Soil Biology & Biochemistry 42 (2010) 435–444

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

Characterizing the impact of diffusive and advective soil gas transport on the measurement and interpretation of the isotopic signal of soil respiration

Zachary E. Kayler [a,*], Elizabeth W. Sulzman [b], William D. Rugh [c], Alan C. Mix [c], Barbara J. Bond [a]

[a] Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331-5752, USA
[b] Department of Crop and Soil Science, Oregon State University, OR 97331-5752, USA
[c] College of Oceanic and Atmospheric Sciences, Oregon State University, OR 97331, USA

ARTICLE INFO

Article history:
Received 27 March 2009
Received in revised form
12 November 2009
Accepted 17 November 2009
Available online 4 December 2009

Keywords:
Soil respiration
Carbon isotope
Advection
Diffusion
Steady-state
Partitioning
Douglas-fir forest

ABSTRACT

By measuring the isotopic signature of soil respiration, we seek to learn the isotopic composition of the carbon respired in the soil ($\delta^{13}C_{R\text{-}s}$) so that we may draw inferences about ecosystem processes. Requisite to this goal is the need to understand how $\delta^{13}C_{R\text{-}s}$ is affected by both contributions of multiple carbon sources to respiration and fractionation due to soil gas transport. In this study, we measured potential isotopic sources to determine their contributions to $\delta^{13}C_{R\text{-}s}$ and we performed a series of experiments to investigate the impact of soil gas transport on $\delta^{13}C_{R\text{-}s}$ estimates. The objectives of these experiments were to: i) compare estimates of $\delta^{13}C_{R\text{-}s}$ derived from aboveground and belowground techniques, ii) evaluate the roles of diffusion and advection in a forest soil on the estimates of $\delta^{13}C_{R\text{-}s}$, and iii) determine the contribution of new and old carbon sources to $\delta^{13}C_{R\text{-}s}$ for a Douglas-fir stand in the Pacific Northwest during our measurement period. We found a maximum difference of $-2.36‰$ between estimates of $\delta^{13}C_{R\text{-}s}$ based on aboveground vs. belowground measurements; the aboveground estimate was enriched relative to the belowground estimate. Soil gas transport during the experiment was primarily by diffusion and the average belowground estimate of $\delta^{13}C_{R\text{-}s}$ was enriched by 3.8–4.0‰ with respect to the source estimates from steady-state transport models. The affect of natural fluctuations in advective soil gas transport was little to non-existent; however, an advection–diffusion model was more accurate than a model based solely on diffusion in predicting the isotopic samples near the soil surface. Thus, estimates made from belowground gas samples will improve with an increase in samples near the soil surface. We measured a $-1‰$ difference in $\delta^{13}C_{R\text{-}s}$ as a result of an experiment where advection was induced, a value which may represent an upper limit in fractionation due to advective gas transport in forest ecosystems. We found that aboveground measurements of $\delta^{13}C_{R\text{-}s}$ may be particularly susceptible to atmospheric incursion, which may produce estimates that are enriched in ^{13}C. The partitioning results attributed 69–98% of soil respiration to a source with a highly depleted isotopic signature similar to that of water-soluble carbon from foliage measured at our site.

1. Introduction

Soil respiration is the second largest carbon flux of terrestrial ecosystems (Schimel, 1995) and it is crucial that we develop a thorough understanding of the physical and biological controls of the evolution and egress of soil CO_2. The isotopic signal of soil respiration ($\delta^{13}C_{R\text{-}s}$) is an integrative measure of the impact of recent environmental conditions on the oxidation of multiple carbon sources belowground, thus, making it a useful tool for carbon cycle research. Studies using $\delta^{13}C_{R\text{-}s}$ have provided valuable insight into plant–soil carbon metabolism, and respiratory carbon sources at various spatial scales (Crow et al., 2006; Steinmann et al., 2004). Yet, requisite to the interpretation of $\delta^{13}C_{R\text{-}s}$ is the need to validate the assumptions behind soil $\delta^{13}CO_2$ and its measurement.

Current methods to estimate $\delta^{13}C_{R\text{-}s}$ can be categorized into those made aboveground via closed or open top chambers (Ekblad and Högberg, 2000; Ohlsson et al., 2005; Takahashi et al., 2008) and those made belowground that use air samples extracted from the soil CO_2 concentration profile (Kayler et al., 2008; Steinmann et al., 2004). Both methods make two key assumptions concerning soil

* Corresponding author. Current address: Institute for Landscape Matter Dynamics, Leibniz-Center for Agricultural Landscape Research (ZALF) e.V., Müncheberg D-15374, DE, Germany. Tel.: +49 33432 82240x485; fax: +49 33432 82343.
E-mail address: zachary.kayler@zalf.de (Z.E. Kayler).

0038-0717/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soilbio.2009.11.022

respiration, i) CO_2 transport through the soil is only by diffusion, and ii) soil CO_2 flux is at steady-state (Cerling et al., 1991; Amundson et al., 1998). Violations of these assumptions can have a large impact on the certainty in $\delta^{13}C_{R\text{-}s}$ estimates and subsequent source partitioning, and they require a thorough assessment.

The assumption that transport is solely by diffusion is critical to estimates of $\delta^{13}C_{R\text{-}s}$ because diffusion leads to a kinetic fractionation of ^{13}C and ^{12}C whereas advection or mass flow of CO_2 does not cause fractionation. The mass of ^{13}C is larger than that of ^{12}C and diffuses through the soil at a slower rate. For estimates of $\delta^{13}C_{R\text{-}s}$ calculated from gas samples withdrawn from the soil profile a correction of 4.4‰ is applied to account for this fractionation (Amundson et al., 1998). However, if gas transport is not only by diffusion but also by advection, then the correction due to diffusion becomes uncertain, and a correction less than 4.4‰ may apply. Advection as a gas transport mechanism has been suggested in many studies of different ecosystem types (Takle et al., 2004; Risk et al., 2002; Flechard et al., 2007) and similar observations have led to advection–diffusion transport models that have been verified where geologic sources predominate soil CO_2 flux (Camarda et al., 2007; Lewicki et al., 2003). However, only a few studies have addressed the influence of advection on the $\delta^{13}C_{R\text{-}s}$; indeed, most reports apply a correction that assumes gas transport is solely diffusive (Steinmann et al., 2004; Mortazavi et al., 2004).

The second assumption concerning the measurement of $\delta^{13}C_{R\text{-}s}$ is soil CO_2 flux is at isotopic steady-state, i.e. the isotopic signal leaving the soil surface is equal to the isotopic source (Amundson et al., 1998). This means that for measurements made at the soil surface, such as with a chamber, a correction for fractionation due to diffusion is unnecessary. If respiration is not at isotopic steady-state then there will be a disequilibrium between the source isotopic signature and the CO_2 emitted through the profile and to the surface. Such a phenomenon might occur with a shift in the dominant carbon substrate of respiration, for instance.

Ultimately, $\delta^{13}C$ analyses allows for the identification of carbon contributions to soil CO_2 efflux as well as the relative contribution of soil carbon pools to overall ecosystem respiration (Ehleringer et al., 2000; Bowling et al., 2008; Tu and Dawson, 2005; Chemidlin Prévost-Bouré et al., 2009). In the context of partitioning carbon sources, a large isotopic range between potential respiration sources is generally required for partitioning with natural abundance ^{13}C, which explains why isotopic labeling is often used. However, significant differences in the isotopic composition of carbon pools also occur in nature. For example, there is a potential 5‰ difference in the soluble carbon extracts of foliage and the bulk isotopic signature of SOM. This isotopic range is reflected in natural abundance measures of $\delta^{13}C_{R\text{-}s}$ which typically varies by 1–4‰ in magnitude over a growing season (Ekblad and Högberg, 2001; Ekblad et al., 2005; Takahashi et al., 2008; Kodama et al., 2008; Chemidlin Prévost-Bouré et al., 2009). The potentially small difference in the seasonal variability of $\delta^{13}C_{R\text{-}s}$ and the relatively narrow range in isotopic sources accentuate the importance of verifying measurement assumptions and accurately measuring $\delta^{13}C_{R\text{-}s}$ for partitioning carbon sources.

During a single day in the early growing season of 2006, we performed a series of field experiments designed to evaluate the impact of soil gas transport on estimates of $\delta^{13}C_{R\text{-}s}$ and the subsequent analysis of new and old carbon contributions. The objectives of this study were:

i. Compare estimates of $\delta^{13}C_{R\text{-}s}$ derived from aboveground and belowground measurement techniques. We hypothesized that there would not be a difference between the two estimates when the estimate from belowground samples was corrected for kinetic fractionation due to diffusion.
ii. Evaluate the roles of diffusion and advection in a forest soil on the estimates of $\delta^{13}C_{R\text{-}s}$. Our strategy to accomplish this included: a) employing both diffusion and advection–diffusion models that predict $^{13}CO_2$ concentrations belowground in the soil profile, and b) experimentally test the impact of advection by inducing a large negative pressure gradient (−4 kPa) at the soil surface to observe changes in $\delta^{13}C_{R\text{-}s}$ measured aboveground.
iii. Determine the contribution of new and old carbon sources to $\delta^{13}C_{R\text{-}s}$ for a Douglas-fir stand in the Pacific Northwest during our measurement period. We used an isotope mixing model to quantify the contribution of the isotopic signature of carbon in soluble extracts from leaves and phloem as well as the isotopic signature of bulk soil organic matter (SOM) to our estimates of $\delta^{13}C_{R\text{-}s}$.

2. Materials and methods

2.1. Site description

The experiment was conducted within a 96 ha watershed, located in the H J Andrews Experimental Forest in the western Cascades of central Oregon, USA (44.2°N, 122.2°W) (see Pypker et al., 2007 for a detailed description). We chose a subplot near the base of the watershed on the south facing slope. The soil has Andic properties and a loamy to silt loam texture. The organic layer is just 2 cm thick and is composed of primarily recognizable litter fragments with almost no discoloring and no signs of amorphous Oa materials. The A horizon extends to a depth of 9 cm where a diffuse AB transition occurs and extends to 30 cm; beyond this the B horizon extends to a depth of 42 cm.

2.2. Experimental design

Over two consecutive 45 min periods on May 2, 2006 we determined soil respiration and $\delta^{13}C_{R\text{-}s}$. We compared $\delta^{13}C_{R\text{-}s}$ estimates made from belowground (soil probe) and aboveground (mini-tower) techniques, described in Sections 2.3 and 2.4 respectively. We used 45 min intervals to accommodate any disturbance to the CO_2 profile caused by withdrawing gas samples from the soil probe. Three soil probes were installed one week prior to the experiment to minimize disturbance. A 45 min period began with the placement of the mini-tower in between the soil probes and on the litter surface. During the 45 min interval, CO_2 diffused through the mini-tower followed by sampling CO_2 from the tower and then from the soil probes. Following the sampling during diffusive transport we induced advection in the mini-tower and re-sampled the mini-tower for CO_2. We compared mini-tower estimates of $\delta^{13}C_{R\text{-}s}$ made during diffusive and the experimentally induced advective gas transport to observe the effects of advection on aboveground estimates of $\delta^{13}C_{R\text{-}s}$.

We used the CO_2 samples collected from soil probes in two soil profile models: one based on diffusion (Amundson et al., 1998) and one based on diffusion and advection (Camarda et al., 2007). These models, based solely on the soil probe samples, were used to test for i) isotopic steady-state and ii) advection due to background variation in pressure. Thus, for the entire study we sampled the soil probes a total of six times (none of which occurred during the advection experiment), and we sampled the mini-tower two times under diffusive transport and two times under advective transport. During the experiment, we also collected samples of foliage,