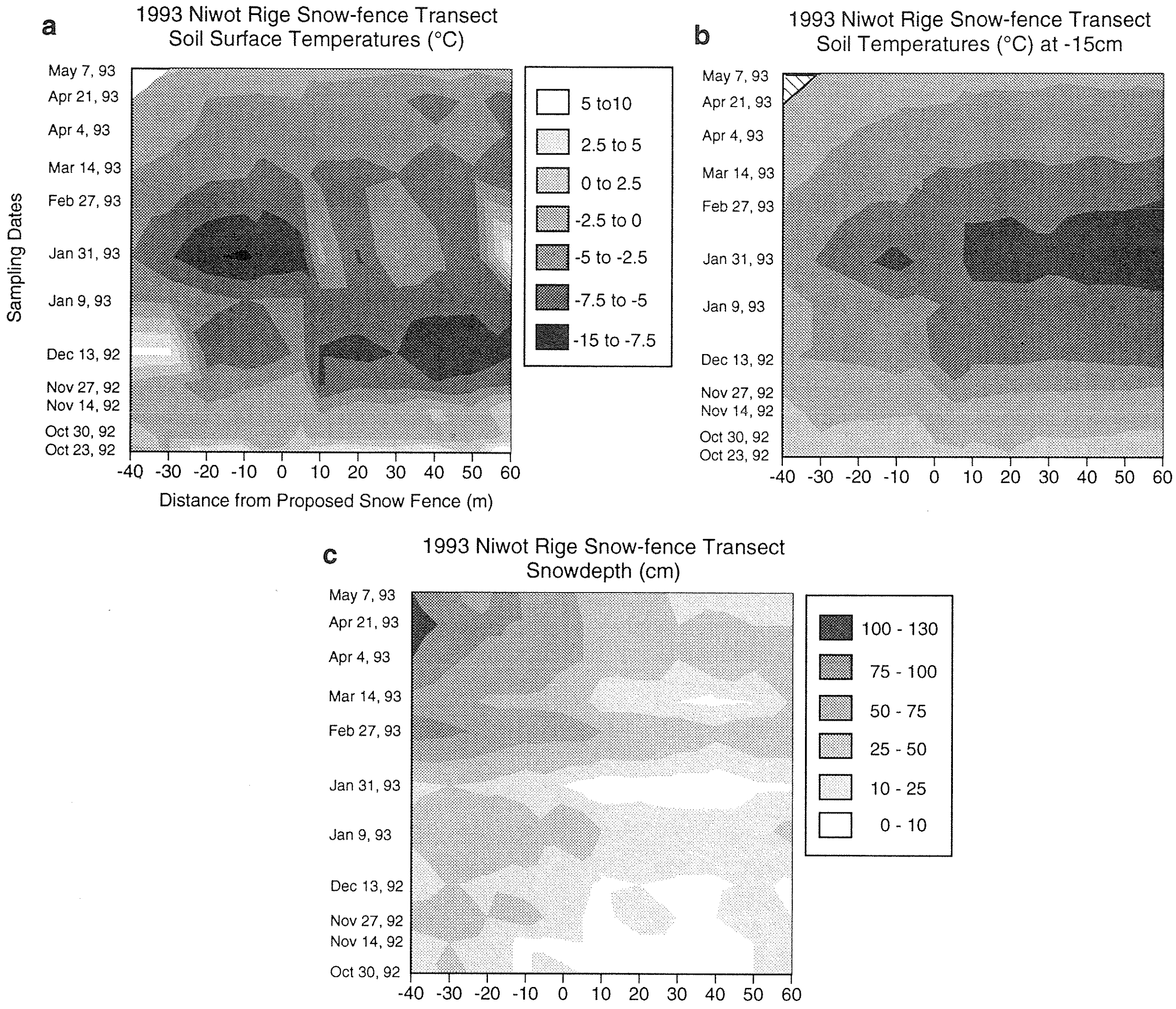

Figure 5. Ground-temperature baseline studies. (a) Ground temperatures were monitored at 12 stations along a transect (see Fig. 3) in the center of grid. Thermisters are placed at the ground surface and 15-cm depth at each station. The thermister leads were placed in a canister for easy monitoring using a Cambell data logger. (b) Ground temperatures at 15-cm depth from October 30, 1992 to May 7, 1993. In the Kobresia meadow (5 to 60 m) at the 15-cm depth, the temperatures gradually cooled to about -11°C on Jan 31. These temperature corresponded to the coldest air temperatures and a period of shallow snow cover. Temperatures were generally 2° to 5°C warmer in the Salix and Acomastylis communities (5 to -40 m). (c) Ground surface temperatures during the same period of time show a much more irregular pattern due to large day-to-day fluctuations in air temperature and complex interactions with the snow cover.

Table 1. Winter 1992-93 temperature and precipitation and comparison with 1951-85 means (Greenland, 1989) at the D-1[1] Station , Niwot Ridge, Colorado. Mean values for 1951-85 are in parentheses.

	NOV	DEC	JAN	FEB	MAR	APR	TOTAL
Precipitation (mm)	**152**	**150**	**98**	**235**	**155**	**271**[2]	**1061**[3]
	(80)	**(90)**	**(102)**	**(80)**	**(128)**	**(100)**	**(580)**
Mean Temperature (°C)	**-11.6**	**-12.3**	**-11.4**	**-12.3**	**-9.2**	**-7.3**	
	(-8.9)	**(-11.8)**	**(-13.2)**	**(-12.8)**	**(-11.2)**	**(-7.0)**	

[1] The D-1 station is 2.3 km west of the Saddle and about 100 m higher (elevation 3749 m).

[2] April 1993 was the wettest month on record at D-1.

[3] November to April precipitation was 183% of the 1951-85 average for the same period.

The experiment is likely to provide many insights into the ecosystem consequences of climate-altered snowpack regimes. However, we expect that the snow-fence drift may have some snowpack properties that are different from natural snow drifts (e.g. density, timing of drift development, and the subnivian environment). Therefore, it will be important to thoroughly compare the physical and biological properties of the snow-fence drifts to natural conditions. If the experiment provides a good analog of altered snowpack conditions, it would be desirable to repeat the experiment in other snow-dominated ecosystems, such as those of the Arctic.

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