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Continuous measurement of soil carbon efflux with Forced Diffusion (FD) chambers in a tundra ecosystem of Alaska

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HIGHLIGHTS

- Continuous monitoring of soil CO_2 efflux is accommodated by a Forced Diffusion (FD) chamber system in all locations and weather conditions.
- Temperature and thaw depth are important parameters for influencing soil CO_2 emissions.
- Growing and non-growing season simulated soil carbon represent 75.7 and 24.3% of annual carbon emissions, respectively.
- Annual CO_2emission with FD chamber would be an effective for quantifying growing and non-growing seasons soil carbon budget in the Arctic.

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ABSTRACT

Soil is a significant source of CO_2 emission to the atmosphere, and this process is accelerating at high latitudes due to rapidly changing climates. To investigate the sensitivity of soil CO_2 emissions to high temporal frequency variations in climate, we performed continuous monitoring of soil CO_2 efflux using Forced Diffusion (FD) chambers at half-hour intervals, across three representative Alaskan soil cover types with underlying permafrost. These sites were established during the growing season of 2015, on the Seward Peninsula of western Alaska. Our chamber system is conceptually similar to a dynamic chamber, though FD is more durable and water-resistant and consumes less power, lending itself to remote deployments. We first conducted methodological tests, testing different frequencies of measurement, and did not observe a significant difference between collecting data at 30-min and 10-min measurement intervals (averaged half-hourly) ($p < 0.001$).
Temperature and thaw depth, meanwhile, are important parameters in influencing soil carbon emission. At the study sites, we observed cumulative soil CO_2 emissions of 62.0, 126.3, and 133.5 gC m^{-2} for the growing period, in sphagnum, lichen, and tussock, respectively, corresponding to 83.8, 63.7, and 79.6% of annual carbon emissions. Growing season soil carbon emissions extrapolated over the region equated to 0.17 $\pm$ 0.06 MgC over the measurement period. This was 47% higher than previous estimates from coarse-resolution manual chamber sampling, presumably because it better captured high efflux events. This finding demonstrates how differences in measurement method and frequency can impact interpretations of seasonal and annual soil carbon budgets. We conclude that annual CO_2 efflux-measurements using FD chamber networks would be an effective means for quantifying growing and non-growing season soil carbon budgets, with optimal pairing with time-lapse imagery for tracking local and regional changes in environment and climate in a warming Arctic.

1. Introduction

Northern High Latitudes are currently experiencing climate and environment changes including increasing temperatures, degrading permafrost, changing snow cover extent, northward movement of shrub communities, and extended vegetative growing seasons (Sturm et al., 2001; ACIA, 2004; AMAP, 2011; Bhatt et al., 2013; Lawrence et al., 2015; Natali et al., 2015). For example, recent summer warming in Arctic Alaska has accelerated. The mean annual air temperature of Nome, western Alaska has increased by 0.73 °C over the last century (National Weather Service, NOAA), and 0.3–0.4 °C of this change has occurred during the past few decades (Chapin et al., 2005). Annual precipitation in Nome has also decreased by 14%, and snow depth has

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increased by 25% (National Weather Service, NOAA), which will translate to warmer soil temperatures via the insulating snow layer.

These changes influence the high-latitude terrestrial carbon cycle, via changes in vegetation productivity (Euskirchen et al., 2006; Barr et al., 2007) and decomposition of soil organic matter (Piao et al., 2007; Wu et al., 2012). Soil CO_2 efflux, produced through the decomposition of soil organic carbon and roots, signifies the second largest terrestrial carbon source on both time and space scales (Raich and Schlesinger, 1992; Schlesinger and Andrews, 2000). Of the changes documented in the Arctic, the increase in temperature is most important, as it drives positive feedbacks on regional and pan-Arctic scales (Chapin et al., 2000; ACIA, 2005; Chapin et al., 2005). Soil carbon dynamics in tundra and boreal forest ecosystems exhibit strong temperature dependence, and is characterized by Q_{10} value, which describes the increase in respiratory rate with a given 10 °C temperature change (Xu and Qi, 2001; Davidson and Janssens, 2006; Bond-Lamberty and Thomson, 2010; Mahecha et al., 2010; Kim et al., 2013, 2014a; Kim, 2014). Bond-Lamberty and Thomson (2010) estimated the global soil respiration rate at 98 ± 12 GtC (1 GtC $= 10^{15}$ gC), indicating an increase of 0.1 GtC year^{-1} over two decades. This rate of increase suggests a CO_2 emission response factor of 1.5 compared to air temperature, which is consistent with enhanced soil CO_2 emission response to a warming global climate.

In Alaska, soil temperature regulates seasonal variations in soil CO_2 efflux, and soil moisture has also been found to affect the inter-annual variation in soil CO_2 emission in a study of two growing seasons by Kim et al. (2014a). In that study, emissions during the wet growing season had been suppressed by 27% compared to the dry summer season, due to higher soil moisture from severe rain (Dunn et al., 2006; Kim et al., 2014a).

The interpreted rates of soil CO_2 efflux are affected, of course, by the spatiotemporal intensity of monitoring, and also by differences in measurement methodology. For example, methodological factors such as chamber size (e.g., active cross-section), measurement frequency (e.g., hourly, weekly, seasonal, and annual), and efflux-measuring system type (e.g., manual or automated chamber) may each affect emissions accounting (Davidson et al., 2002; Savage and Davidson, 2003). Normally, different methodologies are used for different purposes, and manual chamber systems are traditionally used to capture spatial heterogeneity, while automated chamber systems offer much improved measurement frequency during snow-free periods (Davidson et al., 2002; Savage and Davidson, 2003). The impact of temporal sampling frequency is particularly important in studies seeking to account for emissions across the year. Darenova et al. (2014) compared manual and continuous measurements of soil CO_2 efflux, and found that interpreted Q_{10} values were significantly different between datasets because of the difference in measurement frequency. They were able to demonstrate that total seasonal carbon emission simulated by continuous soil temperatures differed by as much as 7.2% from continuously measured data. Annual and/or seasonal soil carbon emissions have been estimated in several studies on the basis of manual measurements over periods as short as some days, and up to many months (Davidson et al., 1998; Epron et

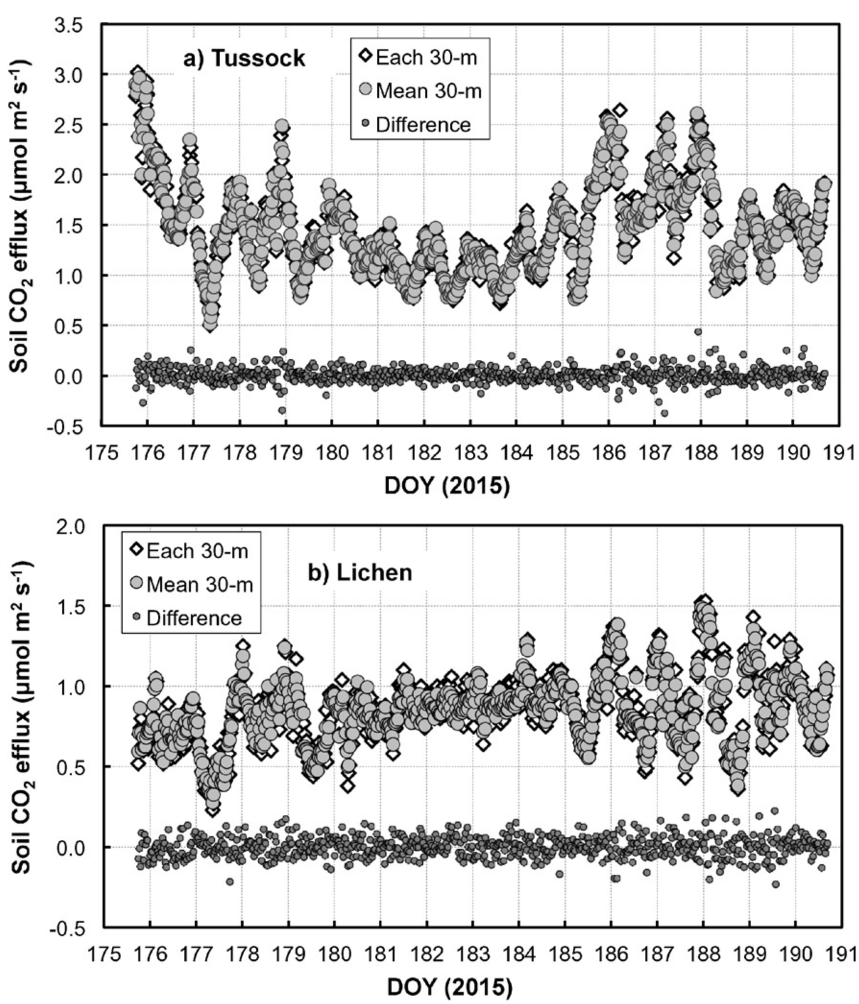

Fig. 1. Temporal variations in CO_2 effluxes at 30-min (diamonds) and 10-min (averaged half-hourly) (grey circles) measurement intervals in (a) tussock and (b) lichen over fifteen days. There is no difference (small circles) between the 30-min interval and mean 30-min at a 10-min interval, suggesting no significant difference based on a one-way ANOVA at the 95% confidence level ($p < 0.001$).