Diurnal hysteresis between soil CO₂ and soil temperature is controlled by soil water content

Diego A. Riveros-Iregui,¹ Ryan E. Emanuel,²,³ Daniel J. Muth,² Brian L. McGlynn,¹ Howard E. Epstein,² Daniel L. Welsch,⁴ Vincent J. Pacific,¹ and Jon M. Wraith¹

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Recent years have seen a growing interest in measuring and modeling soil CO₂ efflux, as this flux represents a large component of ecosystem respiration and is a key determinant of ecosystem carbon balance. Process-based models of soil CO₂ production and efflux, commonly based on soil temperature, are limited by nonlinearities such as the observed diurnal hysteresis between soil CO₂ concentration ([CO₂]) and temperature. Here we quantify the degree to which hysteresis between soil [CO₂] and soil temperature is controlled by soil water content in a montane conifer forest, and how this nonlinearity impacts estimates of soil CO₂ efflux. A representative model that does not consider hysteresis overestimated soil CO₂ efflux for the entire growing season by 19%. At high levels of soil water content, hysteresis imposes organized, daily variability in the relationship between soil [CO₂] and soil temperature, and at low levels of soil water content, hysteresis is minimized. Citation: Riveros-Iregui, D. A., R. E. Emanuel, D. J. Muth, B. L. McGlynn, H. E. Epstein, D. L. Welsch, V. J. Pacific, and J. M. Wraith (2007), Diurnal hysteresis between soil CO₂ and soil temperature is controlled by soil water content, Geophys. Res. Lett., 34, L17404, doi:10.1029/2007GL030938.

1. Introduction

Soil CO₂ efflux, often referred to as soil respiration, is a substantial component of the carbon budget for terrestrial ecosystems [Valentini et al., 2000; Barford et al., 2001; Schimel et al., 2001], and it is an important part of the global carbon cycle [Raich and Schlesinger, 1992; Schlesinger and Andrews, 2000; Ryan and Law, 2005]. Rates of soil respiration are correlated with soil temperature across multiple spatial and temporal scales [Raich and Potter, 1995; Risk et al., 2002]. As such, soil temperature plays an important role in many model representations of soil CO₂ production and transport [Lloyd and Taylor, 1994; Winkler et al., 1996; Fang and Moncrieff, 2001; Reichstein et al., 2003]. However, interactions among environmental variables such as temperature and soil moisture may introduce uncertainty into these models. Among the sources of uncertainty in models of soil CO₂ production and transport is daily hysteresis between soil CO₂ flux and soil temperature [Parkin and Kaspar, 2003; Tang et al., 2005; Gaumont-Guay et al., 2006].

Because soil CO₂ flux is controlled by soil [CO₂] [Hirano et al., 2003; Tang et al., 2005; Baldocchi et al., 2006], we investigated hysteresis between soil [CO₂] and soil temperature. Such hysteretic, nonlinear behavior results from diurnal variations in soil [CO₂] and soil temperature that are out of phase with each other, limiting the ability of many power or exponential models (e.g., Q₁₀ [Winkler et al., 1996], Arrhenius [Lloyd and Taylor, 1994]) to adequately predict soil respiration as a function of soil temperature [Davidson et al., 2006]. While hysteresis has been previously observed in natural systems [O’Kane, 2005; O’Kane and Flynn, 2007], a satisfactory explanation of hysteresis in the context of the soil [CO₂] - soil temperature relationship remains unknown. Our objectives are (1) to demonstrate the decay of hysteresis in diurnal cycles of soil [CO₂] - soil temperature relationships as a function of seasonality (i.e., soil water content) in a typical northern Rocky Mountain forest; (2) to discuss the role of hysteresis as a source of uncertainty in the relationship between soil temperature and soil respiration; and (3) to propose a theoretical explanation for the emergence of hysteretic behavior.

2. Methods

We collected 89 days of data during the 2006 growing season in a montane conifer forest in the northern Rocky Mountains. This location is subject to a seasonal drydown in soil water content [Woods et al., 2006] and is representative of the high-altitude, semi-arid forests of the western United States. These areas are known to contribute significantly to the North American carbon sink [Schimel et al., 2002; Monson et al., 2006]. We measured soil temperature (Tₚ; CSI Model 107, Campbell Scientific Inc., Logan, UT), volumetric soil water content (θ; CSI Model 616, Campbell Scientific Inc., Logan, UT), and soil [CO₂] (GMP221 with transmitter, Vaisala, Helsinki, Finland) at 20 cm below the soil surface, logging continuously at 20-minute intervals in a datalogger (model CR10x, Campbell Scientific Inc., Logan, UT). Soil [CO₂] was corrected for temperature and pressure following compensatory procedures described by Tang et al. [2003]. The predominant vegetation in the understory is bluejoint reedgrass (Calamagrostis canadensis). Additionally, we measured precipitation and photosynthetically active radiation (PAR) during the same period in a clearing 50 m away. For each day of the growing season, we calculated the magnitude of hysteresis (Hₘ) as the range of the residuals of a linear least-squares regression between soil [CO₂] and soil temperature, projected on an axis.

¹Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, Montana, USA.
²Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA.
³Now at Department of Geology, Appalachian State University, Boone, North Carolina, USA.
⁴Department of Geography, Frostburg State University, Frostburg, Maryland, USA.

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perpendicular to the regression slope. In estimating $H_M$, we calculated the slope angle after rescaling the entire seasonal range of $[\text{CO}_2]$ and temperature from 0 to 1. This metric provides a simple means of quantifying $H_M$ for comparison between days. The absolute scale of $H_M$ is determined a priori by the range of variability in the original data.

3. Results

[5] During the growing season, soil $[\text{CO}_2]$ declined in response to the seasonal drying of the soil, yet fluctuated daily with soil temperature (Figure 1). Soil $[\text{CO}_2]$ also responded to periodic precipitation. The relationship between soil $[\text{CO}_2]$ and $T_S$ is presented in Figure 2. When viewed in aggregate, the relationship between 20-minute measurements of soil $[\text{CO}_2]$ and $T_S$ appears disorganized (Figure 2a). However, it is actually a superposition of highly organized daily hysteresis loops (Figure 2b). An important characteristic of these data is a decline in $H_M$ that corresponds to $\theta$, or seasonality, as these two factors are correlated. Early in the growing season, the relationship exhibits considerable hysteresis, but $H_M$ decays until the relationship between soil $[\text{CO}_2]$ and $T_S$ is nearly linear (i.e., little or no hysteresis) by the end of the growing season.

[6] To illustrate the decay in hysteresis through the growing season, we present $H_M$ as a function of time (Figure 3a) and $\theta$ (Figure 3b). We observed an apparent change in dynamics of the system at $\theta$ levels above approximately 0.25 m$^3$ m$^{-3}$. Above this water content, $H_M$ is large and exhibits a high degree of variability, ranging from approximately 1000 ppm to 4000 ppm. For drier conditions, $H_M$ is much lower and less variable, ranging from approximately 100 ppm to 1400 ppm. The magnitude of hysteresis increases following late season precipitation events (e.g., on August 18). This supports the argument that $H_M$ is a function of soil moisture; however, large increases in $H_M$ associated with small increases in soil moisture following late season precipitation suggest that the relationship between $H_M$ and $\theta$ is both nonlinear and season-dependent.

4. Discussion

[7] Previous studies [Parkin and Kaspar, 2003; Tang et al., 2005; Gaumont-Guay et al., 2006] have reported the existence of hysteresis between soil $[\text{CO}_2]$ and $T_S$. However, to date a mechanistic explanation of the processes inducing this hysteresis and determining its seasonal variability is still missing. Lack of a process-based understanding of soil moisture controls on soil respiration limits our ability to assess CO$_2$ fluxes from terrestrial ecosystems under current and future climate conditions. Having quantified $H_M$, we
now present a framework for explaining the mechanisms underlying the observed hysteresis between soil temperature and soil \( \text{CO}_2 \) and its effects on soil \( \text{CO}_2 \) production and efflux.

The dynamics of the gas-phase \( \text{CO}_2 \) can be explained by the following equation [Suwa et al., 2004]:

\[
\frac{\partial f_a [\text{CO}_2]}{\partial t} = - \frac{\partial F}{\partial z} + S
\]  

(1)

where \( f_a \) is the air-filled porosity, \( S \) is the net source of the gas-phase \( \text{CO}_2 \), and \( F \) is given by the following relationship:

\[
F = -D(f_a) \frac{\partial [\text{CO}_2]}{\partial z}
\]  

(2)

where \( D \) is the diffusion coefficient of \( \text{CO}_2 \) in the air-filled pore space. Combining equations (1) and (2) and assuming that soil moisture does not vary over the course of a day, the daily dynamics of the gas-phase \( \text{CO}_2 \) in the soil are explained by:

\[
f_a \frac{\partial [\text{CO}_2]}{\partial t} = - \frac{\partial}{\partial z} \left[ D(f_a) \frac{\partial [\text{CO}_2]}{\partial z} \right] + k_d (\text{PAR}, \theta) + k_H (T_S, \theta)
\]  

(3)

where \( k_d \) and \( k_H \) are the rates of \( \text{CO}_2 \) production from autotrophic and heterotrophic activities, respectively. Diffusivity of \( \text{CO}_2 \) in the gas phase is about 10,000 times higher than in the liquid phase [Simunek and Suarez, 1993; Welsch and Hornberger, 2004], therefore we assume that solubility of the gas-phase \( \text{CO}_2 \) is negligible. We note that \( \text{PAR} \) and \( T_S \) vary in time on a daily basis and \( \theta \) varies in time on a seasonal basis. We also note that changes in \( \theta \) influence two key physical attributes of the soil: (1) the \( \text{CO}_2 \) diffusivity, which can be seen directly in equation (3); and (2) the thermal diffusivity [Oke, 1987], which induces lags between

Figure 3. (a) Magnitude of hysteresis \( H_M \) throughout the growing season. (b) Relationship of \( H_M \) and soil water content (\( \theta \)).

Figure 4. (a) Normalized response of PAR, soil \( [\text{CO}_2] \), and soil temperature on June 18. Shaded areas are the indicated times of the day in Figure 4b. (b) Hysteresis between soil \( [\text{CO}_2] \) and soil temperature on the same day. The direction of the hysteresis loop is indicated by the arrow. In the morning hours, soil \( [\text{CO}_2] \) increases rapidly independent of the soil temperature. This coincides with increasing PAR levels. In the evening soil \( [\text{CO}_2] \) declines as soil temperature continues to increase. This coincides with decreasing PAR levels. At night, soil \( [\text{CO}_2] \) declines with decreasing soil temperature.
air temperature and soil temperature as daily variations in PAR influence the air temperature.

Since PAR reaches a maximum earlier in the day than soil temperature (resulting from delayed heat propagation through the soil, Figure 4a), there is a time lag between daily maxima of $k_A$ and $k_H$, as autotrophic respiration responds to PAR [Liu et al., 2006] and air temperature, whereas heterotrophic respiration responds primarily to soil temperature [Lloyd and Taylor, 1994; Winkler et al., 1996]. This time lag creates hysteresis between soil temperature and the accumulation of CO$_2$ at a specific depth (Figure 4b). However, if $D$ is large enough to facilitate transport of autotrophic and heterotrophic CO$_2$ from the soil (such as during dry or late-season conditions), the system remains at or near steady state throughout the day, where $\partial[CO_2]/\partial t \approx 0$ (e.g., August 28). Under steady state conditions, production of CO$_2$ ($k_A + k_H$) and transport ($-\frac{n}{\rho D}[D \partial[CO_2]/\partial t]$) are balanced and there is little or no hysteresis between $T_S$ and soil CO$_2$. During wet conditions, production of CO$_2$ prevails over transport because (1) $D$ is much smaller than during dry conditions and (2) microbial activity is enhanced by high soil moisture [Or et al., 2007]. Under such conditions, where $\partial[CO_2]/\partial t \neq 0$, hysteresis forms between soil CO$_2$ and $T_S$. Soil CO$_2$ increases when production of CO$_2$ exceeds transport, and decreases when transport exceeds production of CO$_2$. The rising limb of the daily hysteresis loop ($\partial[CO_2]/\partial t > 0$) occurs when autotrophic respiration is likely to dominate CO$_2$ production, whereas the falling limb ($\partial[CO_2]/\partial t < 0$) occurs when heterotrophic respiration is likely to dominate CO$_2$ production (Figure 4b). As a result of the daily lag between $k_A$ and $k_H$, well-defined daily hysteresis loops may allow visualization of contributions of autotrophic and heterotrophic activities to total soil CO$_2$ production.

In our study system, the time of daily maximum soil CO$_2$ fell between the times of daily maximum PAR and daily maximum $T_S$. While it is known that root respiratory fluxes can lag PAR by times that vary from hours to weeks [Stoy et al., 2007], it has been suggested that this time may be very short for understory grasses (<4 h [Carbone and Trumbore, 2007]). Furthermore, Carbone and Trumbore [2007] and similar soil respiration studies [Carbone et al., 2007; Stoy et al., 2007], used soil efflux chambers to measure soil respiration at the soil surface. In our study, we measured soil CO$_2$ concentrations (soil CO$_2$) in the root zone, thereby excluding the time lag introduced by diffusive transport of CO$_2$ from the root zone to the soil surface. This greatly shortens the time lag between PAR and the measured respiratory increase caused by plant activity. The sequence of daily maxima (PAR, soil CO$_2$ and $T_S$, Figure 4a) generates a clockwise pattern of hysteresis between soil CO$_2$ and $T_S$ (Figure 4b). In the hypothetical absence of a PAR effect on soil CO$_2$ (i.e., no contribution from $k_A$), clockwise hysteresis may not develop since daily maximum in soil CO$_2$ may not occur before daily maximum in $T_S$. In fact, counterclockwise hysteresis loops have been reported [Parkin and Kaspar, 2003; Tang et al., 2005; Gaumont-Guay et al., 2006], which suggests that PAR has a smaller effect on soil CO$_2$ in those systems than in ours. By altering thermal diffusivity of the soil, $\theta$ affects the time lag between daily maximum PAR and daily maximum $T_S$ contributing, although only to a degree, to hysteresis in this system. As the soil becomes drier, microbial activity declines and the time lag between PAR and $T_S$ decreases due to accelerated soil heat diffusion.

5. Conclusions

During the early (wet) growing season ($\theta > 0.25 m^2 m^{-3}$), hysteresis has a strong effect on the relationship between soil CO$_2$ and soil temperature. Although the relationship is highly organized, soil temperature alone is insufficient to explain changes in soil CO$_2$. The seasonality of soil water content introduces physical effects on soil CO$_2$ diffusivity and thermal diffusivity that must be considered to explain more fully the response of soil CO$_2$ to soil temperature. Late in the growing season when the soils are drier, hysteresis diminishes and the relationship between these two variables is much more linear. During these periods, traditional relationships between soil CO$_2$ and soil temperature (e.g., Q10, Arrhenius) apply, except after isolated rainfall episodes. Based on chamber measurements at our site, a developed Q10 relationship overestimates CO$_2$ flux by 42 $g C m^{-2} (19\%$) for the entire growing season due to its inability to account for the daily cycle of soil CO$_2$, the variability of soil moisture, and moisture-dependent diffusive transport of CO$_2$ through the soil column. Only under late-season dry conditions is the Q10-relationship able to predict CO$_2$ flux.

These results have implications for quantitative assessment, process-based understanding, and modeling of production and eflux of CO$_2$ from soils subjected to strong diurnal and seasonal changes in temperature and moisture. In this study, we demonstrate that diurnal hysteresis between soil CO$_2$ and soil temperature is due mostly to the balance (or imbalance in wet soils) between production and diffusion. The seasonality in soil moisture controls the transition from an imbalanced system (where diurnal hysteresis is observed) to a balanced system (no diurnal hysteresis observed). The magnitude of hysteresis in the soil CO$_2$–soil temperature relationship is an important indicator of the existence of concomitant, yet independent, autotrophic and heterotrophic soil CO$_2$ processes. As such, the role of soil water content in controlling the relationship between soil CO$_2$ and soil temperature should be considered when modeling the dynamics of carbon cycling in ecosystems with strong seasonality in soil water content.

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References


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R. E. Emanuel, Department of Geology, Appalachian State University, 195 Rankin Science, 572 Rivers Street, Boone, NC 28608, USA.

H. E. Epstein and D. J. Muth, Department of Environmental Sciences, University of Virginia, 291 McCormick Road, Charlottesville, VA 22904, USA.

B. L. McGlynn, V. J. Pacific, D. A. Riveros-Iregui, and J. M. Wraith, Department of Land Resources and Environmental Sciences, Montana State University, 334 Leon Johnson Hall, Bozeman, MT 59717, USA.

D. L. Welsch, Department of Geography, Frostburg State University, 211 Gunter Hall, Frostburg, MD 21532, USA.