SHORT COMMUNICATION

Reduced mineralizable carbon in a boreal forest soil after three years of artificial warming

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D'Orangeville, L., Côté, B., Houle, D. and Whalen, J. 2013. **Reduced mineralizable carbon in a boreal forest soil after three years of artificial warming**. Can. J. Soil Sci. **93**: 567–572. Soil warming is expected to reduce organic carbon pools. We incubated soils from a balsam fir stand previously subjected to 3 yr of in situ experimental warming (+4°C). Mineralizable carbon was significantly reduced (16–25%) in heated soils, corresponding to a 0.4–0.8% decline in the organic carbon pool.

Key words: Balsam fir, carbon mineralization, climate change, nitrogen deposition, soil warming

D'Orangeville, L., Côté, B., Houle, D. et Whalen, J. 2013. **Réduction du carbone minéralisable dans un sol de forêt boréale après trois années de chauffage artificiel**. Can. J. Soil Sci. **93**: 567–572. Le réchauffement du sol devrait réduire son contenu en carbone organique. Nous avons incubé des sols d'une sapinière boréale précédemment soumise à trois années de réchauffement expérimental *in situ* (+4°C). Le carbone minéralisable était significativement réduit (16–25%) dans les sols chauffés, ce qui correspond à un déclin de 0.4–0.8% du contenu en carbone organique.

Mots clés: Sapin baumier, minéralisation du carbone, changements climatiques, dépôts d′azote, réchauffement du sol

Increasing soil organic carbon (SOC) reserves will help to offset greenhouse gas emissions, but the response of the SOC pool to future climate scenarios is still highly uncertain (Friedlingstein et al. 2006). Under non-limiting availability of water and nutrients, the SOC decomposition rates and carbon (C) release to the atmosphere are expected to increase with temperature (Davidson and Janssens 2006). However, long-term in situ warming experiments in temperate forests (Melillo et al. 2011) and prairie ecosystems (Luo et al. 2001) suggest that the effects of temperature on soil respiration may be temporary, with increased rates persisting only a few years. The rapid depletion of the most labile pools of SOC in the first years of soil warming could explain why soil respiration rates decline over longer time scales. Decreasing soil respiration rates could also be explained by the thermal adaptation of soil microbes to warmer soil temperatures (Davidson and Janssens 2006). Both mechanisms were observed in a long-term (>15 yr) soil warming experiment in a hardwood forest of eastern North America (Bradford et al. 2008). In boreal ecosystems, decomposition of labile C is generally limited by the low levels of available N as well as soil temperature (Hobbie et al. 2002). An increase of 70% in atmospheric N deposition is projected for 2050 relative to 1990 (Galloway et al. 2004). However, the interactive effect of soil warming and increased N deposition on C mineralization and SOC dynamics has not been verified for boreal forest soils.

In order to test the effects of warming on soil labile C, we sampled soils from a climate change simulation experiment (in situ soil warming and increased N deposition) that had run for 3 yr in a boreal balsam fir forest of eastern Canada and incubated them under standard laboratory conditions. After 3 yr of soil warming, the soil biota may have had time to adapt to their new environment. Incubations under controlled conditions of temperature (5, 10, 15, 20°C for 72 d) and moisture compared with measurements conducted in the field improve our capacity to detect changes in soil C

Abbreviations: **ANOVA**, analysis of variance; $\mathbf{C_o}$, potential mineralizable C; $\mathbf{F_{CO_2}}$, mineralized C; $\boldsymbol{k}$, respiration constant; $\mathbf{Q_{10}}$, temperature response coefficient; $\mathbf{R^2}$, coefficient of determination; **SOC**, soil organic carbon; **SWC**, soil water content; **t**, time; $\mathbf{t_1}$ and $\mathbf{t_2}$, incubation temperature

mineralization associated with changes in the microbial community (composition, abundance and dynamics) and substrate. We hypothesized that previously heated soils would have a lower rate of respiration due to labile C depletion and that increased N deposition would exacerbate the depletion of labile C.

MATERIALS AND METHODS

Study Area

The soil warming–N deposition experiment was established in a 60-yr-old even-aged boreal balsam fir [*Abies balsamea* (L.) Mill.] stand (lat. 47°17′N, long. 71°14′W; 800 m above sea level), about 100 km north of Québec City, in the province of Québec, Canada. The soil is an Orthic Ferro-Humic Podzol lying on a bedrock of Precambrian charnockitic gneiss. The average thicknesses for LFH, Ae, Bhf and Bf horizons are 7.4, 3.6, 7.6 and 28.7 cm, respectively. In 2011, the organic and upper mineral horizons contained an average of 399 ± 11 g SOC kg^{-1} and 39.9 ± 3.2 g SOC kg^{-1}, respectively, with a C:N ratio of 25 and 23, respectively. The pH of the organic and upper mineral horizons was 3.03 ± 0.03 and 4.05 ± 0.03, respectively. From 1981 to 2006, mean annual air temperature and total precipitation, measured in a clearing located $\sim$300 m from the plots, were -0.3°C and 1535 mm, respectively, with maximum and minimum daily temperature averaging 21°C in July and -22°C in January, respectively. In the summer, the temperature of the organic soil horizon can reach 16°C.

Experimental Design and Treatments

The experiment was established in autumn 2008 and laid out as a randomized split-plot design with two levels of soil temperature (ambient, between 0 and 16°C, and 4°C above ambient) nested within two levels of artificial precipitation (without added N and three times the natural NH_4NO_3 concentration in ambient precipitation; details below) for a total of four treatments. The treatments were distributed among 12 plots covering a 60-m × 60-m area, each plot centred on a single balsam fir tree, evenly distributed amongst three blocks.

Based on climate model projections for the site for the 2070–2100 period (Houle et al. 2012), a +4°C difference was maintained in the organic and upper mineral soil layers of heated plots during the 2009, 2010 and 2011 growing seasons with heat-resistance cables buried 5–10 cm below ground [see D'Orangeville et al. (2013) for details]. Increased atmospheric N deposition was simulated based on predicted global increases of 70% in N emissions in 2050 relative to the 1990s (Galloway et al. 2004). Each year and every week from mid-June to mid-September, all plots received identical amounts of artificial rainwater (70 L) applied on the canopy using nozzles set up above each individual tree using a system of pumps and reservoirs. The rain solution in N-enriched plots contained 1.0 and 3.4 mg L^{-1} of NH_4 and NO_3, respectively, approximately three times the concentrations measured in the precipitation at the site.

Soil Sampling and Analysis

In September 2011, three soil cores were collected within each plot from the FH and Bhf horizons, referred to as organic and mineral horizons hereafter, and pooled by soil layer to form one bulk sample per horizon per plot. Moist samples were gently sieved (6 mm) in order to remove coarse fragments and woody debris while preserving as much as possible the soil structure and aggregations. The water content of each soil sample was determined by the difference of weight after drying a subsample (10 g) to a constant weight at 105°C for 24 h. Assuming a similar soil structure and texture between samples, the soil water content (SWC) for all samples from each horizon was adjusted to that of the sample with the highest moisture in the organic (74.2%) and mineral (31.8%) horizons with the addition of demineralized water, in order to standardize moisture conditions between samples.

For each soil sample, four subsamples (15 g for organic soil, 50 g for mineral soil; fresh weight) were put in 120 cm^3 acid-washed graduated plastic vials and placed inside open 1-L Mason jars along with 10 mL of distilled water to maintain soil humidity, for a total of 96 jars. The exact weight and volume of soil were noted. All jars were sealed with an air-tight lid and incubated at 4°C for 10 d in the dark to stabilize the soil microbial community (Bowden et al. 2004). Air-tight rubber septa were fitted into the lids to allow CO_2 sampling.

The four subsamples were then incubated in the dark for 72 d at four temperatures covering the natural range of temperatures experienced at the site during the growing season: 5, 10, 15 and 20°C. Gas samples (20 mL) were taken at the beginning of incubation and after 1, 3, 6, 10, 17, 31, 45 and 72 d with a gas-tight syringe and injected into pre-evacuated 12 mL Exetainers (Labco, Wycombe, UK) with an extra 60 mil thick Teflon-silicone septa (National Scientific, Rockwood, TN) containing a small amount of magnesium perchlorate to absorb moisture. After sampling, jar lids were removed 30 min to allow air circulation into the jar. Within 1 wk of gas sampling, the CO_2 concentration in every sample was measured using a gas chromatograph (6890 Series II, Hewlett-Packard Company, Avondale, PA) equipped with a Porapak Q column (ethylvinylbenzene and divinylbenzene copolymer beads; 80–100 mesh; length 25 m; internal diameter, 0.2 mm; Supelco 20331). The carrier gas was He (50 mL min^{-1}). Oven and detector temperatures were 120 and 250°C, respectively, and CO_2 detection was achieved with a thermal conductivity detector. Fluxes of CO_2 (F_{CO2}, mg CO_2-C kg^{-1} soil h^{-1}) were calculated according to Rochette and Bertrand (2007) and the volume of air inside the jar was calculated following Poirier et al. (2013).

We calculated temperature response coefficients Q_{10} according to the following equation:

$$Q_{10} = \left(\frac{F_{CO_2(t_1)}}{F_{CO_2(t_2)}}\right)^{10/(t_1 - t_2)}$$

where t_1 and t_2 are incubation temperatures and F_{CO_2} values are the corresponding mineralized C value measured at each sampling. We averaged the Q_{10} values across multiple sampling dates in order to obtain one Q_{10} value per sample. An exponential function was fitted to cumulative CO_2 concentrations for each soil sample at each incubation temperature (Stanford and Smith 1972):

$$C_{min} = C_o(1 - e^{-kt})$$

where C_o is the upper asymptote corresponding to potential mineralizable C, C_{min} is C respiration at time t (in days) and k is the respiration constant (d^{-1}). Parameter estimation was achieved through an iterative approach using nonlinear least-squares estimates, giving a mean coefficient of determination (R^2) of 0.979 and normal distribution of the residuals.

Statistical Analysis

A linear mixed-effects analysis of variance (ANOVA) was used to analyse the effects of the treatments on C respired and temperature sensitivity coefficients Q_{10}, assuming a compound symmetry variance-covariance structure. Parameters of the C respiration function (C_o and k) were tested against soil warming, N deposition and incubation temperature as fixed factors and plot within a block as random factors. A similar ANOVA structure was used to test Q_{10} values, this time with soil warming, N deposition and temperature range as fixed factors. Data were tested a priori to meet the assumptions of ANOVA, log-transformed when necessary and Tukey post-hoc tests were used for multiple comparisons of means. Statistical analysis, modelling and plots were done using the R software (R Development Core Team 2012).

RESULTS

In both soil horizons and for all incubation temperatures, the general pattern of CO_2 production was similar, with high rates in the first 3 d followed by an exponential decrease until day 17 and a steady CO_2 production rate for the remainder of the incubation (Fig. 1). Three years of artificial soil warming and/or increased N deposition had no significant effect on the decomposition constant k or temperature sensitivity coefficient Q_{10} (Table 1). Relative to control soils, soils exposed to higher temperatures in situ had significantly less C_o, with a 15–32% (average 25%) and 2–23% (average 16%) reduction in C_o in the organic and mineral horizons, respectively ($P \leq 0.04$; Table 1). Nitrogen additions alone had no significant effect on potential mineralizable C (C_o). However, the decrease in C_o for the organic horizon relative to controls was significantly less in heated-fertilized plots than in heated-only plots ($P = 0.01$; Table 1).

In the organic and mineral horizons, C_o ranged from 3.8 to 18.7 g C kg soil^{-1} and from 0.5 to 1.5 g C kg soil^{-1}, respectively, and was found to differ significantly among incubation temperatures ($P < 0.01$; Table 1). In both soil horizons, C_o was similar at 5 and 10°C, but increased significantly from 10 to 15°C and from 15 to 20°C ($P < 0.05$). The corresponding temperature response coefficient Q_{10} was 2.9 ± 0.2 and 2.5 ± 0.1 in the organic and mineral horizons, respectively (Table 1). The incubation temperature also had a significant effect on the respiration constant k in both soil horizons ($P < 0.01$; Table 1). In the organic horizon, k was higher at 10°C (0.13) than at 5, 15 or 20°C (0.07; $P < 0.05$). The post-hoc tests did not reveal significant differences between incubation temperatures in the mineral horizon ($P \geq 0.06$).

DISCUSSION

The measured absolute rates and patterns of CO_2 production are consistent with studies of various soil types, including boreal soils, using similar incubation protocols (Cook and Allan 1992; Dalias et al. 2001; Rey et al. 2008; Gillabel et al. 2010). The differences in the initial total C content of the organic (399 g kg^{-1}) and the mineral (40 g kg^{-1}) horizons could account for the different respiration rates between soil horizons, since C_o values, relative to total C, varied little in both horizons (on average, 2.5 and 2.3% of the total C was mineralizable in the organic and mineral horizons, respectively). Being mineralized in a matter of weeks and months in this experiment, C_o can be considered as a readily decomposable substrate, as opposed to other C pools with slower turnover rates caused by greater chemical (i.e., association with silt and clay minerals) or physical protection (i.e., aggregation) (Davidson and Janssens 2006). We considered the active C_o pool to represent "labile C", susceptible to mineralization by soil microorganisms. We did not identify the chemical characteristics of the SOC before and after incubation, but labile C is generally composed of carbohydrates and some lignin-containing compounds (Berg 2000). The labile C fraction of this boreal forest soil represented 1.0–4.7% of the total C, a range that is closer to that of temperate soils (0.7–4.3%; Townsend et al. 1997) than with cold tundra ecosystems (9–41%; Neff and Hopper 2002). This suggests that the climate and vegetation at the site are conducive to high rates of labile C turnover in comparison with other cold ecosystems. The temperature dependence of C_o has been previously reported for similar incubation temperature ranges (Dalias et al. 2001; Gillabel et al. 2010). Higher incubation temperatures increase enzymatic depolymerisation rates, giving microbes better access to nutrients, and also reduce the physical occlusion of SOC within soil aggregates as well as the strength of SOC–mineral bonds (Conant et al. 2011). Thus, more C is mineralized at higher temperatures, especially during the first 3 d. The calculated

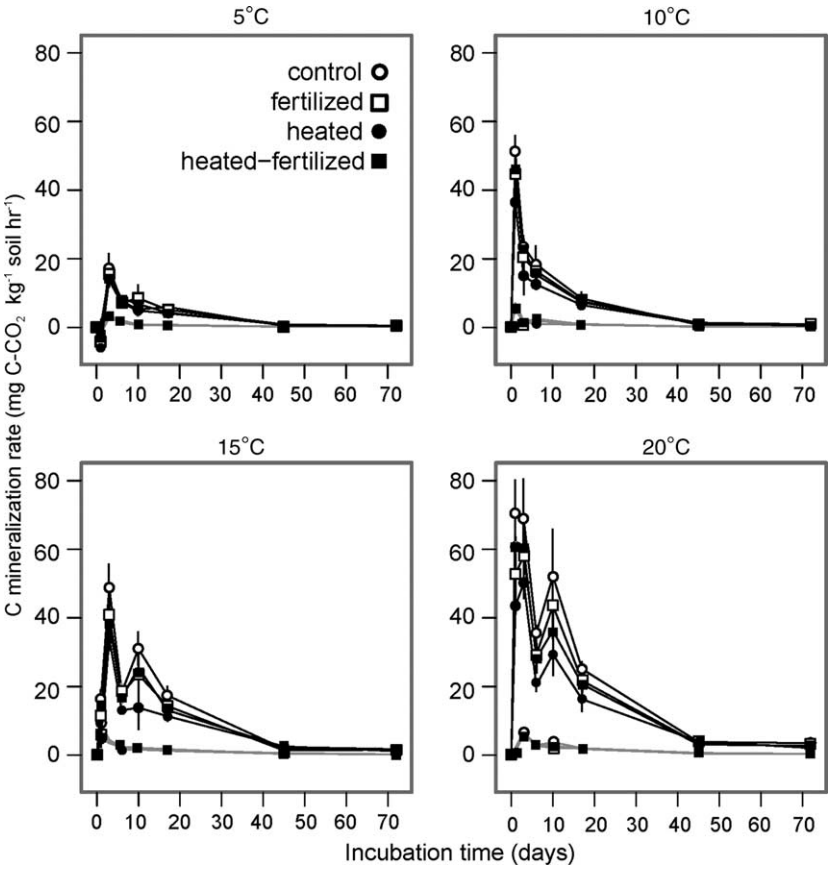

Fig. 1. Average hourly C mineralization rates in organic (black) and mineral soils (grey) for control, heated, fertilized and heated-fertilized soils at 5, 10, 15 and 20°C.

Table 1. Potential mineralizable C (C_o), decomposition rate constant (k) and temperature response coefficient (Q_{10}) in the organic and mineral horizons of control, fertilized, heated and heated-fertilized soils incubated for 72 d at four temperatures, and mixed-model ANOVA treatment effects ($N=12$). Values are the mean ± standard error. ANOVA interactions were removed when non-significant

	Organic horizon			Mineral horizon		
	C_o (g CO_2-C kg^{-1} soil)	k (d^{-1})	Q_{10}	C_o (g CO_2-C kg^{-1} soil)	k (d^{-1})	Q_{10}
Control	11.5±2.3	0.09±0.01	2.9±0.3	1.0±0.2	0.12±0.02	2.3±0.3
Fertilized	10.0±1.9	0.08±0.01	2.9±0.3	0.9±0.2	0.11±0.03	2.3±0.3
Heated	8.2±1.5	0.08±0.01	2.8±0.3	0.8±0.1	0.11±0.01	2.9±0.4
Heated-fertilized	9.8±1.8	0.09±0.01	2.8±0.3	0.9±0.1	0.13±0.03	2.4±0.3
5°C	3.8±0.2*a*	0.07±0*a*	–	0.5±0*a*	0.07±0	–
10°C	5.9±0.3*a*	0.13±0.01*b*	–	0.6±0.1*a*	0.19±0.03	–
15°C	11.2±0.8*b*	0.07±0*a*	–	1.0±0.1*b*	0.13±0.02	–
20°C	18.7±1.4*c*	0.08±0*a*	–	1.5±0.1*c*	0.07±0	–
			P values			
Warming (H)	0.004**	0.74	0.89	0.05*	0.80	0.64
Fertilization (N)	0.92	0.75	0.89	0.84	0.83	0.54
Temperature	<0.0001**	<0.0001**	0.60	<0.0001**	<0.0001**	0.09
H × N	0.01*	0.13	0.80	0.47	0.49	0.62

a–c Within a column, values with the same letter within a treatment did not differ significantly at $P<0.05$ (Tukey test).
*, ** Treatment effects significant at $P<0.05$ and $P<0.01$, respectively.

temperature sensitivity, or Q_{10} values, fell within the 1.6–3.2 range observed for various soil types at temperatures from 10 to 40°C (Schlesinger 1977). As for k, the higher k observed at 10°C, relative to lower and higher incubation temperatures, is close to the average soil temperature of 11.0°C measured at the site during the growing season (June to September of 2009 to 2011). Because microbial communities adapt to their environment, their efficiency is often characterized by a temperature optimum corresponding to their natural climate (Dalias et al. 2001). Therefore, we interpret the k value to represent the optimal respiration conditions for the naturally occurring microbial community, since respiration did not increase at temperatures above the average soil temperature of 11.0°C at the site (15 and 20°C). Our results suggest that the optimal temperature for the soil microbial community was not changed by the three-year warming treatment.

Based on the calculated Q_{10} values, the 4°C difference maintained in heated plots for 3 yr corresponded to a 53.1% increase in respiration. Based on a calculated annual heterotrophic C efflux of 381.4 g C m^{-2} yr^{-1} in the LFH and first 20 cm of the mineral horizon at the site (Paré et al. 2006), this increase would correspond to an additional 132.3 g C m^{-2} respired annually. Such an increase without a concomittant increase in litter inputs would eventually reduce the mineralizable C pool. According to Paré et al. (2006), litterfall at the site (below and above ground) represents 283.5 g C m^{-2} yr^{-1}; thus, an additional 47% of litterfall would be required to compensate for the temperature-induced increase in respiration. In our study, 3 yr of soil heating significantly reduced that C pool by an average of 16–25%, a range that is consistent with results obtained for a hardwood forest (14–41%; Bradford et al. 2008) and with simulations for balsam fir forests (9–26%; Larocque et al. 2006). This reduction represents an average of 0.4–0.8% of the total SOC found in the organic and mineral horizons.

The quantities of N deposited on top of the canopy were small and had no detectable effect on the availability of soil inorganic N (D'Orangeville et al. 2013). Earlier studies conducted at the site with higher amounts of N fertilizer showed that soil available N concentration did not change with N fertilizer applications up to 57 kg N ha^{-1} yr^{-1} on the forest floor for 3 yr, and the short-term dilution of ^{15}N tracers demonstrated that the added mineral N was readily immobilized in the soil organic matter and 95% retained within the rooting zone (Ste-Marie and Houle 2006; Houle and Moore 2008). Contrary to our hypothesis, the effects of N fertilization on soil respiration were small or non-significant. Nitrogen additions in N-limited environments are generally expected to increase the amount of labile C, but the amounts of N added could have been too small to induce soil C mineralization. A recent N tracer experiment ($^{15}NH_4$–1^5NO_3 at 98% purity) conducted close to our experimental design has shown that 64–71% of the N deposited from the atmosphere was retained in the above-ground vegetation (Gélinas-Pouliot 2013). Thus, more time could be needed in order to detect an effect of increased N deposition on the soil C dynamics and composition.

As we hypothesized, 3 yr of in situ artificial soil warming in a boreal forest were sufficient to reduce the amount of labile organic C. However, the additional N deposited on top of the tree canopy did not exacerbate the depletion of the SOC. Whether the treatments could also have affected the microbial community structure, activity or composition remains to be determined.

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Berg, B. 2000. Litter decomposition and organic matter turnover in northern forest soils. For. Ecol. Manage. **133**: 13–22.

Bowden, R. D., Davidson, E., Savage, K., Arabia, C. and Steudler, P. 2004. Chronic nitrogen additions reduce total soil respiration and microbial respiration in temperate forest soils at the Harvard Forest. For. Ecol. Manage. **196**: 43–56.

Bradford, M. A., Davies, C. A., Frey, S. D., Maddox, T. R., Melillo, J. M., Mohan, J. E., Reynolds, J. F., Treseder, K. K. and Wallenstein, M. D. 2008. Thermal adaptation of soil microbial respiration to elevated temperature. Ecol. Lett. **11**: 1316–1327.

Conant, R. T., Ryan, M. G., Ågren, G. I., Birge, H. E., Davidson, E. A., Eliasson, P. E., Evans, S. E., Frey, S. D., Giardina, C. P., Hopkins, F. M., Hyvönen, R., Kirschbaum, M. U. F., Lavallee, J. M., Leifeld, J., Parton, W. J., Megan Steinweg, J., Wallenstein, M. D., Martin Wetterstedt, J. Å. and Bradford, M. A. 2011. Temperature and soil organic matter decomposition rates – synthesis of current knowledge and a way forward. Global Change Biol. **17**: 3392–3404.

Cook, B. D. and Allan, D. L. 1992. Dissolved organic carbon in old field soils: Total amounts as a measure of available resources for soil mineralization. Soil Biol. Biochem. **24**: 585–594.

D'Orangeville, L., Houle, D., Côté, B., Duchesne, L. and Morin, H. 2013. Increased soil temperature and atmospheric N deposition have no effect on the N status and growth of a mature balsam fir forest. Biogeosciences **10**: 4627–4639.

Dalias, P., Anderson, J. M., Bottner, P. and Coûteaux, M.-M. 2001. Temperature responses of carbon mineralization in conifer forest soils from different regional climates incubated under standard laboratory conditions. Global Change Biol. **7**: 181–192.

Davidson, E. A. and Janssens, I. A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature **440**: 165–173.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K. G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C. and Zeng, N. 2006. Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison. J. Clim. **19**: 3337–3353.

Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., Asner, G. P., Cleveland, C. C., Green, P. A., Holland, E. A., Karl, D. M., Michaels, A. F., Porter, J. H., Townsend, A. R. and Vöosmarty, C. J. 2004. Nitrogen cycles: past, present, and future. Biogeochemistry **70**: 153–226.

Gélinas-Pouliot, M. 2013. The fate of ^{15}N-labeled ammonium and nitrate applied on the trees canopy in a mature balsam fir stand, Québec. M.Sc. thesis, Université du Québec à Chicoutimi, Chicoutimi, QC.

Gillabel, J., Cebrian-Lopez, B., Six, J. and Merckx, R. 2010. Experimental evidence for the attenuating effect of SOM protection on temperature sensitivity of SOM decomposition. Global Change Biol. **16**: 2789–2798.

Hobbie, S. E., Nadelhoffer, K. J. and Högberg, P. 2002. A synthesis: The role of nutrients as constraints on carbon balances in boreal and arctic regions. Plant Soil **242**: 163–170.

Houle, D. and Moore, J.-D. 2008. Soil solution, foliar concentrations and tree growth response to 3-year of ammonium-nitrate addition in two boreal forests of Québec, Canada. For. Ecol. Manage. **255**: 2049–2060.

Houle, D., Bouffard, A., Duchesne, L., Logan, T. and Harvey, R. 2012. Projections of future soil temperature and water content for three southern Quebec forested sites. J. Clim. **25**: 7609–7701.

Larocque, G. R., Paré, D., Boutin, R., Robitaille, G. and Lacerte, V. 2006. Assessing a new soil carbon model to simulate the effect of temperature increase on the soil carbon cycle in three eastern Canadian forest types characterized by different climatic conditions. Can. J. Soil Sci. **86**: 187–202.

Luo, Y., Wan, S., Hui, D. and Wallace, L. L. 2001. Acclimatization of soil respiration to warming in a tall grass prairie. Nature **413**: 622–625.

Melillo, J. M., Butler, S., Johnson, J., Mohan, J., Steudler, P., Lux, H., Burrows, E., Bowles, F., Smith, R., Scott, L., Vario, C., Hill, T., Burton, A., Zhou, Y.-M. and Tang, J. 2011. Soil warming, carbon-nitrogen interactions, and forest carbon budgets. Proc. Nat. Acad. Sci. **108**: 9508–9512.

Neff, J. C. and Hooper, D. U. 2002. Vegetation and climate controls on potential CO_2, DOC and DON production in northern latitude soils. Global Change Biol. **8**: 872–884.

Paré, D., Boutin, R., Larocque, G. R. and Raulier, F. 2006. Effect of temperature on soil organic matter decomposition in three forest biomes of eastern Canada. Can. J. Soil Sci. **86**: 247–256.

Poirier, V., Angers, D., Rochette, P. and Whalen, J. 2013. Initial soil organic carbon concentration influences the short-term retention of crop-residue carbon in the fine fraction of a heavy clay soil. Biol. Fertility Soils **49**: 527–535.

R Development Core Team. 2012. R: A language and environment for statistical computing. R version 2.13.1. R Foundation for Statistical Computing, Vienna, Austria. [Online] Available: http://www.R-project.org.

Rey, A., Pegoraro, E. and Jarvis, P. G. 2008. Carbon mineralization rates at different soil depths across a network of European forest sites (FORCAST). Eur. J. Soil Sci. **59**: 1049–1062.

Rochette, P. and Bertrand, N. 2007. Soil-surface gas emissions. Pages 851–861 *in* M. Carter and E. G. Gregorich, eds. Soil sampling and methods of analysis. CRC Press, Boca Raton, FL.

Schlesinger, W. H. 1977. Carbon balance in terrestrial detritus. Annu. Rev. Ecol. Syst. **8**: 51–81.

Stanford, G. and Smith, S. J. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. J. **36**: 465–472.

Ste-Marie, C. and Houle, D. 2006. Forest floor gross and net nitrogen mineralization in three forest types in Quebec, Canada. Soil Biol. Biochem. **38**: 2135–2143.

Townsend, A. R., Vitousek, P. M., Desmarais, D. J. and Tharpe, A. 1997. Soil carbon pool structure and temperature sensitivity inferred using CO_2 and $^{13}CO_2$ incubation fluxes from five Hawaiian soils. Biogeochemistry **38**: 1–17.