Permafrost Thawing and Vegetation Change Effects on Cryoturbation Rates and C and CH4 Dynamics

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Introduction

Permafrost soils cover 8.6% of the Earth land area but contain 50% of the global soil organic carbon (SOC) pool, 20-25% of which may be stored in the upper 30 cm, making it highly vulnerable to changes in climate. Predicted warming in northern latitudes may lead to strong forcing feedbacks on the climate system. Cryoturbation in permafrost results in the mixing of soil during freeze-thaw cycles. Cryoturbation rates are predicted to be affected during Arctic warming at centurial time scales and therefore affect the C storage capacity of permafrost soils. It has been shown that the C content in the active layer of cryoturbated soils can be roughly 60% higher than in non-cryoturbated ones. However other cryogenic processes can affect the Arctic soil C pool at shorter time scales. For instance, warming may lead to increases winter precipitation resulting in a deeper snow cover with consequent thermal insulation of Arctic soils. Warmer soils may elicit summer and winter decomposition rates decreasing the SOC pool.

During the first months of the project we developed a method to measure the soil carbon effects of snow pack accumulation on Arctic SOC dynamics in a moist acidic tundra by exposing soils to experimental accumulated snow pack (using fence experiments, Toolik Lake) in order to increase soil thermal insulation. Radioisotope tracers (natural and weapon derived) were used to identify changes in geomorphology and assess the effects of thermal insulation on SOC dynamics.

Methodology

Our study utilized the long- and short-term snow depth manipulation experiments of Welker and colleagues (Welker et al. 2000, 2005) as part of the ITEX (International Tundra Experiment), IPY (International Polar Year) and AON (Arctic Observing Network). The experimental set was designed to simulate the increased precipitation patterns and continuous snow-cover episodes predicted under a global warming scenario (*see below*). We used archived samples from moist acidic tundra (68^{o}37'N, 149^{o}32'W) near Toolik Lake in 2008. Two sites were sampled: a) long-term (14-years) and b) short-term (2-years) deep snow-cover. At each plot four soil cores were collected from the short- and long-term snowfence experiment drifts and corresponding control sites to average thaw depth.

Each soil core was sectioned into 1-cm depth increments to obtain the vertical distribution of ^{137}Cs (man-made radioisotope deposited at the surface with atmospheric peak in 1964) and ^{40}K (naturally occurring and mobile radiochemical species) to account for leaching and hydrological effects on Cs^{+} using gamma ray counting analysis (Model GR3020-Reverse electrode). We also analyzed unsupported

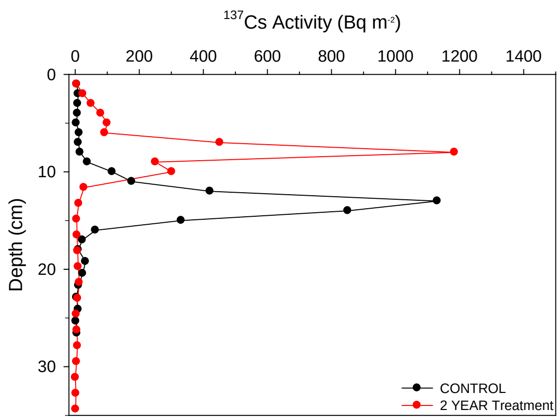
210Pb, a radioisotope derived from radon that is deposited on the surface at a constant annual rate. Data were corrected to account for soil compression at the organic and mineral horizons during sampling. After counting, acid washed samples were run for Organic Carbon (OC) using an Elemental Analyzer with a zero-blank autosampler (Costech Analytical, USA). The density of OC along the soil profile was measured as:

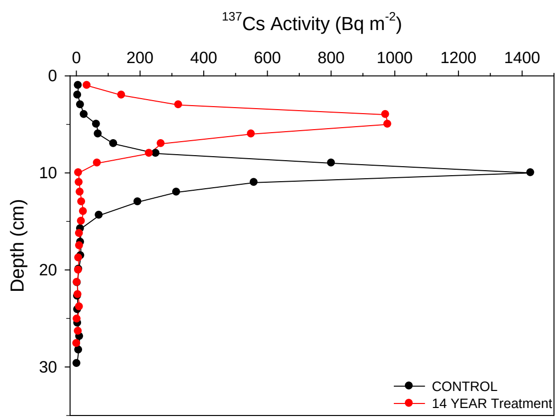
$$\text{OC Density}_n\ (\text{Kg}\cdot\text{m}^{-2}) = \text{Bulk Density}_n\ (\text{g}_{DW}\cdot\text{cm}^{-3}) \cdot \%\ \text{C}_n \cdot \text{Interval depth (cm)} /10$$

Stable and radioisotopes of C in soil organic matter were also analyzed using isotope ratio mass spectrometry and accelerator mass spectrometry, respectively.

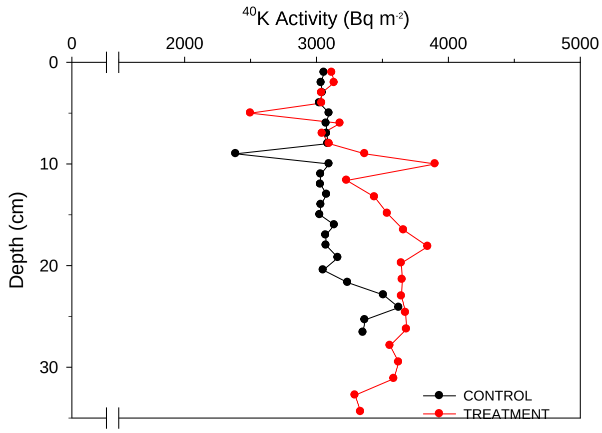
<u>Results to Date</u>

The soil vertical ^{137}Cs activity profile was dramatically altered in the snow manipulation treatment sites likely due to compression by higher snow pack. As a result the organic layer was compressed by 6 ± 0.1cm at the 2-year treatment site (Fig 1) and by 4.9 ± 0.3cm at the 14-year treatment (Fig 2) site when compared to control sites. This suggests that increased snowpack leads to compression of the organic layer exposing deeper C to the surface, which may be more vulnerable to microbial decomposition.

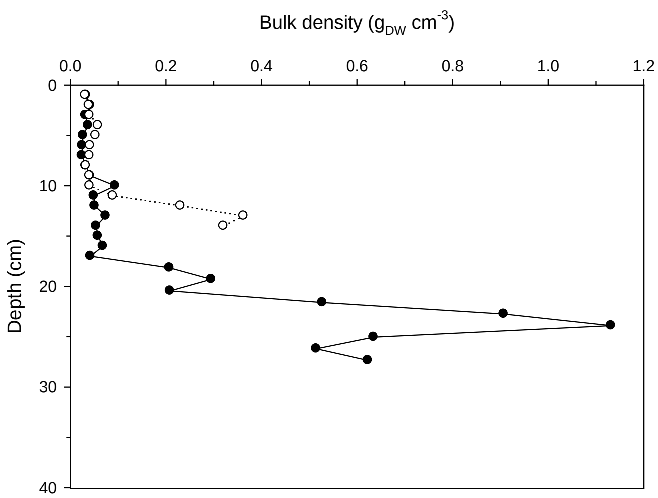




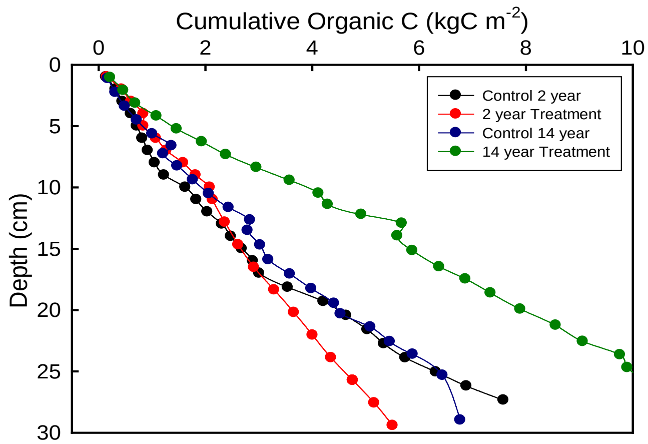
The distribution of ^{40}K along the soil profile was independent of that of ^{137}Cs, indicating that physical processes (as oppose to hydrological or biological) are responsible for ^{137}Cs re-distribution within the soil in response to increased snowpack treatments.



Increased Bulk density (BD, Fig 3) at the surface organic layers was observed in both short- and long-term snow accumulation sites compared to control ones (p<0.05). Bulk Density increased up to 4-fold in the long-term and up to 2-fold in the short-term experiment when compared to control sites. These results indicate a progressive compression of surface organic layers as a result of increased snow winter pack and it is consistent with the radionuclide profiles (Fig 1).



Cumulative Organic Carbon density (Fig 4) within the top 30cm significantly increased (p<0.01) at the long-term treatment site compared to the control one, whereas no significant changes were found between short-term treatment and corresponding control site (p=0.68). This suggests that increased soil thermal insulation will not necessarily result in a net C-lost across the first 30cm of the organic layer after more than a decade of treatment.



<u>Discussion</u>

The compression of the organic layer by accumulated winter snow increases bulk density and brings deeper C to the surface (Tables 1 and 2). Based on a 0-10 cm depth, increased snow pack and resulting thermal insulation would seem to lead to higher SOC content (~30%) at treatment sites (T) when compared to controls (C; Table 1). However, comparisons of SOC by soil depth are not appropriate. When SOC is compared at equal cumulative ^{137}Cs activity (*i.e.* depth corrected for organic layer compression) a large loss of shallow C in treatment sites is revealed (~50). A depth-based comparison will induce a substantial error on SOC estimates in response to thermal insulation treatments.

	C accounting based on depth		C accounting based on ^{137}Cs profiles affected by increased snow depth			
	At 0-10 cm		At 6.74% ^{137}Cs activity		At 96.5% ^{137}Cs activity	
	% ^{137}Cs activity	kgC m^{-2}	kgC m^{-2}	Depth (cm)	kgC m^{-2}	Depth (cm)
Control (C)	6.74	1.63	1.63	10	2.96	16.61
2-year (T)	96.49	2.08	0.84	4.19	2.08	10
T-C	+0.46 kgC m^{-2}		-0.78 kgC m^{-2}		-0.88 kgC m^{-2}	

As in the case of the 2yr treatment, comparing SOC by depth in the 14 year snow fence experiment is not adequate (SOC at a 0-10cm deep will overestimate thermal effects at treatment (T) compared to control sites (C) by 75%). At shallow depths (10 cm for C and 5.3cm for T) there is still a net loss of C although as in the case of the 2 yr experiment, but much smaller in magnitude. However, at 96% cumulative ^{137}Cs activity (~5 decades of SOC) there is a net gain of SOC after 14 years of snow-pack thermal insulation treatment when compared to control sites (Table 2), suggesting that most of the C lost initially is recovered at decadal time scales as shown on the incorporation of modern 14C in the 14yr treatment with respect to the 2yr and control plots in the top 15-20cm (Fig 5).

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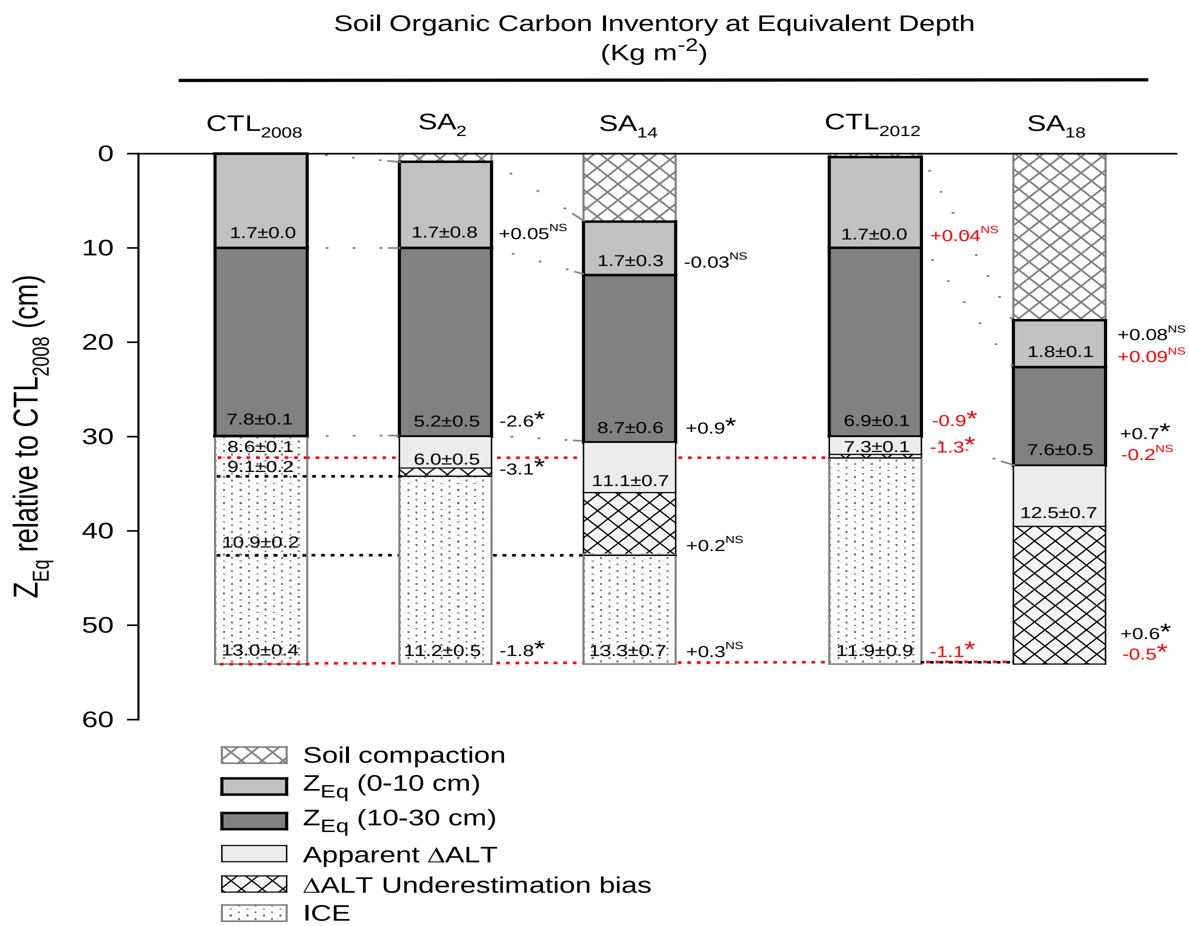
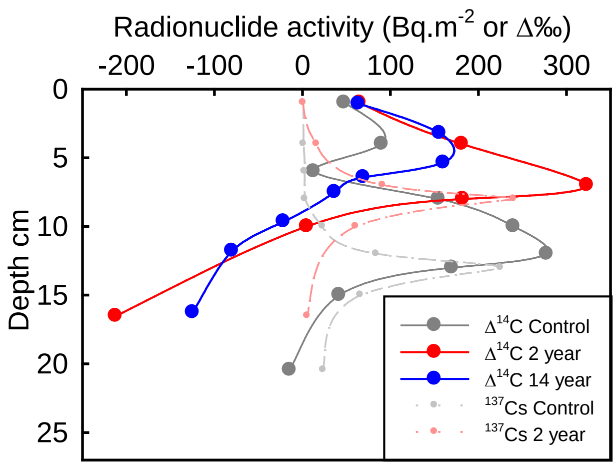


Radiocarbon data suggest that recovery of initially lost SOC stocks after 14 years of treatment is likely to be the result of the addition of new C as $\Delta^{14}C$ values decreased at above the ^{137}Cs peak and increased below the ^{137}Cs peak.



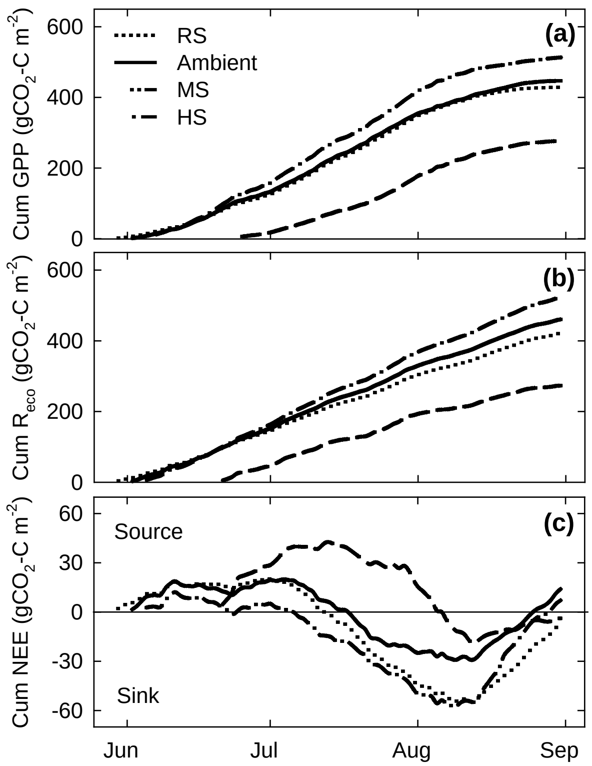
<u>Conclusions to date</u>:

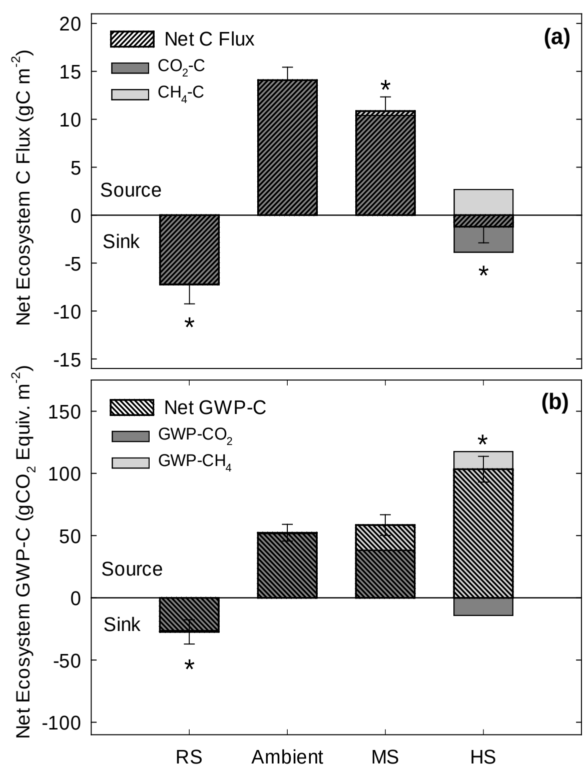
- Snowpack accumulation results in an apparent compression of organic horizons in moist acidic tundra sites. Compression of the organic layer exposes deeper C to the surface enhancing the decomposition of shallow C (perhaps including winter decomposition). However, most of the SOC lost can be recovered within a few decades. Because of the compression of the organic layer with experimental increases in winter precipitation, depth comparisons will induce a substantial error on SOC estimates in response to thermal insulation treatments (Tables 1&2).

- Fallout radionuclides are a viable alternative to establish SOC comparisons in systems affected by various levels of snow pack accumulation and consequent thermal insulation (Figs 1&2). Radiocarbon measurements (Fig.5) support the notion of organic matter compression.

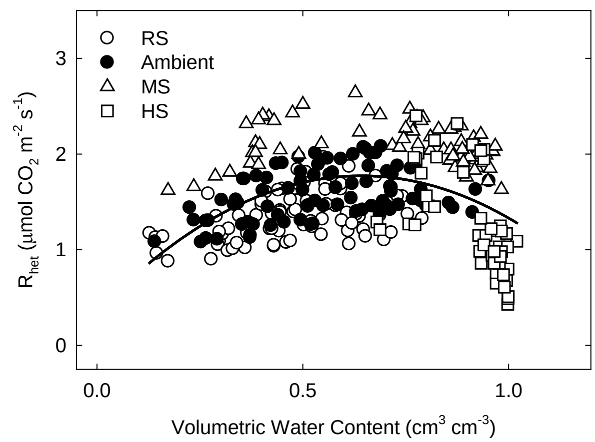
Gas Exchange and CO2 and CH4 dynamics

Projected changes in winter precipitation accompanying future warming may lead to major climate/C-cycle feedbacks from Arctic regions. However, the sign, magnitude and form (CO_2 and CH_4) of C fluxes and derived climate forcing (i.e. global warming potential - GWP) from Arctic tundra under future precipitation scenarios remain unresolved. We investigated how 18-yrs of experimental snow depth increases and decreases affects ecosystem C fluxes (figure 6), and GWP (figure 7) of moist acidic tundra over the growing season. The response of Arctic tundra C fluxes to snow accumulation was markedly non-linear and was dominated by impacts on ecosystem CO_2 dynamics. Both reduced- (RS, –15-30%) and increased- (MS, +20-45%; HS, +70-100%) winter snow decreased the Arctic tundra CO_2 source strength relative to Ambient, reducing net ecosystem C losses over the growing season. The ecosystem CO_2 source strength responded to constraints on heterotrophic respiration (R_{het}) by 1- temperature limitation within colder soils at RS, and 2- by snow- and thaw-induced increases in soil moisture (Figure 8). Soil moisture increases promoted anaerobic metabolism and dampened the temperature sensitivity of R_{het} at MS and HS. Heterotrophic respiration was less affected by changes in available SOC and decomposability of organic matter. Increase soil moisture enhanced CH_4 emissions within wetter soils increased the GWP of Arctic tundra at MS and HS despite decreases in Arctic tundra C losses (figure 7). Our results further suggest certain ecosystem productivity resilience to altered snow accumulation regimes. Shifts in plant community composition and canopy structure rather than physiological adjustments cause the changes seen in net ecosystem exchange. Overall, our findings indicate the potential of Arctic tundra to dampen C losses but significantly contribute to the ecosystem GWP (because of CH4) under future precipitation scenarios. We argue that an improved conceptualization and adequate parameterization of the response of Arctic tundra to projected changes in precipitation would help reduce current uncertainty of climate/C-cycle feedbacks from the Arctic region.





In summary, deeper winter snow reduced the C source strength but increased the GWP of Arctic tundra over the growing season. Our results suggest that the mechanisms underlying the response of Arctic tundra C balance to altered winter precipitation patterns diverge in some important ways from the binary conceptualization of Arctic C dynamics under future climate scenarios (climate change attenuation by warming-induced productivity or amplification by warming-induced mobilization of permafrost C). Increases in the Arctic tundra C sink strength resulted from impacts on the predominant microbial function and activity rather than from enhanced plant productivity, and variations in heterotrophic soil activity responded primarily to temperature constraints under reduced snow, and to enhanced soil wetness rather than on changes in C availability or decomposability with deeper snow. Notably, in contrast with model estimates predicting a large attenuating effect of climate-driven Arctic C losses from increased plant productivity associated with shrub expansion and enhanced greenness, net ecosystem exchange responded to snow treatments by shifting plant community composition. Overall, our findings indicate the potential of Arctic tundra to reduce C losses but significantly contribute to the ecosystem GWP under future climate scenarios. However, the sign and magnitude of these feedbacks hinge on intensity of the disturbance and operating time spans. Predictions of climate/C-cycle feedbacks from Arctic regions would greatly benefit from improved representations of the timing and intensity of changes in winter precipitation and impacts on soil hydrology.



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