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# The age of $CO_2$ released from soils in contrasting ecosystems during the arctic winter

Short communication

Date: 10th February 2013

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## Abstract

In arctic ecosystems, winter soil respiration can contribute substantially to annual $CO_2$ release, yet the source of this C is not clear. We analysed the $^{14}C$ content of C released from plant-free plots in mountain birch forest and tundra-heath. Winter-respired $CO_2$ was found to be a similar age (tundra) or older (forest) than C released during the previous autumn. Overall, our study demonstrates that the decomposition of older C can continue during the winter, in these two contrasting arctic ecosystems.

*Key words: $^{14}CO_2$, passive sampling, mountain birch, radiocarbon, tree-line, tundra-heath, winter respiration*

Arctic soils contain globally significant C stores (Post et al., 1982; Ping et al., 2008). As these areas are warming rapidly (AMAP, 2012), C may be lost if decomposition rates increase in response (Davidson and Janssens, 2006). There is growing recognition that the $CO_2$ released during the long winters in high-latitude/altitude ecosystems can represent a substantial proportion (up to 30%) of annual respiration (Elberling, 2007; Williams et al., 2009), but, for practical reasons, flux measurements are biased towards the growing season. Furthermore, debate continues as to whether the source of the $CO_2$ released during the winter is similar to that released during the summer, or is derived mainly from recently-fixed, labile C (Grogan et al., 2001; Grogan and Jonasson, 2005; Nobrega and Grogan, 2007). Importantly, climate change has greater potential to affect rates of winter respiration in the long term, either positively or negatively, if there is a substantial contribution from the large reserves of older SOM, than if most of the respired $CO_2$ is derived from small labile C pools (Jones et al., 2005; Hartley and Ineson, 2008). Here, by undertaking the first $^{14}C$ analyses of $CO_2$ released from soils during the arctic winter, we investigated whether the decomposition of older SOM continues during the winter.

The study took place in mountain birch forest (68°19'35"N, 18°50'00"E; elevation ~520 m) and tundra-heath (68°18'07"N, 18°51'16"E; elevation ~710 m), near Abisko, northern Sweden. We collected samples of $CO_2$ released over the 2007-2008 winter from three non-vegetated plots in each ecosystem. To allow only soil-respired $CO_2$ to be collected, the plots were clipped and trenched in late summer 2006. In the centre of each plot, 7-cm tall collars were sealed to the surface using putty, with respiration rates and $^{14}CO_2$ contents being monitored during the 2007 growing season (Hartley et al. 2012). To collect winter-respired $CO_2$, we developed a new technique using molecular sieve cartridges (MSCs) to collect passively (by diffusion) representative samples of $CO_2$ over extended time periods (Garnett et al., 2009).

In order to minimise chamber height and potential effects on snow lie, lids were directly placed on top of the collars. MSCs were then connected through the collar sides via auto-shut-off Quick Couplings™ (Colder Products Company, USA), with hydrophobic filters (Accurel PP V8/2 HF, Membrana GmbH, Germany) attached inside each collar to prevent liquid water passing into the MSCs (Fig. 1). For protection, the MSCs were then placed inside foam insulation, PVC pipes and guttering. The lids were closed on 16$^{th}$-17$^{th}$ September 2007 and the MSCs connected on 20$^{th}$ September. MSCs were recovered on 23$^{rd}$-24$^{th}$ May 2008. Air samples were collected at the tundra-heath site on 20$^{th}$ September 2007 and 24$^{th}$ May 2008, by pumping air through MSCs for approximately 60 minutes.

Soil temperatures at 5 cm were monitored throughout the winter (thermistor probes and CR10x datalogger, Campbell Scientific, Leics, UK). After MSC collection, soil temperatures at 2, 5 and 8 cm depth (digital thermometer, E.T.I. Ltd., West Sussex, UK) and soil moisture at 6 cm (Theta probe: ML2, Delta-T Devices, Cambridge, UK) were measured inside and outside the collars.

All $^{13}C$ and $^{14}C$ analyses were performed on $CO_2$ recovered from the MSCs using established procedures (Hardie et al., 2005). Following convention, $^{14}C$ results were normalised to a $\delta^{13}C$ value of -25 ‰ and expressed as %modern (Stuiver and Polach, 1977). Because collars were not inserted into the soil, it was not possible to avoid some atmospheric contamination. Samples were corrected for atmospheric contamination using the approach of Hartley et al. (2012), after accounting for the 4 ‰ $^{13}C$ fractionation associated with passive sampling (see Garnett et al., 2009).

After MSC collection, on the tundra, both soil moisture and temperature were near identical inside and outside the collars. In the forest, temperatures at 5 and 8 cm were 0.6-0.7$^{o}$C higher within the collar, but there was no significant effect on soil moisture. Therefore, the chambers appeared to have little effect on the soil physical environment. During the winter, temperature at 5 cm was greater in the forest (mean: 0.07$^{o}$C, range: -3.02$^{o}$C to 6.94$^{o}$C) than the tundra (mean: -1.73$^{o}$C, range: -7.18$^{o}$C to 4.66$^{o}$C). Warmer winter temperatures can increase winter $CO_2$ production, and thus influence annual carbon balances (Grogan and Jonasson, 2006; Nobrega and Grogan, 2007; Sullivan, 2010), potentially contributing to the lower C storage in forest than tundra soils. However, it should be emphasised that previous research at the current field sites (Hartley et al., 2012), as well as studies at lower latitudes (Mitchel et al., 2007), have identified the important role plant-soil interactions and priming play in controlling soil carbon storage in forest-heath transitions.

Consistent with warmer temperatures increasing winter respiraton, our molecular sieves collected more $CO_2$ in the forest than tundra (means of 102.3 ml and 71.8 ml, respectively). However, the amount of $CO_2$ collected on our MSCs depends on the average $CO_2$ concentration within the chamber (Garnett et al., 2009). This is controlled not only by respiration rates, but also by rates of exchange between the atmosphere and the headspace, which may have been greater on the tundra due to higher wind speeds and reduced snow cover; atmospheric contamination was greater in tundra samples (Table 1). Therefore, volumes collected cannot be translated directly into respiration rates.

On the tundra, the $^{14}C$ content of the $CO_2$ respired during the winter was similar to that collected the previous September (Fig. 2), while in the birch forest, the $^{14}C$ content of winter-respired $CO_2$ was significantly greater than at any point during the growing season. Mean residence time modelling, based on soil $^{14}C$ measurements, indicated that C fixed before the 1950s should contribute only a small proportion to total $CO_2$ release (Hartley et al., 2012). Therefore, the increase in the $^{14}C$ content of the winter-respired $CO_2$ in the birch forest indicates that more 'older' C, enriched in $^{14}C$ from 20$^{th}$ century nuclear weapons testing, was being released (Fig. 2). This was possibly caused by the gradual loss of recently-fixed, labile C which would have been relatively $^{14}C$-depleted (atmospheric $CO_2$ = 105.15 %modern). This process may have been more pronounced in the forest due to both the smaller soil C stocks and the greater inputs of contemporary C associated with the higher plant productivity (Hartley et al. 2012). Overall, our results indicate that the decomposition of decade-old SOM can continue during the protracted arctic winter in both forest and tundra ecosystems (Table 1). The fact that such C can be released during the Arctic winter makes it possible for changes in winter conditions to affect substantially the C balance of arctic ecosystems. Finally, in the future, comparative analyses of the $CO_2$ released from both plant-free and vegetated plots, would help further identify the sources of winter-respired $CO_2$ in intact Arctic ecosystems.

**Acknowledgements**

This work was carried out within the UK Natural Environment Research Council (NERC) funded Arctic Biosphere Atmosphere Coupling at Multiple Scales (ABACUS, www.abacus-ipy.org) project (a contribution to International Polar Year 2007e2008). The additional 14C analyses carried out for this paper were funded through an award from the NERC Radiocarbon Facility steering committee (reference number 1281.0408). We are also very grateful for the help of the staff at the Abisko Scientific Research Station.We thank Jonathan Evans (CEH Wallingford) for collecting the long-term soil temperature data.

**References**

AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

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

Elberling, B., 2007. Annual soil $CO_2$ effluxes in the High Arctic: the role of snow thickness and vegetation type. Soil Biology and Biochemistry 39, 646–654.

Garnett, M.H., Hartley, I.P., Hopkins, D.W., Sommerkorn, M., Wookey, P.A., 2009. A passive sampling method for radiocarbon analysis of soil respiration using molecular sieve. Soil Biology and Biochemistry 41, 1450-1456.

Grogan, P., Illeris, L., Micelsen, A., Jonasson, S., 2001. Respiration of recently-fixed plant carbon dominates mid-winter ecosystem $CO_2$ production in sub-arctic heath tundra. Climatic Change 50, 129–142.

Grogan, P., Jonasson, S., 2005. Temperature and substrate controls on intra-annual variation in ecosystem respiration in two subarctic vegetation types. Global Change Biology 11, 465–475.

Grogan, P., Jonasson, S., 2006. Ecosystem $CO_2$ production during winter in a Swedish subarctic region: the relative importance of climate and vegetation type. Global Change Biology 12, 1479–1495.

Hardie, S.M.L., Garnett, M.H., Fallick, A.E., Rowland, A.P., Ostle, N.J., 2005. Carbon dioxide capture using a zeolite molecular sieve sampling system for isotopic studies ($^{13}C$ and $^{14}C$) of respiration. Radiocarbon 47, 441-451.

Hartley, I.P., Garnett, M.H., Sommerkorn, S., Hopkins, D.W., Fletcher, B.J., Sloan, V.L., Phoenix, G.K., Wookey, P.A., 2012. A potential loss of carbon associated with greater plant growth in the European Arctic. Nature Climate Change, 2, 875-879.

Hartley, I.P., Ineson, P., 2008. Substrate quality and the temperature sensitivity of soil organic matter decomposition. Soil Biology and Biochemistry 40, 1567-1574.

Jones, C., McConnell, C., Coleman, K., Cox, P., Falloon, P., Jenkinson, D., Powlson, D., 2005. Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. Global Change Biology 11, 154-166.

Levin, I., Hammer, S., Kromer, B., Meinhardt, F., 2008. Radiocarbon observations in atmospheric $CO_2$: Determining fossil fuel $CO_2$ over Europe using Jungfraujoch observations as background. Science of the Total Environment 391, 211-216.

Mitchell, R.J., Campbell, C.D., Chapman, S.J., Osler, G.H.R., Vanbergen, A.J., Ross, L.C., Cameron, C.M., Cole L., 2007. The cascading effects of birch on heather moorland: a test for the top-down control of an ecosystem engineer. Journal of Ecology 95, 540–554.

Nobrega, S., Grogan, P., 2007. Deeper snow enhances winter respiration from both plant-associated and bulk soil carbon pools in birch hummock tundra. Ecosystems 10, 419–431.

Ping, C.L., Michaelson, G.J., Jorgenson, M.T., Kimble, J.M., Epstein, H., Romanovsky, V.E., Walker, D.A., 2008. High stocks of soil organic carbon in the North American Arctic region. Nature Geoscience 1, 615–619.

Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones. Nature 298, 156–159.

Stuiver, M., Polach, H.A., 1977. Reporting of $^{14}C$ data. Radiocarbon 19, 355-363.

Sullivan PF (2010) Snow distribution, soil temperature and late winter $CO_2$ efflux from soils near the Arctic treeline in northwest Alaska. Biogeochemistry 99, 65–77.

Williams, M.W., Helmig, D., Blanken, P., 2009. White on green: under-snow microbial processes and trace gas fluxes through snow, Niwot Ridge, Colorado Front Range. Biogeochemistry 95, 1–12.

**Table 1**

The $^{14}C$ content and $\delta^{13}C$ values of samples collected from the tundra-heath and birch forest, with associated measurement uncertainty ($\pm 1\sigma$) and radiocarbon laboratory codes. The $\delta^{13}C$ values have been corrected for fractionation during passive sampling (Garnett et al., 2009). The $^{14}C$ content of the respired $CO_2$ was calculated after correction for contamination with atmospheric $CO_2$ based on the average $\delta^{13}C$ value of the atmospheric $CO_2$ at the site, and the $\delta^{13}C$ of pure samples of respired $CO_2$ collected from monoliths incubated on site in closed containers (see Hartley et al., 2012). The average age of the respired $CO_2$ (relative to the sampling date) was calculated from its bomb-$^{14}C$ concentration by reference to records of direct atmospheric $^{14}CO_2$ measurements (Levin et al., 2008).

| Site | $^{14}C$ (%modern) | Collected $CO_2$ Measured $\delta^{13}C$ | Corrected $\delta^{13}C$ | Lab code | Monolith $\delta^{13}C$ ratio | Atmospheric $CO_2$ $^{14}C$ (%modern) | Atmospheric $CO_2$ $\delta^{13}C$ ratio | Atmospheric Fraction | Respired $CO_2$ $^{14}C$ (%modern) | Age (years) |
|---|---|---|---|---|---|---|---|---|---|---|
| Tundra | 108.30±0.51 | -24.4±0.1 | -20.4 | SUERC-19528 | -26.60 | 105.16 | -8.8 | 0.350 | 109.98 | 9 |
| Tundra | 108.19±0.48 | -25.3±0.1 | -21.3 | SUERC-19529 | -26.60 | 105.16 | -8.8 | 0.300 | 109.49 | 8 |
| Tundra | 108.61±0.51 | -24.4±0.1 | -20.4 | SUERC-19532 | -26.60 | 105.16 | -8.8 | 0.349 | 110.46 | 10 |
| Forest | 108.70±0.51 | -24.0±0.1 | -20.0 | SUERC-19533 | -26.83 | 105.16 | -8.8 | 0.380 | 110.86 | 11 |
| Forest | 109.67±0.49 | -26.5±0.1 | -22.5 | SUERC-19534 | -26.83 | 105.16 | -8.8 | 0.243 | 111.12 | 11 |
| Forest | 110.25±0.52 | -26.2±0.1 | -22.2 | SUERC-19535 | -26.83 | 105.16 | -8.8 | 0.259 | 112.04 | 13 |

**Figure legends**

**Fig. 1.** Photographs showing the installation of one of the systems for passively sampling soil respiration during the arctic winter. Panel (a) shows the hydrophobic filter inside the collar cover, prior to lid being attached. Panel (b) shows the MSC cartridge being attached, before the clips were removed, while panel (c) shows the final arrangement after the cartridge has been covered in insulating foam, protected inside pipe and plastic guttering, pegged in place, taped up and surrounded by stones. Although the sampling system was only 7 cm tall, the stones were arranged to smooth out the vertical profile and minimise any impact on snow drifting patterns.

**Fig. 2.** The bars indicate the $^{14}C$ content of the $CO_2$ respired from two sites during the winter. Mean values ±1SE are shown (n = 3). The $^{14}C$ contents of the $CO_2$ released during the previous growing season are also indicated (May/June, light grey line; July, dark grey line; September, black line; see also Hartley et al., 2012). The dashed line indicates the $^{14}C$ content of the $CO_2$ in the contemporary atmosphere (~105.16% modern. On the tundra-heath, the $^{14}C$ content of the winter respired $CO_2$ did not significantly differ from the growing season measurements made in July and September [All statistical tests were carried out using the SPSS version 16 (SPSS Science, Birmingham, UK)]. In contrast, in the birch forest, the '*' indicates that the winter respired $CO_2$ was significantly enriched in $^{14}C$ compared with all growing season measurements ($P < 0.05$, repeated measures ANOVA). The winter respired $CO_2$ was also significantly more enriched in $^{14}C$ in the birch forest compared with the tundra-heath ($P < 0.05$, *t*-test).

Fig. 1.

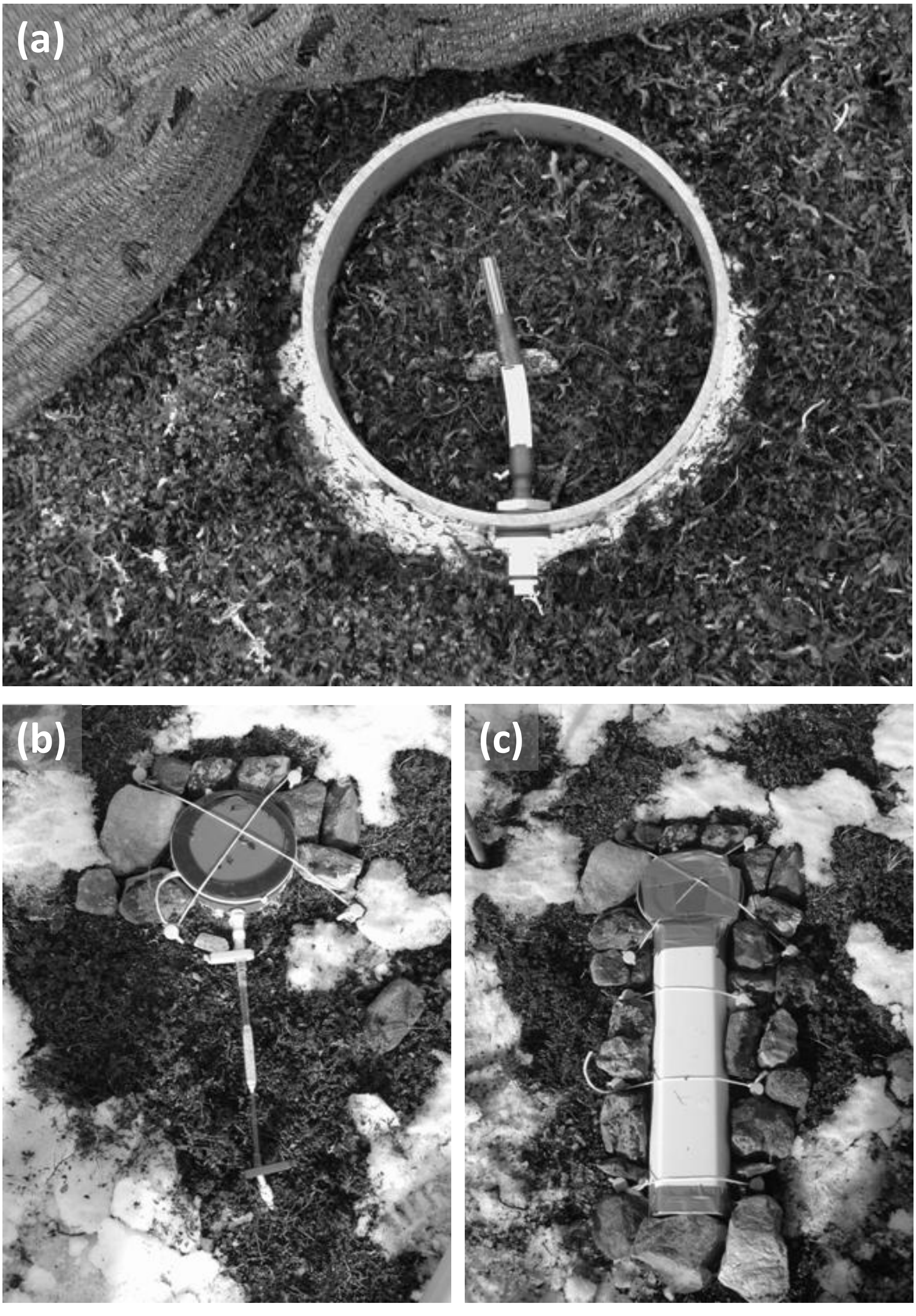
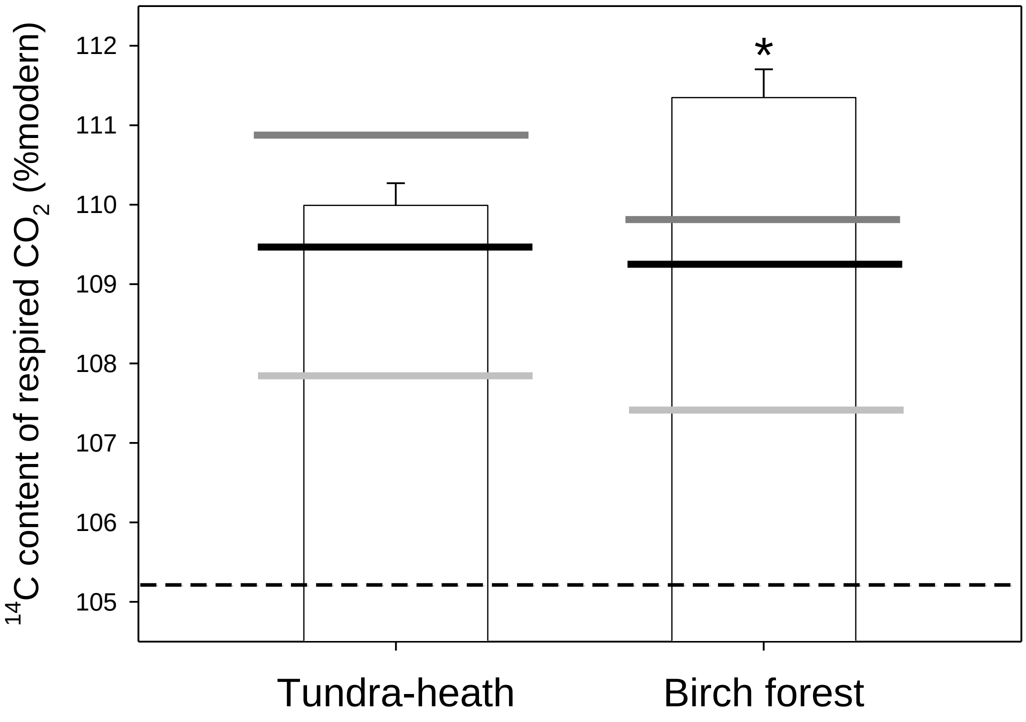


Fig. 2.


14C content of respired CO2 (%modern)
112
111
110
109
108
107
106
105
*
Tundra-heath
Birch forest