ORIGINAL PAPER

Paul S. J. Verburg

Soil solution and extractable soil nitrogen response to climate change in two boreal forest ecosystems

Abstract Several studies show that increases in soil temperature result in higher N mineralization rates in soils. It is, however, unclear if additional N is taken up by the vegetation or accumulates in the soil. To address this question two small, forested catchments in southern Norway were experimentally manipulated by increasing air temperature (+3°C in summer to +5°C in winter) and CO_2 concentrations (+200 ppmv) in one catchment (CO_2T-T) and soil temperature (+3°C in summer to +5°C in winter) using heating cables in a second catchment (T-T). During the first treatment year, the climate treatments caused significant increases in soil extractable NH_4 under *Vaccinium* in CO_2T-T. In the second treatment year extractable NH_4 in CO_2T-T and NO_3 in T-T significantly increased. Soil solution NH_4 concentrations did not follow patterns in extractable NH_4 but changes in soil NO_3 pools were reflected by changes in dissolved NO_3. The anomalous behavior of soil solution NH_4 compared to NO_3 was most likely due to the higher NH_4 adsorption capacity of the soil. The data from this study showed that after 2 years of treatment soil inorganic N pools increased indicating that increases in mineralization, as observed in previous studies, exceeded plant demand and leaching losses.

Keywords Climate change · Soil extracts · Soil solution · Nitrogen

P. S. J. Verburg
Laboratory of Soil Science and Geology,
Department of Environmental Sciences,
Wageningen Agricultural University,
PO Box 37, 6700 AA Wageningen, The Netherlands

P. S. J. Verburg (✉)
Division of Earth and Ecosystem Sciences,
Desert Research Institute,
2215 Raggio Parkway, Reno, NV, 89512, USA
e-mail: paul.verburg@dri.edu
Tel.: +1-775-6737425
Fax: +1-775-6737485

Introduction

Increased emissions of CO_2 and other greenhouse gases due to combustion of fossil fuels and changes in land use may contribute to increases in global temperatures (IPCC 2001). An increase in atmospheric temperature may stimulate decomposition of soil organic matter and nutrient mineralization in terrestrial ecosystems (Kirschbaum 1995; MacDonald et al. 1995). A meta-analysis of data from a wide range of soil/ecosystem warming and gradient studies showed that warming led to significant overall increases in N mineralization, nitrification and litter decomposition (Rustad et al. 2001). Despite these general patterns, effects of elevated temperature on soil nutrient pools are less clear. Few data are available addressing the effects of warming on soil extractable N. Peterjohn et al. (1994) measured increases in soil inorganic N pools in response to warming. Shaw and Harte (2001) measured no increase despite increases in N mineralization rates, which was ascribed to increased plant uptake. Effects of warming on soil solution concentrations of dissolved inorganic N (DIN; NH_4 and NO_3) have been mixed as well with studies reporting increases (Joslin and Wolfe 1993; McHale and Mitchell 1996), decreases (Ineson et al. 1998) or no change (Peterjohn et al. 1994) in soil solution DIN concentrations upon soil heating. Rustad et al. (2000) hypothesized that soil solution DIN concentrations will increase only in N-saturated ecosystems, whereas most N will be taken up by vegetation in N-limited ecosystems.

To study potential impacts of climate change on nutrient cycling in a boreal ecosystem, the Climate Change Experiment (CLIMEX) was initiated in southern Norway (Van Breemen et al. 1998). Previous studies have shown that mineralization rates increased in response to climate manipulations (Verburg et al. 1999; Verburg and Van Breemen 2000). This paper presents 3 years of data (one pre-treatment year and two treatment years) describing the effects of ecosystem warming on extractable soil inorganic N pools and soil solution DIN concentrations.

Materials and methods

The CLIMEX site is located at Risdalsheia (58°23′N, 8°19′E) in southern Norway. The site is 300 m above sea level on a large biotite granite plateau representative of large upland areas in southern Norway. Mean annual precipitation is 1,400 mm, and mean annual temperature is 5°C (−3°C in January and +16°C in July). Depressions in the granite surface are filled with post-glacial soil material in which acidic, peaty podsolic soils have developed. Mean soil depth is 20 cm with a maximum of 70 cm. Between 30% and 50% of the bedrock is exposed. Vegetation is dominated by shrubs—*Calluna vulgaris* (L.) Hull, *Vaccinium myrtillus* L., *V. uliginosum* L. and *V. vitis-idaea* L. Overstory trees include Scots pine (*Pinus sylvestris* L.) and birch (*Betula pubescens* Ehrh.).

In 1983, two small headwater catchments were covered with transparent roofs as part of the Reversing Acidification in Norway (RAIN) project (Wright et al. 1993). Precipitation collected from the roof of one catchment was treated to remove all acidifying components. In 1993, this catchment was completely enclosed with transparent walls and the greenhouse was separated into two parts using another transparent wall. Starting in June 1994, 80% of the greenhouse (CO_2T-T) was manipulated by increasing CO_2 concentrations by 200 ppmv during the growing season and increasing air temperature by 5°C in January and 3°C in July with intermediate temperature increases in the intervening months. The average annual soil temperature increase was 2.6°C at 5-cm and 1.9°C at 30-cm depth. The upper 20% of the greenhouse (CO_2T-C) served as an untreated control.

The second covered catchment received ambient acid rain. Starting in April 1994, soil temperature was increased by 5°C in January and 3°C in July with intermediate temperature increases in the intervening months using heating cables in the lower 80% of the catchment (T-T; Lükewille and Wright 1997). Average annual soil temperature increases were 3.4°C at 5 cm and 2.5°C at 30 cm. The upper 20% of the catchment (T-C) served as an untreated control. A third, uncovered catchment served as outside control (Out-C). An overview of the experimental treatments is given in Table 1.

In all treated and control areas ten subplots of 0.1 m^2 were established both in *Calluna*- and *Vaccinium*-dominated areas. In T-C and T-T, no *Vaccinium* was present. Soils were sampled in each subplot four times between April and October during 1993 (pre-treatment year), 1994 and 1995 (treatment years). Winter sampling was impossible due to snow cover and limited site access. Soil cores (2.8-cm diameter) were taken to a depth of 10 cm unless bedrock was shallower. Samples were weighed and stored overnight at 4°C. The following day, 20 g field moist soil was extracted by shaking for 1 h with 50 ml 1 M KCl. The KCl extracts were filtered (Whatman GF C) and analyzed colorimetrically for NH_4-N and NO_3-N on a Technicon auto analyzer. A subsample of the soil was dried at 105°C for 24 h to determine soil moisture content.

To measure treatment effects on soil solution DIN concentrations, Rhizon mini-lysimeters (Eijkelkamp Agrisearch, The Netherlands) were installed in two locations in CO_2T-C and T-C and three locations in CO_2T-T, T-T and Out-C in October 1992. Vegetation was dominated by *Vaccinium* (80% of the vegetated surface area; soils under *Calluna* were too shallow to install lysimeters) in Out-C, CO_2T-C and CO_2T-T. Subplots in T-C and T-T were dominated by *Calluna*. The lysimeters were installed horizontally in the walls of a small pit (30×30×40 cm, L × W × D) at 5-, 15- and 25-cm depths unless soils were too shallow. After installation, the pits were backfilled with the same soil. Soil water was collected overnight using pre-evacuated (50 kPa), 100-ml glass bottles connected to the lysimeters. Volume-weighted samples were pooled by depth for each pit. Soil solution was sampled within 2 days of the soil sampling dates. The samples were stored at 4°C prior to analysis. Samples were analyzed colorimetrically for NH_4 and by ion chromatography for NO_3 and Cl. Soil solution Cl concentrations were used as a proxy for soil moisture assuming that Cl behaves as a conservative ion (e.g. Johnson et al. 2001). Under this assumption, a decrease in soil moisture would be reflected by an increase in soil solution Cl concentration.

Treatment effects on average annual soil extractable NH_4 and NO_3 concentrations for *Calluna* and *Vaccinium* as well as soil solution concentrations were analyzed by analysis of co-variance (ANCOVA) for both manipulated catchments using control vs treated plots ("treatment") as main factor. Data from the pre-treatment year were used as co-variable to account for pre-treatment differences between control and treated plots. All soil solution data were log transformed prior to the ANCOVA analysis. To include element concentrations below the detection limit (reported as "zero"), 1 µEq l^{-1} was added to all values before the log transformation. All statistical analyses were carried out using DataDesk version 6.0 and treatment effects were considered significant if $P < 0.05$.
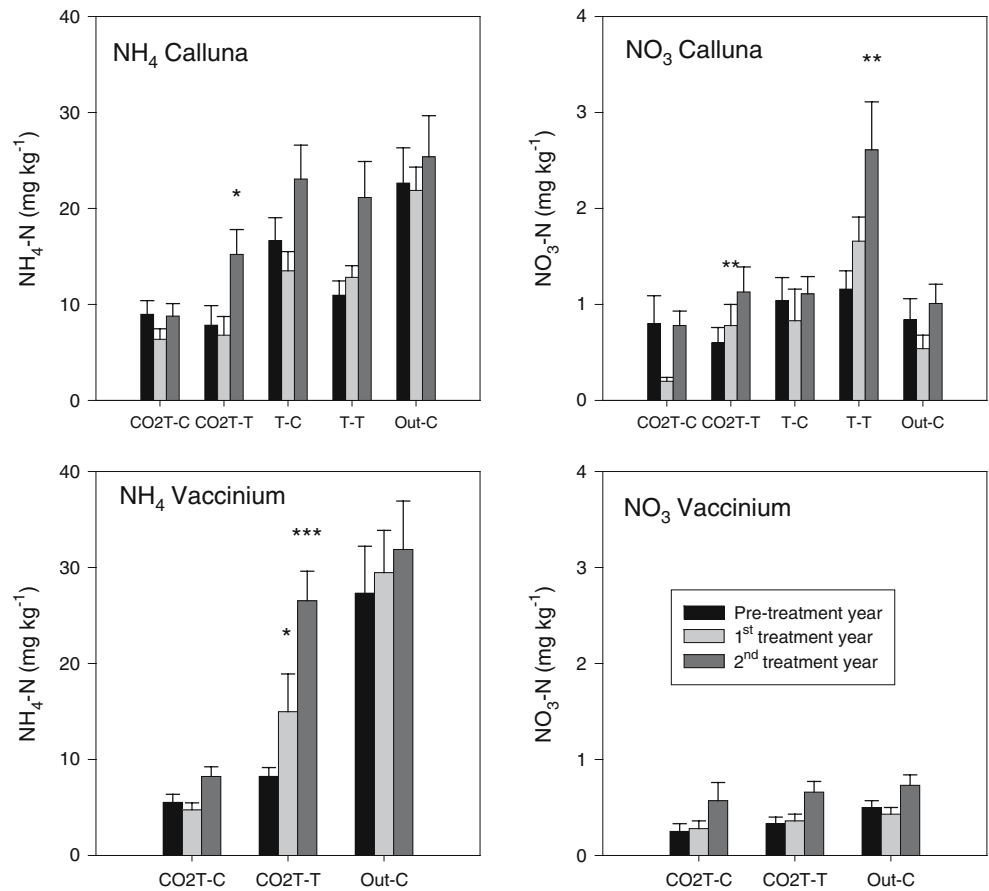
Table 1 Experimental treatments in the studied catchments

Catchment	Area (m^2)	Enclosure	N deposition	Climate treatment
CO_2T-C	170	Roof	Low	0
CO_2T-T	690	Roof	Low	+4°C (air), +200 ppmv CO_2
T-C	80	Roof	High	0
T-T	320	Roof	High	+4°C (soil)
Out-C	650	No roof	High	0

Results and discussion

The effects of the climate manipulations on soil extractable N varied by nutrient, vegetation, and plot. During the first treatment year the treatments did not affect soil NH_4 concentrations under *Calluna* in CO_2T-T and T-T (Fig. 1). During the second treatment year soil NH_4 concentrations increased by 100% in CO_2T-T compared to the pre-

Fig. 1 Average annual extractable soil NH_4 and NO_3 concentrations under *Calluna* and *Vaccinium* in control (CO_2T-C, T-C, Out-C) and heated (CO_2T-T, T-T) parts of the studied catchments during pre-treatment and treatment years (see Table 1 for catchment details). *Error bars* represent standard errors of the mean. The *asterisks* indicate significant treatment effects as determined by ANCOVA using pre-treatment data as co-variable (* $P <0.05$, ** $P <0.01$, *** $P <0.001$)

treatment year while concentrations remained constant in CO_2T-C and Out-C. Soil NH_4 concentrations doubled in T-T in the second treatment year as well but a similar increase was observed in T-C indicating that the increase in T-T reflected interannual variability in ambient conditions. During the first treatment year soil NO_3 concentrations under *Calluna* remained constant in CO_2T-T but decreased by 75% in CO_2T-C. Soil NO_3 concentrations also tended to decrease in Out-C ($P =0.052$) suggesting that the treatment effect in CO_2T-T was caused by the climate manipulations. No treatment effect was observed during the second treatment year in CO_2T-T. Soil warming caused an increase in soil NO_3 concentrations by 110% in T-T during the second treatment year while concentrations remained unchanged in T-C and Out-C. Soil NH_4 concentrations under *Vaccinium* increased by 80% in CO_2T-T during the first treatment year and by 200% during the second treatment year but remained constant in CO_2T-C and Out-C in both treatment years. Soil NO_3 concentrations under *Vaccinium* in CO_2T-T doubled during the second treatment year but similar increases were found in the control plots CO_2T-C and Out-C indicating that the increase in CO_2T-T was due to interannual variability. Prior to the start of the treatments NH_4 under *Calluna* and *Vaccinium* and NO_3 under *Vaccinium* were significantly lower (NH_4, $P <0.001$; NO_3, $P =0.02$) in the reduced-N plots (CO_2T-C and CO_2T-T) than in the plots receiving ambient N inputs (T-C, T-T, Out-C). The 2 years of climate

manipulation in CO_2T-T caused soil NH_4 and NO_3 concentrations to become similar to those in the ambient deposition plots.

The effects of the climate treatments on extractable N concentrations were consistent with patterns in net mineralization as measured in previous studies. The increase in net mineralization in CO_2T-T was mainly caused by an increase in ammonification while in T-T only nitrification increased (Verburg et al. 1999; Verburg and Van Breemen 2000). These studies also showed that contribution of nitrification to the total mineralization was higher for *Calluna* (10%) than for *Vaccinium* (2%). The 2 years of climate manipulations caused an increase in vegetation N uptake in CO_2T-T (Van Breemen et al. 1998) while DIN leaching increased by approximately 0.07 g m^{-2} year^{-1} in both catchments (Lükewille and Wright 1997; Wright 1998). Still, soil extractable N pools increased showing that the increases in mineralization exceeded vegetation demand and leaching. The increase in inorganic soil N pools represented a significant N flux. For instance, assuming a bulk density of 0.67 g cm^{-3} for topsoils at the site (Lotse and Ottabong 1985), soil NH_4 increased from 0.6 to 1.0 g N m^{-2} under *Vaccinium* in CO_2T-T during the first treatment year. In this period net ammonification in these plots increased from 4.1 to 5.7 g N m^{-2} year^{-1} (Verburg and Van Breemen 2000) suggesting that 25% of the additionally mineralized N was transferred to the extractable inorganic N pool.
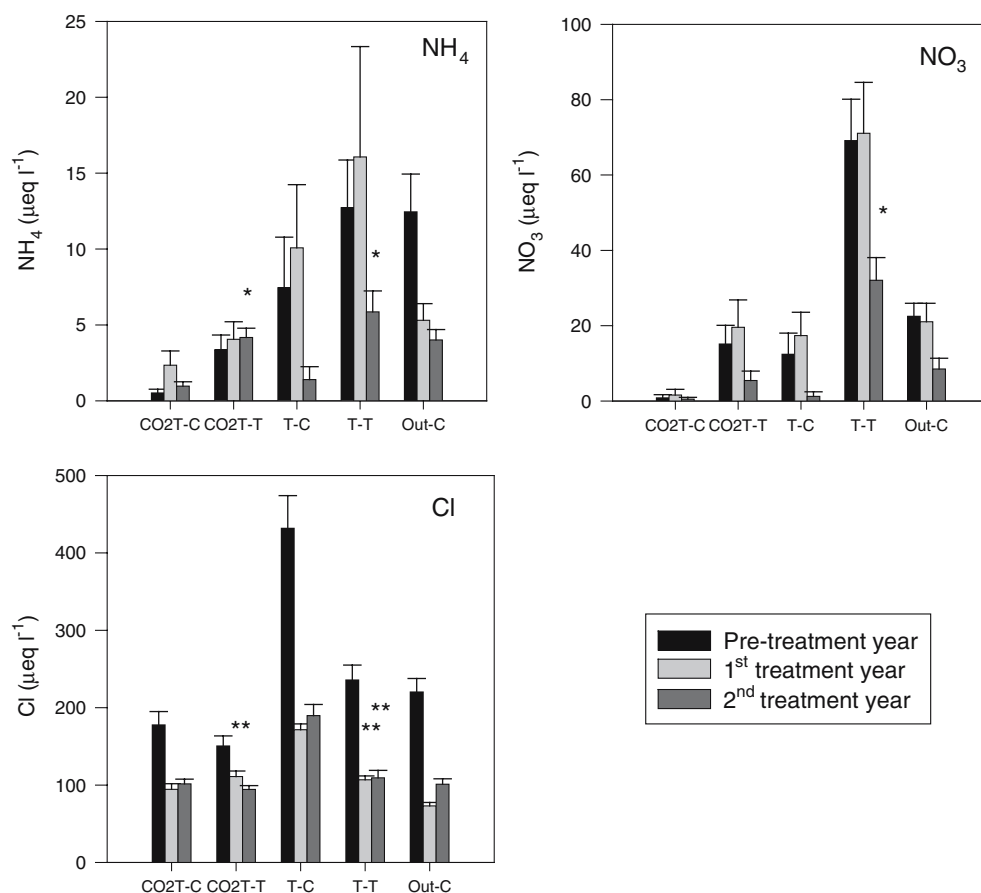
During the first treatment year, soil solution NH_4 and NO_3 concentrations did not show any significant treatment effects in CO_2T-T and T-T even though soil extractable NH_4 under *Vaccinium* and NO_3 under *Calluna* significantly increased in CO_2T-T (Fig. 2). During the second treatment year, average annual soil solution NH_4 concentration increased by 86% in CO_2T-C but only by 24% in CO_2T-T compared to the pre-treatment year indicating that soil solution NH_4 concentrations decreased in response to the treatments. In T-T soil solution NH_4 and NO_3 concentrations increased during the second treatment year. Soil solution NH_4 concentration decreased by 81% in T-C and by 54% in T-T and NO_3 concentration decreased by 90% in T-C and by 54% in T-T compared to the pre-treatment year suggesting a relative increase in DIN concentrations in T-T.

The patterns in soil solution DIN concentrations were not caused by changes in soil moisture. During the first treatment year the average annual Cl concentration showed a significantly smaller decrease in CO_2T-T (26%) than in CO_2T-C (47%; Fig. 2) compared to the pre-treatment year while soil warming caused a slight but significantly smaller decrease in Cl concentration in T-T (54%) than in T-C (58%) in both treatment years. Data from both catchments suggest a reduction in soil moisture in the treated plots (CO_2T-T and T-T) but the changes in soil moisture based on Cl data were too small to explain the changes in DIN concentrations. Neither in CO_2T-T nor in T-T did soil solution

NH_4 concentrations reflect patterns in soil extractable NH_4; in CO_2T-T NH_4 concentrations decreased despite an increase in extractable NH_4 while in T-T soil solution NH_4 increased even though extractable NH_4 did not change. The patterns found in CO_2T-T were similar to those observed in Harvard forest (Peterjohn et al. 1994). Behavior of dissolved NH_4 is more complicated than that of NO_3 since NH_4 more easily adsorbs to the soil than NO_3; soil solution NO_3 concentrations were four to five times higher than NH_4 concentrations even though soil extractable NO_3 concentrations were ten times lower. Consequently, dissolved NH_4 concentrations will not only depend on extractable soil NH_4 pool size but also on soil chemical parameters including pH and cation exchange capacity. As a result, dissolved NH_4 concentrations are probably less sensitive to changes in extractable pool size than NO_3. Soil solution and soil extractable NO_3 responses appear to support the hypothesis of Rustad et al. (2000) since the increase in soil and soil solution NO_3 concentrations was smaller in the plots receiving reduced N inputs. However, the increase in nitrification rate was lower in CO_2T-T than in T-T (Verburg et al. 1999; Verburg and Van Breemen 2000), which could also account for the difference in NO_3 response between CO_2T-T and T-T.

The soil solution data presented in this paper are consistent with changes in runoff observed by Lükewille and Wright (1997) and Wright (1998). During the 2 years of

Fig. 2 Average annual soil solution NH_4, NO_3 and Cl concentrations in control (CO_2T-C, T-C, Out-C) and heated (CO_2T-T, T-T) parts of the studied catchments during pre-treatment and treatment years (see Table 1 for catchment details). *Error bars* represent standard errors of the mean. The *asterisks* indicate significant treatment effects as determined by ANCOVA using pre-treatment data as co-variable (* $P <0.05$, ** $P <0.01$)

treatment, soil warming in T-T increased the runoff NH_4 concentration by 3 µEq l^{-1} and NO_3 concentration by 4 µEq l^{-1} (Lükewille and Wright 1997). Increases in runoff NH_4 and NO_3 concentrations in response to climate treatments in CO_2T-T were smaller (Wright 1998), as were soil solution responses. Changes in runoff and soil solution concentrations in response to the climate treatments were relatively small compared to changes due to long-term manipulation of N inputs. Eleven years of reduced N inputs in CO_2T-C and CO_2T-T resulted in significantly lower soil solution NH_4 and NO_3 concentrations than in the plots receiving ambient N inputs (Out-C, T-C and T-T, $P < 0.001$). During this period, runoff NH_4 concentrations in CO_2T decreased by 15 µEq l^{-1} and NO_3 concentrations by 30 µEq l^{-1} (Wright 1998). Therefore, it is very likely that if changes in N cycling in response to the climate treatments persist, soil solution responses may become more pronounced.

The results of this study showed that the climate manipulations in both catchments caused soil inorganic N pools to increase because of increases in N mineralization rates. Since KCl-extractable N is assumed to be readily exchangeable (e.g. Johnson et al. 2000) the observed increases in inorganic N pools most likely represented "leftover N" after plant and microbial demands were satisfied. Still, some competition between plant microbial uptake and adsorption may occur especially for NH_4 enhancing accumulation of extractable NH_4. In addition to N uptake by the vegetation and microbes, several laboratory studies have demonstrated abiotic incorporation of NH_4 and NO_3 into soil organic matter as a potential removal mechanism of inorganic N (e.g. Johnson et al. 2000; Fitzhugh et al. 2003). Although these studies indicate that abiotic N immobilization is common in forest soils, its importance on an ecosystem scale has yet to be determined (Johnson et al. 2000). Finally, it is unknown if the increased mineralization rates and thus increase in soil inorganic N pools will be sustained indefinitely. In Harvard forest soil warming initially resulted in an increase in N mineralization, but this stimulation decreased after several years most likely due to a decrease in labile N pools (Melillo et al. 2002). Despite the importance of these potential acclimation effects little experimental evidence exists that allows for evaluation of long-term impacts of environmental change on N cycling.

References

Fitzhugh RD, Lovett GM, Venterea RT (2003) Biotic and abiotic immobilization of ammonium, nitrite, and nitrate in soils developed under different tree species in the Catskill Mountains, New York, USA. Global Change Biol 9:1591–1601

Ineson P, Benham DG, Poskitt J, Harrison AF, Taylor K, Woods C (1998) Effects of climate change on nitrogen dynamics in upland soils. 1. A soil warming study. Global Change Biol 4:153–161

IPCC (2001) Climate change 2001: the scientific basis. Intergovernmental panel on climate change, Geneva

Johnson DW, Cheng W, Burke IC (2000) Biotic and abiotic nitrogen retention in a variety of forest soils. Soil Sci Soc Am J 64:1503–1514

Johnson DW, Susfalk RB, Dahlgren RA, Caldewell TG, Miller WW (2001) Nutrient fluxes in a snow-dominated, semi-arid forest: spatial and temporal patterns. Biogeochemistry 55:219–245

Joslin JD, Wolfe MH (1993) Temperature increase accelerates nitrate release from high-elevation red spruce soils. Can J For Res 23:756–759

Kirschbaum MUF (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biol Biochem 27:753–760

Lotse E, Ottabong E (1985) Physiochemical properties of soils at Risdalsheia and Sogndal: rain project. Norwegian Institute for Water Research Report 8/195. NIVA, Oslo

Lükewille A, Wright RF (1997) Experimentally increased soil temperature causes release of nitrogen at a boreal forest catchment in southern Norway. Global Change Biol 3:13–21

MacDonald NW, Zak DR, Pregitzer KS (1995) Temperature effects on kinetics of microbial respiration and net nitrogen and sulfur mineralization. Soil Sci Soc Am J 59:233–240

McHale PJ, Mitchell MJ (1996) Disturbance effects on soil solution chemistry due to heating cable installation. Biol Fertil Soils 22:40–44

Melillo JM, Steudler PA, Aber JD, Newkirk K, Lux H, Bowles FP, Catricala C, Magill A, Ahrens T, Morrisseau S (2002) Soil warming and carbon-cycle feedbacks to the climate system. Science 298:2173–2176

Peterjohn WT, Melillo JM, Steudler PA, Newkirk KM, Bowles FP, Aber JD (1994) Responses of trace gas fluxes and N availability to experimentally elevated soil temperatures. Ecol Appl 4:617–625

Rustad LE, Melillo JM, Mitchell MJ, Fernandez IJ, Steudler PA, McHale PJ (2000) Effects of soil warming on C and N cycling in northern U.S. forest soils. In: Mickler R, Birdsey R, Hom J (eds) Responses of northern U.S. forests to environmental change. Springer-Verlag, Berlin Heidelberg New York, pp 357–381

Rustad LE, Campbell J, Marion GM, Norby RJ, Mitchell MJ, Hartley AE, Cornelissen JHC, Gurevitch J, GCTE-NEWS (2001) A meta-analysis of the response of soil respiration, net N mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologia 126:543–562

Shaw MR, Harte J (2001) Response of nitrogen cycling to simulated climate change: differential responses along a subalpine ecotone. Global Change Biol 7:193–210

Van Breemen N, Jenkins A, Wright RF, Arp WJ, Beerling DJ, Berendse F, Beier C, Collins R, Van Dam D, Rasmussen L, Verburg PSJ, Wills MA (1998) Impacts of elevated carbon dioxide and temperature on a boreal forest ecosystem (CLIMEX project). Ecosystems 1:345–351

Verburg PSJ, Van Breemen N (2000) Nitrogen transformations in a forested catchment in southern Norway subjected to elevated temperature and CO_2. For Ecol Manage 129:31–39

Verburg PSJ, Van Loon WKP, Lükewille A (1999) The CLIMEX soil-heating experiment: soil response after 2 years of treatment. Biol Fertil Soils 28:271–276

Wright RF (1998) Effect of increased CO_2 and temperature on runoff chemistry at a forested catchment in southern Norway (CLIMEX project). Ecosystems 1:216–225

Wright RF, Lotse E, Semb A (1993) RAIN project: results after 8 years of experimentally reduced acid deposition to a whole catchment. Can J Fish Aquat Sci 50:1–11