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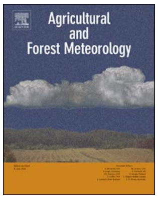

Using a Bayesian framework to account for advection in seven years of snowpack CO_2 fluxes in a mortality-impacted subalpine forest

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ABSTRACT

In subalpine forests where snowpacks can persist for 50% of the year or longer, wintertime subnivean soil respiration constitutes a significant, but poorly understood, portion of the carbon (C) cycle. The temporal and seasonal dynamics of this flux are difficult to measure compared to snow-free respiration. This makes it challenging to fully address key knowledge gaps in high-elevation forests, including effects of tree mortality on ecosystem C fluxes. Our paper attempts to overcome these challenges by developing a new method for estimating wintertime CO_2 flux from soil underneath winter snowpack based on CO_2 profiles in the snow and using this to examine potential effects of a tree mortality event on wintertime respiration. The chief problem for estimates based on snow CO_2 measurements is that during strong winds, vertical CO_2 profiles can depart significantly from linearity, resulting in CO_2 fluxes that are not steady-state diffusive fluxes. Consequently, these fluxes include an advective component induced by wind and atmospheric pressure, resulting in above-snowpack fluxes that may be temporally decoupled from biological flux production in the soil. These advective fluxes lead to errors in estimates of the total amount of CO_2 produced from the soil surface during the winter, and may complicate the detection of significant seasonal and interannual trends in snowpack CO_2 fluxes. Our goal was twofold: first, to improve methods for estimating wintertime subnivean soil respiration; and second, to use this new method to examine potential effects of forest mortality on respiration. We develop a Bayesian-based model of CO_2 snowpack profiles and accounts for CO_2 storage flux within the snowpack to calculate diffusive and advective fluxes from both the bottom and the top of the snowpack. We apply this model to hourly snowpack CO_2 profile data collected over 7 years at an AmeriFlux eddy covariance (EC) site in a Wyoming subalpine forest that had recently experienced a mass tree mortality event. Hourly advective fluxes from the snowpack surface are less variable over time than hourly EC fluxes. Nonetheless, on a daily time scale, the two methods agree well with each other. We found that soil biological CO_2 production entering the bottom of snowpack peaked 3 years after the onset of the bark beetle outbreak and 1-year after dead trees dropped their needles, presenting the first evidence of a short-term increase in respiration following bark beetle mortality. Our findings emphasize the importance of accounting for the role of wind-driven advection in wintertime respiration and suggest that tree mortality may nearly double wintertime respiration in the first few years.

1. Introduction

Soil respiration, from plant roots and soil heterotrophs, is an indispensable measurement for terrestrial carbon (C) cycle research, but characterizing its variability across time and space is often a challenge (Ryan and Law, 2005; Phillips et al., 2016). Automated measurement techniques have allowed higher-resolution temporal measurements of soil respiration, advancing our understanding of diel, seasonal and interannual controls over this significant portion of the annual C budget (Carbone and Vargas, 2008; Vargas and Allen, 2008; van Asperen et al., 2017). However, in non-tropical areas, most of these advancements deal only with respiration during the growing season, leaving much to be understood about respiration during the winter. Wintertime respiration is especially important in seasonally snow-covered ecosystems where the insulative properties of snow keep soil temperature at or above freezing, maintaining biological activity (McDowell et al., 2000; McGuire et al., 2000; Brooks et al., 2004; Tucker et al., 2016). In fact, wintertime snowpack respiration may show some seasonality (Hubbard et al., 2005), which should be taken into account in sampling designs if the goal is to close annual C budgets. Improving our ability to capture

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spatial and temporal variability in wintertime respiration is necessary to understand interannual dynamics of the C cycle in snow-dominated forests. Eddy covariance captures high (e.g., half-hourly) temporal variability in C fluxes, and its large footprint makes it a useful tool for aggregating spatial variability.

However, it is challenging to glean detailed information about wintertime soil respiration from EC. The method tends to have signal-to-noise issues with low CO_2 fluxes typical of wintertime (Webb et al., 2016). Also, EC fluxes at half-hourly timescales may not represent contemporaneous CO_2 production in the soil due to temporal dynamics of transport processes through snowpack, including advection (Euskirchen et al., 2012). Consequently, there is a need for an independent method to measure wintertime soil respiration underneath snowpack at a high temporal resolution similar to that of EC.

Automated measurements of snowpack CO_2 concentrations can be made at fine time scales (Seok et al., 2009), and these data can help address a major methodological challenge with measuring soil respiration that exits through the snowpack. Typically, wintertime soil respiration is calculated by applying Fick's first law of diffusion to a vertical CO_2 gradient measured in the snowpack (Sommerfeld et al., 1993; Hubbard et al., 2005), assuming steady-state conditions wherein flux emanating from the snowpack surface is equivalent to respiration from the soil into the snowpack. Under conditions where snowpack CO_2 concentrations are largely diffusion dominated, this method estimates soil respiration with high confidence. However, wind generates advective fluxes in which CO_2 is pumped from the surface layer of snow, generating non-linear CO_2 profiles that result in erroneous fluxes when only Fick's first law is used for calculation (Massman et al., 1995; Takagi et al., 2005; Bowling and Massman, 2011). Thus, we need some way to infer soil respiration into the bottom of the snowpack when advective fluxes from the snowpack surface create nonlinearity in snowpack CO_2 profiles. Measuring vertical snowpack CO_2 profiles at frequent (e.g., hourly) timescales can provide enough information to calculate (1) storage, advective and diffusive fluxes, (2) flux from the soil into the snowpack for ecological interpretation, and (3) flux from the top of the snowpack to the atmosphere for comparison to eddy covariance.

Despite its low magnitude, winter respiration may be an indicator of changing C cycle dynamics in forests that have experienced mass tree mortality events, but no results have been presented to date. Studies have found either no significant effect of bark beetle mortality on growing season soil respiration or only a modest, short-term change (Morehouse et al., 2008; Moore et al., 2013; Speckman et al., 2015; Borkhuu et al., 2015). Detecting change in growing season soil respiration is complicated by its sensitivity to short-term changes in soil temperature and moisture (Davidson et al., 1998) that may obscure mortality effects. However, microclimate forcings on respiration are lessened during the winter, when snowpack insulates the soil surface and maintains soil temperature slightly above freezing and holds soil moisture at a more constant level (Contosta et al., 2016). Thus, mortality impacts on respiration may be easier to detect in under-snowpack respiration compared to growing season soil respiration. We hypothesize that tree mortality effects on substrate availability for respiration will result in a noticeable increase in wintertime soil respiration underneath snowpack in the first few years following tree mortality from fine root mortality and needlefall.

One key challenge with ecological measurements that are made with high temporal frequency but low spatial replication is assigning measures of uncertainty. Calculation of soil respiration from vertical CO_2 profiles requires information about variables that influence the rate at which CO_2 moves through the snowpack. The precise values of these variables (e.g., snowpack temperature, porosity, and density) at the locations of CO_2 measurements are usually unknown; rather, they are estimated from nearby snow pits. These sources of uncertainty, even when not precisely known, can be taken into account in a Bayesian analytical framework. Having a reliable measure of uncertainty around these fluxes will allow a comparison between our snowpack CO_2 profile method and accompanying EC tower, as well as allowing the quantification of significance in observed variation of fluxes over time.

In this study, we calculate total CO_2 flux from the snowpack surface at hourly timescales to compare with contemporaneous half-hourly EC measurements. In addition, we examine factors related to overall flux uncertainty and the contribution of advective versus diffusive processes to total flux from the snowpack. Lastly, we hypothesize that the biological flux of CO_2 from soil into the bottom of the snowpack would increase as a result of the tree mortality event. To achieve this, we develop a Bayesian-based method to estimate both advective and diffusive components of CO_2 fluxes from both the bottom of the snowpack (interpreted as biological soil respiration) and from the top of the snowpack (comparable to eddy covariance measurements) and apply it over a 7-year time period at an AmeriFlux site located within a subalpine forest in the Rocky Mountains of southern Wyoming, USA, that had recently experienced tree mortality.

2. Methods

2.1. Study site and data collection

Research was conducted at the Glacier Lakes Ecosystem Experiments Site (GLEES) in southeastern Wyoming which is part of the AmeriFlux network of eddy covariance sites (US-GLE, ameriflux.lbl.gov). GLEES is a mature subalpine forest at 3190 m elevation and receives 1250 mm of average annual precipitation, about 80% as snow. Snowpack persists an average of 8 months per year; development typically begins in October and persists until June or July. Forest species composition consists of old growth Engelmann spruce (*Picea engelmanii* Parry ex Engelm.) with subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). A spruce bark beetle outbreak that peaked in 2008 caused 80–90% overstory spruce mortality; most trees died by 2010 and dead needles soon fell from the canopy (Frank et al., 2014).

In 2009, four 2-m tall mini-towers (Replicates 1 through 4) were erected within 0.25 ha of the eddy covariance tower for the purpose of measuring hourly vertical snowpack CO_2 profiles. Each tower consisted of 11 horizontal gas collector disks (Sommerfeld et al., 1991) with 0.2 m vertical spacing from the soil surface up to the top. Each disk was connected to a solenoid manifold which reduced the inlets through a single tube (Dekabon, 6.35 mm O.D., Synflex, Aurora, OH) that ran along the soil surface from the mini-towers to the AmeriFlux shelter at distances between 20 m and 40 m. Inside the shelter, snowpack air was pulled through a sampling system controlled by a micrologger (CR23X, Campbell Scientific, Logan, UT) and featuring a CO_2 analyzer (LI-800 until January 2015 then LI-820 afterward, LiCor Inc., Lincoln, NE). The sampling system pulled air through a magnesium perchlorate desiccant, monitored the volume of air pulled from each inlet, cut off the flow after air from each gas collector disk had filled the CO_2 analyzer, allowed the analyzer to equilibrate for 4 s, then measured the sample at 1 Hz for 20 s; internal averaging was turned off in the CO_2 analyzer. The system cycled through every inlet once an hour. Ancillary micrometeorological data for turbulence (u_*, $\mathrm{ms^{-1}}$), and CO_2 flux ($\mathrm{\mu mol\, m^{-2} s^{-1}}$) were taken from the co-located US-GLE AmeriFlux scaffold (Frank et al., 2014). Data quality was achieved through periodic calibrations of the CO_2 analyzer and the mass flow controller and omitting measurements from frozen inlets, frozen tubes, or meltwater contamination in the CO_2 analyzer, based on physical inspection and evaluation of summary statistics.

For calculation of fluxes from snowpack CO_2 concentrations, information about physical snowpack properties (density (ρ_{snow}), height (h), and temperature (T)) is required at the same temporal resolution as the hourly CO_2 measurements. Consequently, we estimate these at hourly timescales using a model that was driven by daily precipitation observations (P (m)) and constrained by field measurements of snowpack properties. The snow accumulation model was constructed by