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The Niwot Ridge snow fence experiment: biogeochemical responses to changes in the seasonal snowpack

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Abstract We have implemented a long-term snow fence experiment at the Niwot Ridge Long-Term Ecological Research site in the Colorado Front Range to assess the effects of climate change on alpine ecology and biogeochemical cycles. During the first winter after construction, the 2.6 × 60 m fence resulted in a snowpack which was significantly deeper than adjacent areas. The average period of continuous snow cover in the main snow fence drift (1994) was approximately 115 days longer than at control sites outside the fence drift (1994), and 90 days longer than at the same sites the year before construction of the fence (1993). The deeper and earlier snowpack behind the fence insulated soils from extreme air temperatures resulting in a 9°C increase in minimum soil surface temperatures, and a 12°C increase in minimum soil temperatures at a depth of 15 cm, compared to prefence (1993) conditions. Warmer soils allowed microbial activity, measured as carbon dioxide flux through the snowpack, to continue through much of the winter. Carbon dioxide production under the deeper, earlier snowpack after construction of the fence was 55% greater than production before construction of the fence. The loss of CO_2 from snow-covered soils was approximately 20% of aboveground primary production before and 31% after construction of the fence. Areas with shallower snowpacks showed opposite trends with greatly reduced CO_2 production. These data suggest that small changes in the timing and depth of snowpack accumulation may have a large effect on carbon balance and associated biogeochemical cycles in alpine ecosystems.

INTRODUCTION

High-elevation ecosystems in the Rocky Mountains are characterized by a 6 to 9 month period of continuous snow cover and freezing temperatures and snow are possible throughout the growing season. The depth and timing of snowfall in these environments is known to exert significant controls on species composition, primary production, and biogeochemical cycles during the growing season (Ehlringer & Miller, 1975; Oberbauer & Billings, 1981; Walker *et al.*, 1993a). The harsh environmental conditions characteristic of these environments suggest that organisms in the alpine are on the edge of environmental tolerances and may be sensitive indicators to small environmental changes. For the biogeochemical processes mediated by soil microorganisms, this sensitivity is most acute during freeze/thaw events and the transition from frozen to thawed soils.

Seasonal snowpacks insulate the soil surface from extreme air temperatures and potentially allow soil microbial activity to continue while vegetation is dormant (Fahey, 1971; Sommerfeld *et al.*, 1993; Brooks *et al.*, 1995). Significant levels of heterotrophic microbial activity in snow covered soils have been suggested by previous research (Skoagland *et al.*, 1988; Taylor & Jones, 1990), yet few studies have quantified the importance of this activity to system carbon cycles. Preliminary work at alpine and subalpine sites in Wyoming suggests that soil heterotrophic respiration under seasonal snowpacks mineralizes 20 to 50% of yearly aboveground primary production (Sommerfeld *et al.*, 1993). Zimov *et al.* (1991) have reported that CO_2 flux from snow covered soils at a high latitude site in the former Soviet Union accounted for 12.5 to 75% of yearly carbon loss from the system. While these studies suggest subnivian heterotrophic respiration may be an important component of the carbon cycle in seasonally snow-covered systems, the factors which control this activity are unknown.

In response to an overall warming of the global climate, high-elevation environments may experience lower temperatures and increased precipitation (Zwally, 1990). Over the last 45 years such a trend has been observed at Niwot Ridge in the Colorado Front Range where a significant decrease in temperature and a significant increase in precipitation have been recorded. It is likely that this combination of a cooler and wetter climate will increase the depth and duration of snow cover in these systems. To evaluate how the alpine ecosystem will respond to these changes in climate, a long-term, multidisciplinary project has been initiated at the Niwot Ridge Long-Term Ecological Research (LTER) study site. This project utilizes a 2.6 × 60 m snow fence to provide a range of snowpack regimes from shallower to much deeper than normal. Complementary data sets at this site, which provide baseline information for evaluating experimentally induced changes, include; climate, community structure, nutrient cycling, and hydrological modeling (Greenland, 1989; Reddy & Caine, 1990; Sievering *et al.*, 1992; Bowman *et al.*, 1993; Williams *et al.*, 1993). This paper presents results comparing prefence and first season postfence data on snowpack accumulation, soil temperature, and CO_2 flux at this site. We hypothesized that the deeper snowpack and longer period of snow cover behind the fence would result in warmer soil temperatures and increased CO_2 flux rates from under the snow.

STUDY SITE

All experiments were conducted on Niwot Ridge, Colorado (40°03′N, 105°35′W) located in the Front Range of the Rocky Mountains, 5 km east of the Continental Divide.

This site is an UNESCO Biosphere Reserve and has been the location of extensive research by the University of Colorado's Long-Term Ecological Research program. The climate is characterized by long, cold winters and short, cool growing seasons. Mean annual temperature is -3 °C, annual precipitation is 900 mm, the majority of which falls as snow (Greenland, 1989). All sites were located on Niwot saddle, an area of intensive research at an elevation of 3510 m. Soils are cryochrepts and vary in depth from approximately 0.3 to 2.0 m overlying granitic parent material (Burns, 1980). Soil pH ranges from 4.6 to 5.0. Vegetation at the snow fence site is dominated by the gramminoid *Kobresia myosuroides* with patchy occurrence of communities dominated by the forb *Acomostylis rossii* and the gramminoid *Deschampsia caespitosa* in protected microsites (Walker *et al.*, 1993a).

METHODS

A 2.6 × 60 m snow fence was constructed during early October 1993 (Walker *et al.*, 1993b). The fence is made of a composite Centaur^R polymer of the type used for livestock fencing. Snowpack depth and soil temperatures at the surface and at a depth of 15 cm were measured approximately biweekly during the winters of 1993 (prefence), and 1994 (postfence). Snow depth was measured manually at predetermined grid points located every 10 m on a 60 × 70 m grid. Soil temperatures were measured using 12 permanent thermistors, located at 10 m intervals along a central transect through the drift, installed during the summer of 1992 and having leads which extended above the seasonal snowpack.

CO_2 flux through the snowpack was calculated using the method of Sommerfeld *et al.* (1993). Two CO_2 flux sites were established in 1993 before construction of the snow fence. One site was in an area projected to be within the drift caused by the snow fence, and one in an area with a similar snowpack regime, but in an area expected to be outside the experimental drift. A total of six sites for CO_2 flux measurements were established in 1994. Three sites were within the area impacted by the snow fence drift and included one site from 1993; and three were in a naturally shallow snowpack area outside of the fence drift and included the second site from 1993. Each site was approximately 10 m^2 and contained three gas collectors at the soil surface for replicate measurements. Gas collectors, constructed of 100 mm diameter by 10 mm thick stainless steel disks covered with 50 μm stainless steel mesh, were installed shortly after a continuous snowpack developed at each site. These disks were connected to sampling ports located above the snow surface by 1.6 mm (id) Teflon tubing. Collectors were not sampled for the first 30 days after installation to avoid effects from soil or snowpack disturbance. CO_2 flux was measured monthly during January and February, and then biweekly to weekly until sites were snow free. All samples were collected in glass syringes and analyzed by gas chromatography (Hewlett-Packard 5880A) at the University of Colorado's Mountain Research Station within 24 h.

A steady state diffusion model, designed to account for changes in snowpack porosity associated with layering, was used to estimate CO_2 flux through the snowpack (Sommerfeld *et al.*, 1993). Boundary conditions for the model were provided by the CO_2 concentrations just above the snowpack and at the snow/soil interface. Profiles of snow density and texture were obtained from snowpits dug at biweekly to weekly intervals throughout the winter. Snowpack air permeability and porosity profiles were computed from the density profiles using the method of Sommerfeld & Rocchio (1993). Snow depth was measured manually at each sampling location during each date. In addition to the thermistors located along the central transect, soil surface temperature adjacent to each gas site was measured manually in 1993 and both manually and using thermistors (installed in October 1993).

RESULTS

The area directly behind the snow fence experienced a 100 to 200% increase in snowpack depth when compared to prefence conditions. Maximum snow depth in 1993 before construction of the fence ranged from 0.85 to 1.1 m, while in 1994 maximum snow depth was 2.4 to 2.6 m in the snow fence drift and 0.60 m at sites outside the drift. The period of continuous snow cover began in late December and continued to late May before the fence (1993). After the fence in 1994, the period of continuous snow cover was increased an average of 90 days (extending from late October until late June) behind the fence and decreased an average of 25 days (extending from early January to early May) in areas outside the fence drift. In 1993 (prefence), maximum snow depth was 0.80 m at the CO_2 flux site expected to be within the drift, and 0.77 m at the flux site expected to be outside the drift. After construction of the fence (1994), maximum snow depth at the three CO_2 flux sites within the snow fence drift was 1.6 m (Fig. 1), while maximum snow depth at the three shallow snowpack sites outside the fence was 0.65 m (Fig. 2). There were no significant differences in physical characteristics or CO_2 flux between either of the shallow sites in 1993 and only data from the site expected to be within the snow fence drift are presented throughout the rest of this paper.

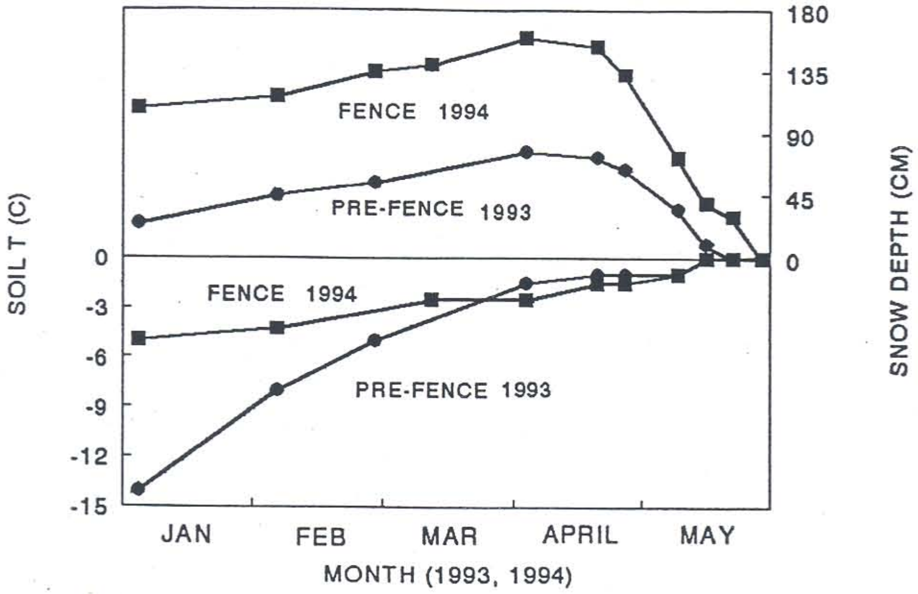

Fig. 1 Relationship between snowpack accumulation (*top*) and soil surface temperatures (*bottom*) at CO_2 flux plots before (1993) and after (1994) construction of the snow fence on Niwot Ridge ($n = 3$ for each date, standard deviation is smaller than size of symbol).

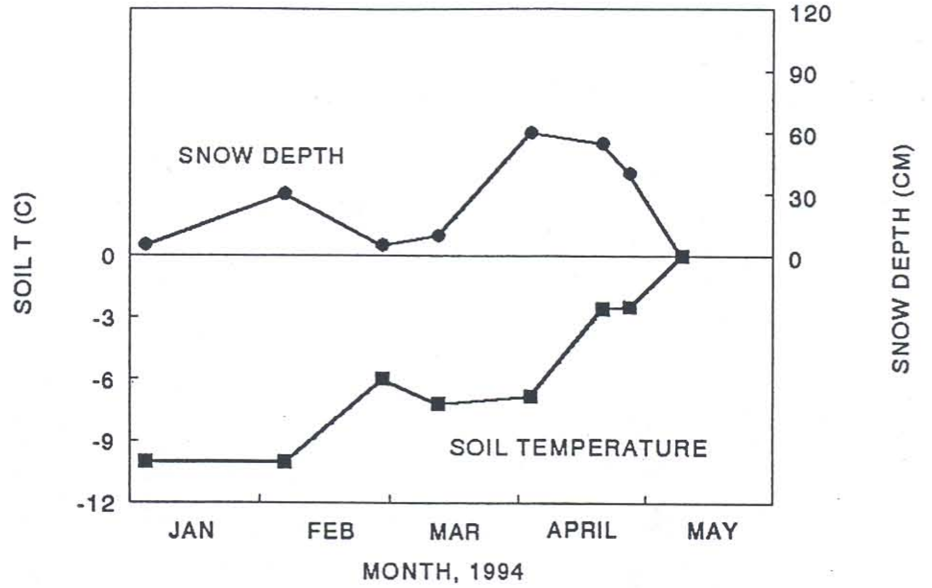

Fig. 2 Relationship between snow accumulation (*top*) and soil surface temperature (*bottom*) at shallow control snowpacks outside of the snow fence drift in 1994 ($n = 3$ for each date, standard deviation for temperature measurements is smaller than size of symbol).

Soils warmed under continuous snow cover at all sites in both 1993 and 1994, with minimum soil temperatures related to the timing of snowpack accumulation. Minimum soil surface temperatures at the CO_2 flux sites in 1993 (prefence) were −14°C (Fig. 1), and temperatures at a depth of 15 cm along the central transect through the drift were −12°C. After fence construction, minimum soil surface temperatures at the flux sites were −6.3°C (Fig. 1), and temperatures at a depth of 15 cm along the central transect through the drift were 0°C. In contrast, at the three CO_2 flux plots in 1994 outside of the fence drift minimum soil surface temperatures of −10°C (C.V. 0.0; n = 3) were significantly cooler ($p < 0.01$) than at the sites behind the fence. Soils at these shallow gas flux sites warmed from −10 to −6°C in early February 1994 when a consistent snowpack first developed. This warming trend was interrupted in February and March as snow depth decreased, and resumed as the snowpack redeveloped (Fig. 2).

Before construction of the fence, subnivian CO_2 production began in early March when the soil temperatures warmed above -5°C (Fig. 3). Production increased from 60 mg C m^{-2} day^{-1} on 4 March 1993 to a maximum flux just under 600 mg C m^{-2} day^{-1} on 18 May 1993. Carbon dioxide production at sites within the snow fence drift in 1994 began much earlier in the winter. By early February, the CO_2 flux from these sites was 450 mg C m^{-2} day^{-1} (Fig. 4). The maximum level of CO_2 production measured at these sites after construction of the fence was slightly over 500 mg C m^{-2} day^{-1}. In contrast to the 1993 season, CO_2 flux did not increase as soils warmed, but was highly variable throughout the season (Fig. 4). The duration and magnitude of subnivian CO_2 flux were lower at the three shallow snowpack sites in 1994 when compared to the snow fence sites. Carbon dioxide production at the shallow sites did not begin until late April, and the sites were snow free by the 10 May. The maximum flux recorded at these site was 175 mg C m^{-2} day^{-1} (Fig. 4). When the observed daily CO_2 flux measurements were integrated over the season, the total amount of carbon mineralized during the winter was 22.7 ± 5.4 g m^{-2} for the shallow sites in 1993, 35.3 ± 13.8 g m^{-2} for the snow fence

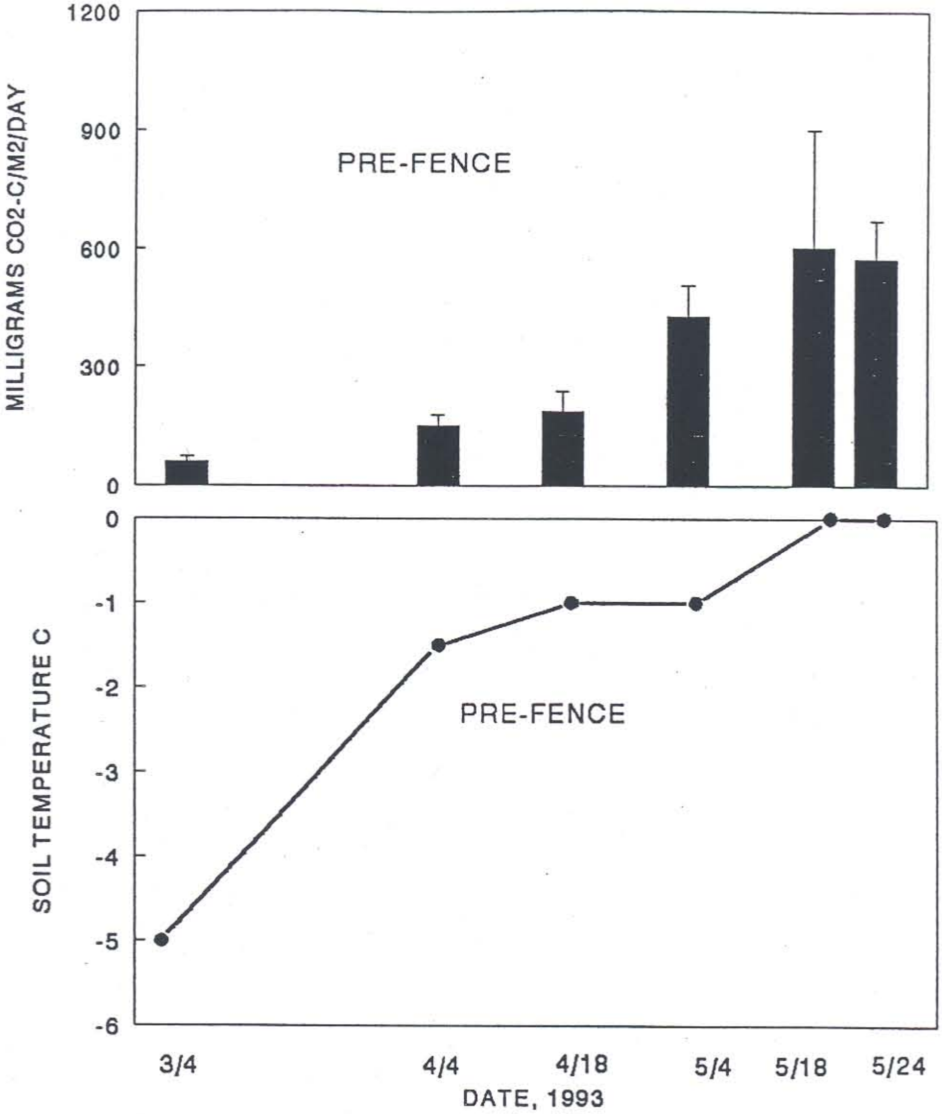

Fig. 3 CO_2 flux (*top*) and soil surface temperatures (*bottom*) under a naturally shallow snowpack, within the area expected to be impacted by the drift, before construction of the fence ($n = 3$ for each date, standard deviation for temperature measurements is smaller than size of symbol).

sites in 1994, and 1.9 ± 1.6 g m^{-2} for the shallow sites in 1994. These fluxes represent a significant ($p < 0.05$) increase in carbon loss following construction of the fence, as well as a significantly higher carbon loss at snow fence verses shallow sites in 1994 ($p < 0.001$). On the basis of an average annual aboveground production of 225 g m^{-2} (Walker *et al.*, 1994), and assuming this production is approximately 50% carbon, subnivian heterotrophic activity mineralized 20% of aboveground production in 1993, 31% in 1994 behind the fence, and 2% under shallow snowpacks in 1994.

DISCUSSION

The construction of the snow fence significantly affected both the timing and duration of snow cover within the study area on Niwot Ridge. Most of the experimental site

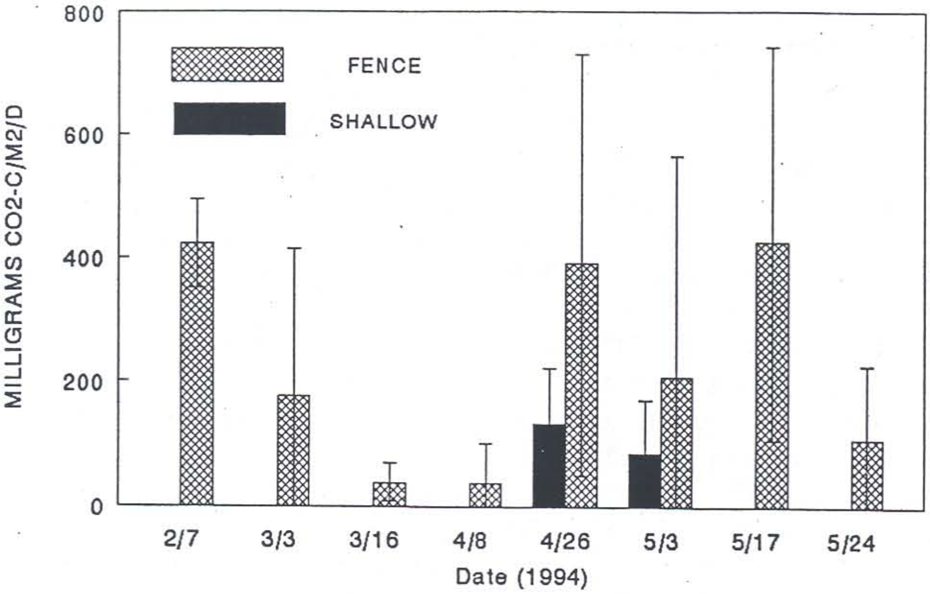

Fig. 4 CO_2 flux from under the snow fence augmented snowpack (hatch) and the shallow control snowpack (solid) in 1994 (n varied between 3 and 9 for each date).

experienced a deeper and earlier snowpack which simulated the conditions which are expected to occur if the current cooler and wetter trend in climate continues. In contrast, the natural interannual variability in snowpack accumulation between the two seasons resulted in a shallow and later-developing snowpack at the three sites outside of the area affected by the snow fence in 1994. Together, the construction of the fence and the variation in climate between the 2 years effectively resulted in three different snowpack regimes for this experiment; shallow and moderate duration (1993), shallow and short duration (1994 outside the fence drift), and deep and long duration (1994 within the fence drift).

Data from the shallow snowpack sites in 1993 and 1994 show that the timing of snowpack accumulation was more important than the depth of the snow in allowing soils to thaw. The importance of biogeochemical processes in thawed soils under seasonal snowpacks have been suggested by a number of other studies (Rascher *et al.*, 1987; Preston *et al.*, 1990; Zimov *et al.*, 1991; Sommerfeld *et al.*, 1993), however, few studies have followed the warming of previously frozen soils under developing snowpacks. At these sites on Niwot Ridge, a natural, continuous snowpack does not develop until December or January allowing exposed soils to freeze during the early portion of the winter. The earlier snowpack caused by the fence in 1994 insulated soils from extreme air temperatures in the early winter and resulted in higher minimum soil temperatures. The minimum snow depth required for soils to warm at these sites was approximately 30 cm. This was supported by the cooling of soils at the shallow sites in 1994 when snow depth fell below this value in February; soils again began to warm when snowpack depth exceeded 30 cm. The seasonal loss of carbon from these sites appears to be directly related to the length of time soils remained covered by a snowpack of this depth, with the shallow, short duration sites losing the smallest amount of carbon, and the deep, long duration sites losing the most.

The minimum temperature for microbial activity under these snowpacks was approximately −5°C at all sites. This is consistent with the temperature at which free water becomes available in soil (Schimel *et al.*, 1995), and similar to the minimum temperature for soil microbial activity of −6.5°C reported by Coxson & Parkinson (1987). The increase in CO_2 production as soils warmed in 1993 suggested temperature was the primary control on microbial activity. It was not clear what portion of this regulation was due to temperature acting directly on microbial respiration, and what portion was due to an increase in the amount of thawed soil and labile substrates for metabolic activity. The order of magnitude increase in CO_2 flux between −5 and 0°C is too large to be due to direct effects on microbial activity, and suggests other processes are contributing to the increased flux. It is likely that the increase in activity was attributable to a combination of increased substrate availability, direct effects of temperature on microbial respiration, and an increase in the active microbial pool through growth as well as recruitment of other organisms as the temperature increased. The decrease in CO_2 production on the last sampling date during both years is probably due to a decrease in oxygen availability as soils become saturated with snowmelt. Brooks *et al.* (1995) have shown that soil moisture remains relatively constant under seasonal snowpacks before melt, and then increases significantly as melt begins.

In contrast to the relationship between temperature and activity observed in 1993, there was no apparent relationship between temperature and CO_2 production from either the snow fence or the shallow sites in 1994. The high variability in CO_2 flux at the snow fence sites in 1994 suggested that either C substrate or oxygen availability may have been limiting activity. The observation that soil surface temperatures were in the range of −3 to −2°C when the snow fence sites were first sampled suggested that the field schedule missed the period of rapidly increasing flux at these sites. CO_2 flux on this date was within 10% of the maximum flux recorded during this season, suggesting microbial activity may have already depleted a significant portion of either labile carbon sources or oxygen. If a significant level of heterotrophic respiration did occur before gas sampling began, this suggests that the calculated carbon loss from the system due to subnivian CO_2 flux in 1994 was an underestimate.

The similarity in maximal flux rates from beneath prefence and postfence snowpacks indicated that 500 to 600 mg C m^{-2} day^{-1} may be an upper limit for soil heterotrophic respiration under snow for these systems. Although very little work has been done on CO_2 flux from soils under alpine snowpacks, this is consistent with the maximal rate of 516 mg C m^{-2} day^{-1} reported by Sommerfeld *et al.* (1993) for an alpine site at the Glacier Lakes Ecosystem Experiment Site (GLEES) in Wyoming. The physical differences between Niwot Ridge and the Wyoming locations make the similarity in these values striking. Niwot Ridge is an unglaciated site with a highly organic soil (Burns, 1980), while the GLEES site is in a glaciated valley with a more mineral soil (Sommerfeld *et al.*, 1993). Together, these data suggest the upper limit on CO_2 flux for alpine tundra may be consistent over a range of environments.

CONCLUSIONS

The construction of the snow fence significantly altered the depth and timing of snowpack accumulation on Niwot Ridge and will allow the evaluation of changes in snowpack regime on primary production and biogeochemical cycles in alpine systems. It appears that the timing of snowpack development is the most important factor controlling CO_2 flux during winter, and this suggests longer periods of snow cover may significantly increase the loss of carbon from these systems during winter. The similarity between peak CO_2 flux rates observed before and after construction of the fence suggests that snow covered soils in alpine systems have an upper limit on subnivian microbial activity. If these observations can be confirmed at other locations, a regional estimate of winter carbon loss from these systems could be obtained if the timing of the snowpack accumulation is known.

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