EXPERIMENTAL SOIL WARMING EFFECTS ON C, N, AND MAJOR ELEMENT CYCLING IN A LOW ELEVATION SPRUCE-FIR FOREST SOIL

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Abstract: The effect of global warming on north temperate and boreal forest soils has been the subject of much recent debate. These soils serve as major reservoirs for C, N, and other nutrients necessary for forest growth and productivity. Given the uncertainties in estimates of organic matter turnover rates and storage, it is unclear whether these soils will serve as short or longer-term net sources or sinks for C and N if mean air and soil temperatures increase over time. In light of these information needs, a thermal manipulation study was initiated in 1991 at the Howland Integrated Forest Study (HIFS) site to investigate the effect of a 5 °C increase in soil temperature on C and N dynamics in a low elevation spruce-fir forest soil. Elevated soil temperatures have been successfully maintained in replicated 15x15 m plots for two field seasons (1993 and 1994) using heat resistance cables buried 2-3 cm from the soil surface at 20 cm spacings. Replicated unheated plots with cables installed ("cabled control") and with no cable installation ("control") serve as the controls. Results to date indicate significantly increased rates of litter decay, fine root production, and CO_2 evolution in the heated plots relative to the controls as well as decreased concentrations of base cations and Mn in buried mineral soil bags. Soil moisture showed a slight but significant decrease in the O horizon in response to the thermal manipulations and no change in the upper B horizon. Although no statistically significant effect of the thermal manipulation has been observed on N mineralization rates during the first two years of this study, the cumulative amount of NH_4-N mineralized over this period was greater in the heated plots relative to the control plots. No net nitrification has been observed at this site to date. Taken together, results from this thermal manipulation study indicate that modest changes in temperature can significantly alter C, N, and major nutrient dynamics at this site.

INTRODUCTION

Considerable scientific uncertainty is associated with both the current predictions of climate change as well as the expected effects of this climate change on forest ecosystems. However, it is well documented that tropospheric concentrations of CO_2 are increasing at a rate of ~ 0.5 percent per year (Houghton et al. 1990, Denmead 1991, Keeling and Whorf 1992) and it is commonly agreed that this increase in CO_2 (as well as other "greenhouse" gases) could raise mean global temperature by 2-5 °C or more in the next 50-100 years, with a greater warming occurring in the higher latitudes than at the equator (Bolin et al. 1986, Hansen et al. 1988, IPCC 1990). Changes of this type would undoubtedly have an effect on the growth and character of northern temperate and boreal forests. The soils in these forests serve as major reservoirs for C, N, and nutrients necessary for forest growth and productivity, as well as sinks for "pollutants" ranging from metals to N to various organic compounds. Given the uncertainties in estimates of turnover rates and storage, it is unclear whether these soils will serve as a short or longer-term net source or sink for C and other materials if mean air and soil temperatures increase over time.

To address these information needs, a field study was initiated in 1991 at the Howland Integrated Forest Study site to investigate the effects of a 5 °C increase in soil temperature on processes controlling C and N dynamics in a representative low elevation spruce-fir forest soil in Maine. Specifically, we evaluated the response of CO_2 evolution, soil air CO_2 concentrations, N mineralization and nitrification, soil and soil solution chemistry, litter decay, fine root dynamics, and overstory foliar chemistry to *in situ* experimental manipulations of soil temperature.

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METHODS

Study Site. The study site is located in a low elevation (60 m) commercial spruce-fir forest in east-central Maine (45° 10' N, 68° 40' W), adjacent to the Howland Integrated Forest Study (HIFS) site. The vegetation is dominated by red spruce (*Picea rubens* Sarg.) (~50 percent of live basal area), with occasional co-dominant white pine (*Pinus strobus* L., ~22 percent) and eastern hemlock (*Tsuga canadensis* Carr., 13 percent). Few balsam fir (*Abies balsamea* Mill.) over 4 cm dbh remain from the last spruce budworm infestation. Soils at the site are classified as Aquic Haplorthods developed from an underlying layer of dense basal till. The climate is continental with mean temperature between 5 and 6 °C and mean precipitation slightly more than 100 cm yr^{-1} (Lautzenheizer, 1972).

Experimental Design. Three 15x15 m plots were established in each of two locations in the study area (separated by ~300 m) in the spring and summer of 1992. One thermal treatment (5 °C above ambient) and two controls (the undisturbed "control" which has no disturbance from cable installation and the "cabled control" in which subsurface cables were installed but not heated) were assigned to one plot in each location in a blocked design. A buried cable method, in which heat resistance cables are installed 2-3 cm below the soil surface at 20 cm intervals, is used to experimentally increase soil temperatures in the heated plots.

Analytical Methods. Soil air CO_2 concentrations were measured by extracting gas samples from soil air access tubes and determining CO_2 concentrations on a Gow-Mac 750P chromatograph (Erikson et al. 1990). Carbon dioxide flux was measured using a static chamber technique (modified from Steudler et al. 1989). Nitrogen mineralization and nitrification rates were measured using an on-site buried bag approach (Pastor et al. 1984). Change in mineral soil chemistry was evaluated using a buried mineral bag approach (David et al. 1990) with subsequent analysis for pH (0.01 $CaCl_2$), exchangeable Ca, Mg, K, Na, extractable P, exchangeable acidity and Al, and total C, N, and S following the methods of Robarge and Fernandez (1986). Soil solutions were sampled with ceramic cup tension lysimeters and analyzed for major chemical constituents following the methods of Hillman et al. (1985). Litter decay rates were determined using the mesh bag technique (Bocock, 1964). Litter element concentrations were determined using a HCl digest followed by ICP analysis for Ca, Mg, K, P, Fe, Mn and Zn (Munter and Grande, 1981); C and N were determined on a Carlo Erbo NA1500 CN Analyzer. Changes in fine root biomass were assessed using root ingrowth cores (modified from Persson, 1984). Fine root and overstory foliage samples were analyzed for total nutrient content using methods identical to those described for litter chemistry.

RESULTS AND DISCUSSION

Results from the initial two years of this experiment indicate that the buried cable method is highly effective at maintaining surface soil temperatures at 5 °C above ambient at this site (Fig. 1). It is noteworthy that this temperature differential is maintained to a depth of 30-50 cm in the mineral soil (Fig. 2).

Both the summers of 1993 and 1994 were relatively dry when compared with previous years' data at the HIFS. Soil moisture tension was inversely related to throughfall volume, with peak moisture tensions occurring in early September. Soil moisture was slightly but significantly ($P < 0.05$) decreased in the O horizon in the heated plots relative to the control plots. A similar decrease in soil moisture in response to soil warming was observed by Peterjohn et al. (1994) in a hardwood forest in Massachusetts.

Carbon dioxide evolution from the soil surface and soil air CO_2 concentrations both showed significant ($P<0.0001$) positive exponential relationships with soil temperature. These results are consistent with data from other temperate forests and reflect an increase in microbial decomposition and/or root respiration with increasing temperature (Edwards 1975, Crill 1991, Peterjohn et al. 1994, MacDonald et al. 1995). Carbon dioxide evolution rates in the heated plots were significantly ($P<0.05$) greater than in the control plots (Fig. 3).

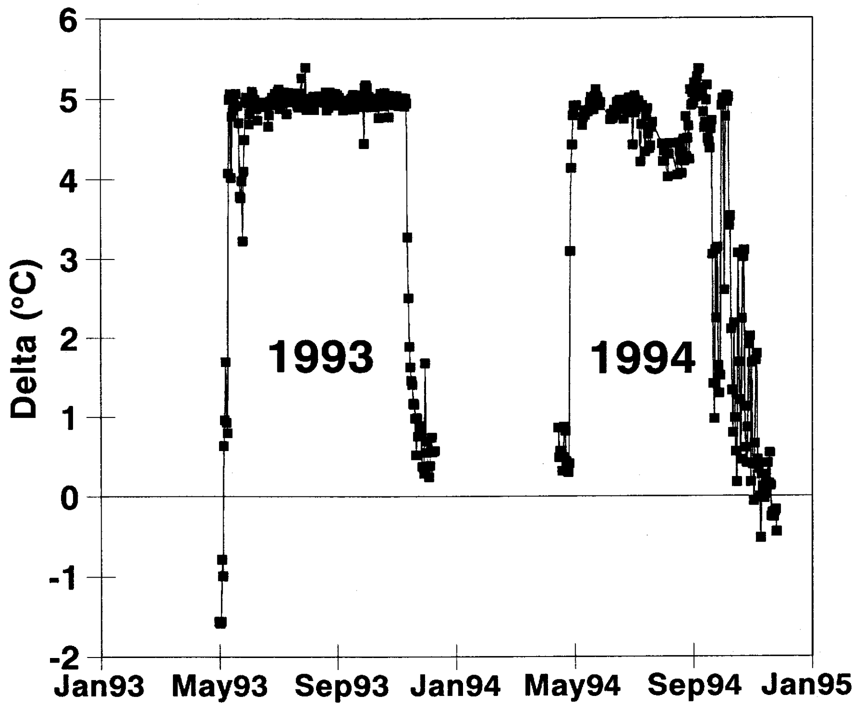

Fig. 1. Mean Temperature Deltas for 1993 and 1994 Field Seasons.

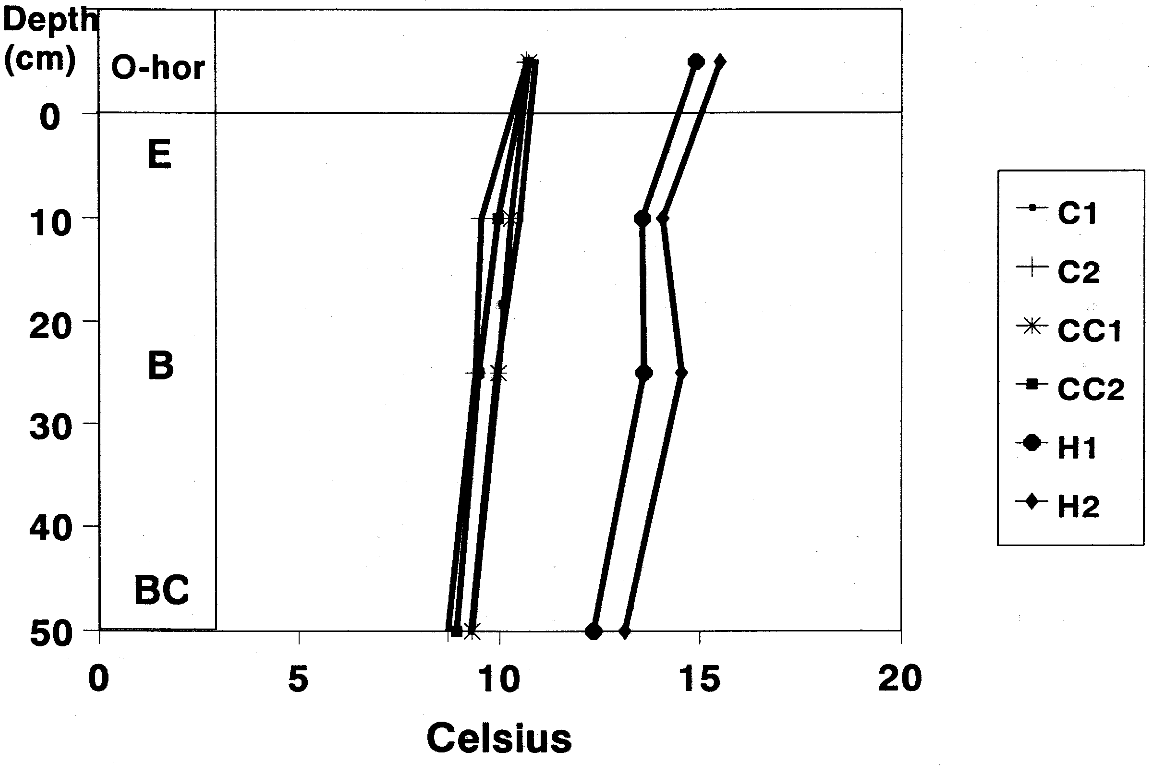

Fig. 2. Average Profile Temperatures for TeMP, 1993.

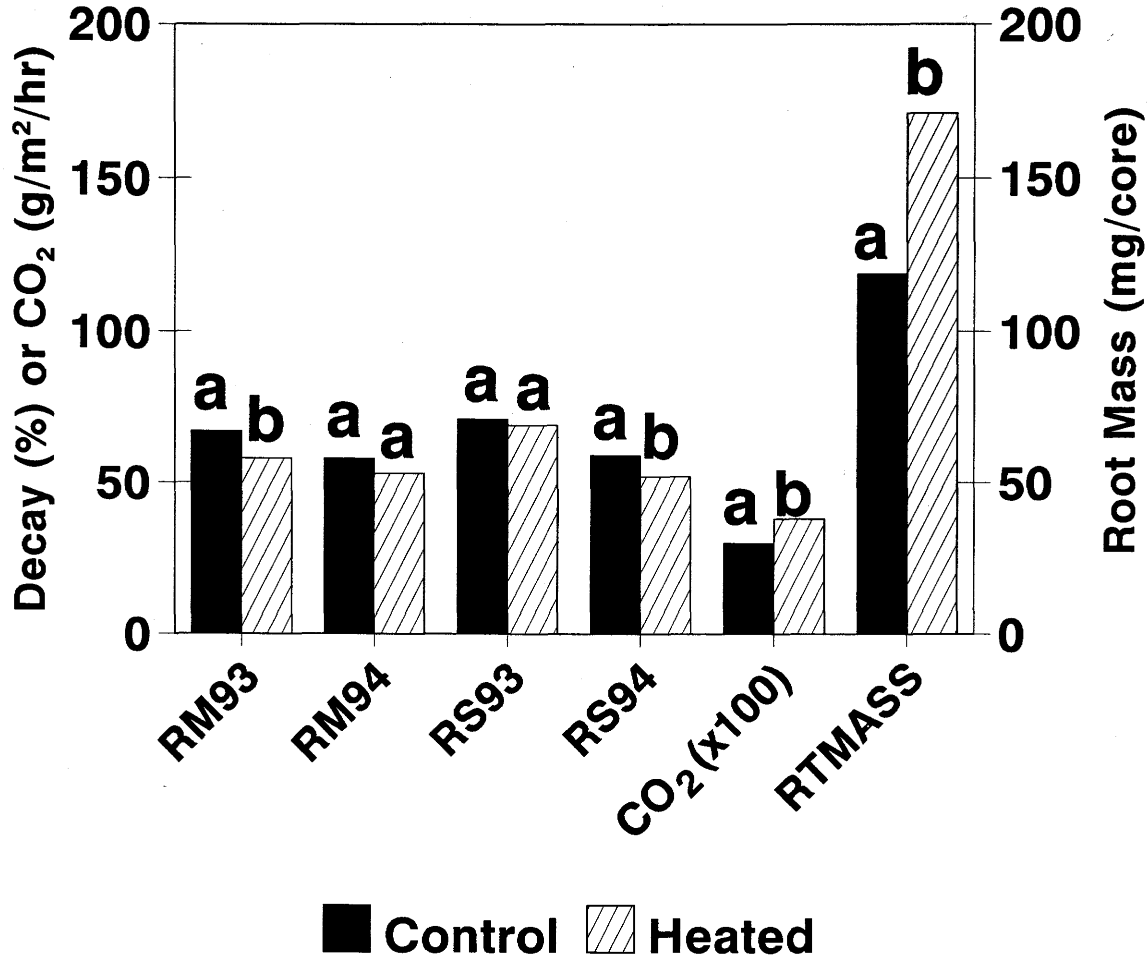

Fig. 3. The response of litter decay, CO_2 evolution, and fine root growth to a 5 °C increase in soil temperature. 'RM93' and 'RM94' are 1993 and 1994 red maple litter, respectively; 'RS93' and 'RS94' are 1993 and 1994 red spruce litter, respectively; 'CO_2' is CO_2 evolution; and 'RTMASS' is soil core fine root mass. Units are percent original mass for litter decay, mg CO_2 m^{-2} hr^{-1} for CO_2 evolution, and mg/core for root mass.

We presume that a large portion of the CO_2 released from these soils is from the O horizon, where both roots and labile organic materials are most abundant. Neither O horizon nor mineral soil PCO_2 showed a response to heating. We attribute this to rapid gas diffusion in the O horizon toward equilibrium with the atmosphere and to minimal biological response to heating in the mineral soils.

Red maple and red spruce litter decay rates were both significantly increased ($P<0.05$) by thermal treatments (see RM93 and RS94, Fig.3). These results are consistent with other studies showing an increase in litter decomposition with increasing air and soil temperature (Witkamp 1966, Meentemeyer 1978, Jansson and Berg 1984, Moore 1986, Ruark 1993). Corresponding to first year mass loss, total red maple litter C, N, and S content were significantly lower ($P < 0.05$) in the heated plots relative to the control plots. Red maple litter Ca, Mg, K, P, and Mn concentrations, however, were generally greater in heated plot litter relative to control plot litter, resulting in no significant differences in the *total content* of these elements between the treatments. Red spruce litter showed only minor differences in chemistry between the heated and control plots after the first year of decay, which reflects it's more recalcitrant mass loss patterns.

First year growth of fine roots in O horizon root cores was significantly greater ($P<0.05$) in the heated plots relative to the control plots (Fig. 3), and root Ca, Mg, K, and Mn concentrations were significantly lower ($P<0.05$). This chemical "dilution effect" may be due to an export of these mobile nutrients out of the fine roots to other sinks within the plants or to insufficient supply of available nutrients to compensate for the increased growth. Second year fine root biomass (not shown), however, was significantly lower ($P < 0.05$) in the heated plots relative to the controls, suggesting that the longevity of fine roots decreases with increasing temperature. This has been shown previously by Marshall and Waring (1985) and Hendrick and Pregitzer (1993), and is attributed to a greater root respiratory maintenance demands at higher temperatures.

The total N content of the soils at this site was low and the corresponding C:N ratio was high (e.g., O Horizon C:N = 44; Fernandez et al., 1993) relative to other sites in Maine, particularly hardwood sites. Nitrogen mineralization rates are also low compared to other nearby hardwood sites, suggesting a slower turnover rate of this nutrient. Overall, no statistically significant effects of the thermal manipulation have been observed on N mineralization rates during the first two years of this experiment. However, the cumulative amount of NH_4-N mineralized over this period was greater in the heated plots relative to the control plots. This trend was driven primarily by spikes of NH_4 that were observed in many buried soil bags in the heated plots during the second summer. No net nitrification has been observed at this site during the two field seasons of study.

Preliminary data on the nutrient elements Ca, Mg, K, and Mn indicate decreased leaching losses in soil solutions, decreased abundance on soil exchange sites, and decreased storage in aboveground live foliage (for Ca and Mg) in the heated plots relative to the controls. We hypothesize that the sink for these nutrients is in microbial biomass.

Although we observed numerous responses to the thermal manipulations, we believe that the unusually dry conditions that characterized both the 1993 and 1994 field seasons precluded more dramatic biological effects of the temperature manipulation. This hypothesis is supported by a laboratory incubation study in which microbial biomass, microbial activity, and N mineralization showed no response to increasing temperatures (in the range of 5 to 25 °C) at low moisture, but showed a significant response to elevated temperatures at higher moisture contents (as shown for N mineralization in Fig. 4). Both field and laboratory studies at this site have underscored the importance of understanding the *interaction* between temperature and moisture on ecosystem processes.

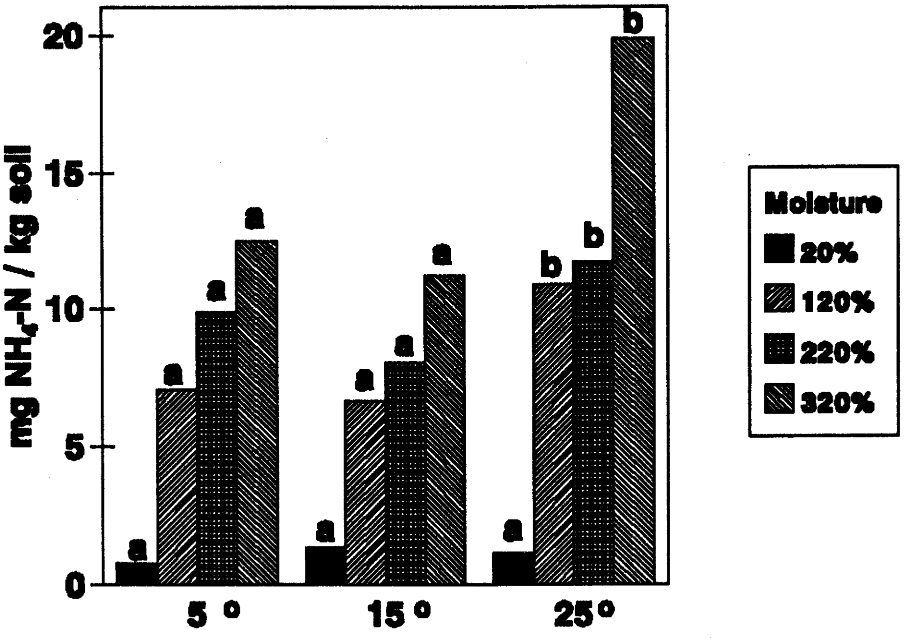

Fig. 4. NH_4-N mineralized after four weeks incubation at three temperatures and four moisture regimes.

CONCLUSIONS

The use of heat resistance cable has proven to be an effective technique for *in situ* experimental warming of forest soils. Results from this study to date indicate that some parameters are responding to the thermal manipulations, e.g. CO_2 efflux, litter decay, and fineroot growth and turnover (as measured by root ingrowth cores) are all greater in the heated plots than the control plots. For other parameters, such as soil air PCO_2, significant relationships were observed with temperature over a range of 0 ° to 20 °C range, although differences were not significant over the narrower range of 5 °C. Although these results suggest that there is a more rapid release of C from the soil-plant system to the atmosphere with increasing temperatures, increases in temperature alone are not sufficient to alter certain parameters. Soil moisture must also be adequate to support biological activity. Ideal available moisture conditions will optimize the biological responses to temperature whereas decreasing available moisture will minimize temperature responses. Thus, a dryer future climate scenario, as has been predicted for some regions, might offset some of the potential effects of a warmer climate. Taken together, results from this thermal manipulation study indicate that modest changes in temperature can significantly alter C, N, and major nutrient dynamics at this site.

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