

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

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[1] 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

[2] 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 temperatures 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].

[3] 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

[4] 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 (*T_s*; 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 (*H_M*) as the range of the residuals of a linear least-squares regression between soil [CO₂] and soil temperature, projected on an axis

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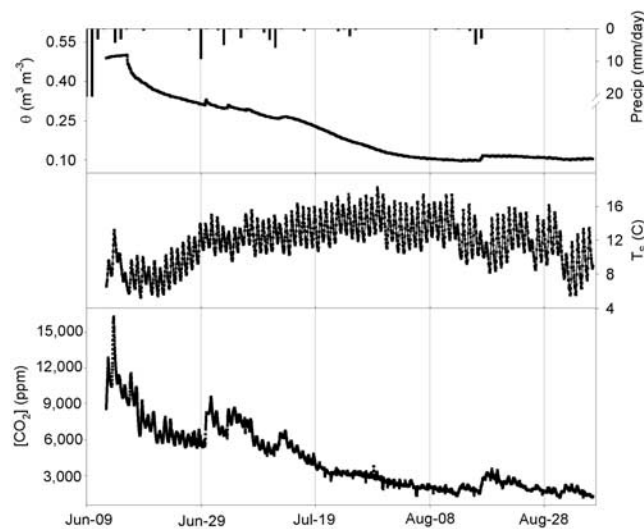


Figure 1. Variability of (top) soil water content and precipitation, (middle) soil temperature, and (bottom) soil [CO₂] for the duration of the study. Measurements are taken at 20-min intervals for the duration of the study. Precipitation is added on a daily basis.

perpendicular to the regression slope. In estimating H_M , we calculated the slope angle after rescaling the entire seasonal range of [CO₂] 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 [CO₂] declined in response to the seasonal drying of the soil, yet fluctuated daily with soil temperature (Figure 1). Soil [CO₂] also responded to periodic precipitation. The relationship between

soil [CO₂] and T_S is presented in Figure 2. When viewed in aggregate, the relationship between 20-minute measurements of soil [CO₂] 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 θ , 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 [CO₂] 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 θ (Figure 3b). We observed an apparent change in dynamics of the system at θ levels above approximately 0.25 m³ 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 θ 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 [CO₂] 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 CO₂ fluxes from terrestrial ecosystems under current and future climate conditions. Having quantified H_M , we

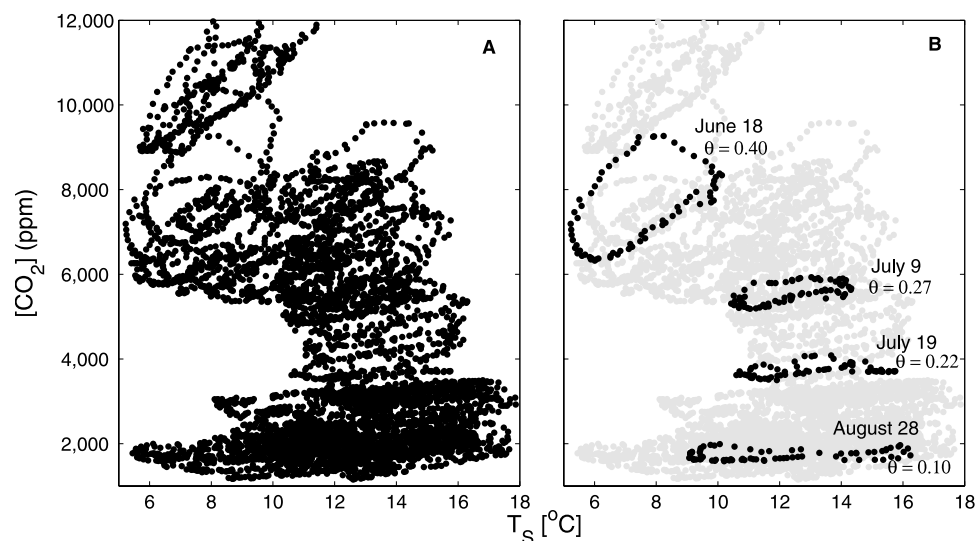


Figure 2. (a) Relationship of soil [CO₂] and soil temperature (T_S) at 20-min intervals for the duration of the study. (b) Highlighted evolution of hysteresis throughout the growing season. Soil water content (θ) values are given for each highlighted day.

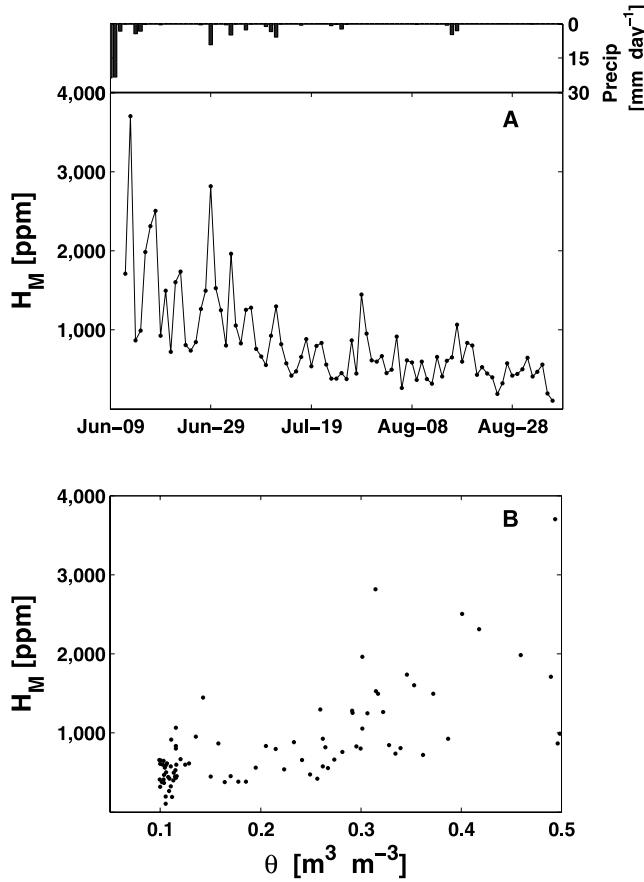


Figure 3. (a) Magnitude of hysteresis H_M throughout the growing season. (b) Relationship of H_M and soil water content (θ).

now present a framework for explaining the mechanisms underlying the observed hysteresis between soil temperature and soil [CO₂] and its effects on soil CO₂ production and efflux.

[8] The dynamics of the gas-phase CO₂ can be explained by the following equation [Suwa *et al.*, 2004]:

$$\frac{\partial f_a[\text{CO}_2]}{\partial t} = -\frac{\partial F}{\partial z} + S \quad (1)$$

where f_a is the air-filled porosity, S is the net source of the gas-phase CO₂, and F is given by the following relationship:

$$F = -D(f_a) \frac{\partial[\text{CO}_2]}{\partial z} \quad (2)$$

where D is the diffusion coefficient of CO₂ 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 CO₂ in the soil are explained by:

$$f_a \frac{\partial[\text{CO}_2]}{\partial t} = -\frac{\partial}{\partial z} \left[D(f_a) \frac{\partial[\text{CO}_2]}{\partial z} \right] + k_A(PAR, \theta) + k_H(T_S, \theta) \quad (3)$$

where k_A and k_H are the rates of CO₂ production from autotrophic and heterotrophic activities, respectively. Diffusivity of CO₂ 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 CO₂ is negligible. We note that PAR and T_S vary in time on a daily basis and θ varies in time on a seasonal basis. We also note that changes in θ influence two key physical attributes of the soil: (1) the CO₂ diffusivity, which can be seen directly in equation (3); and (2) the thermal diffusivity [Oke, 1987], which induces lags between

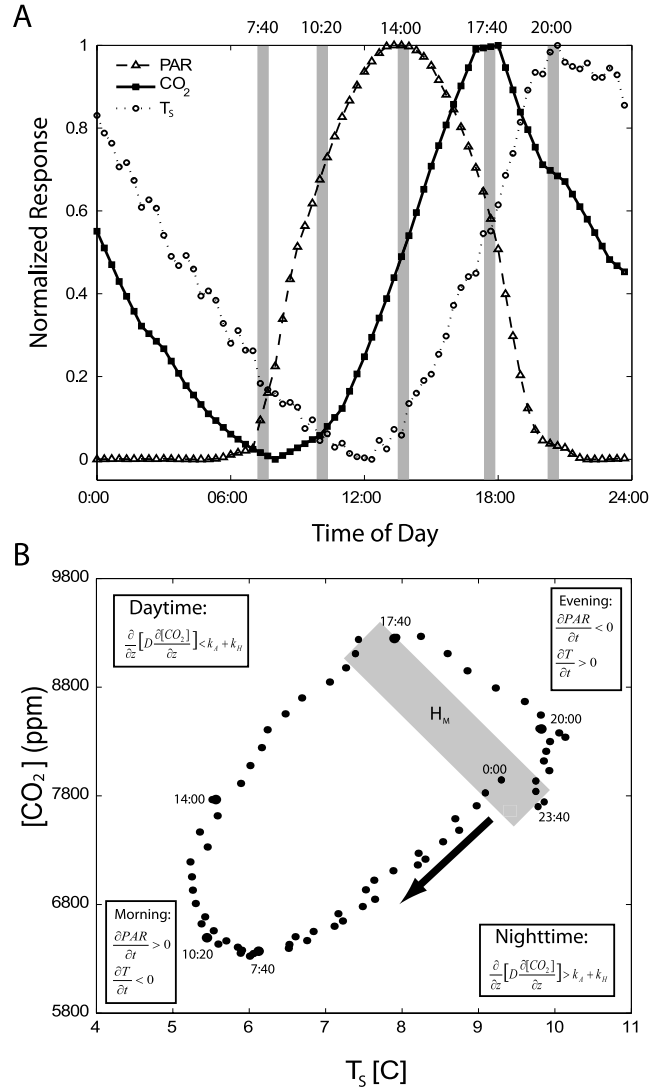


Figure 4. (a) Normalized response of PAR, soil [CO₂], and soil temperature on June 18. Shaded areas are the indicated times of the day in Figure 4b. (b) Hysteresis between soil [CO₂] and soil temperature on the same day. The direction of the hysteresis loop is indicated by the arrow. In the morning hours, soil [CO₂] increases rapidly independent of the soil temperature. This coincides with increasing PAR levels. In the evening soil [CO₂] declines as soil temperature continues to increase. This coincides with decreasing PAR levels. At night, soil [CO₂] declines with decreasing soil temperature.

air temperature and soil temperature as daily variations in *PAR* influence the air temperature.

[9] 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 CO₂ at a specific depth (Figure 4b). However, if D is large enough to facilitate transport of autotrophic and heterotrophic CO₂ from the soil (such as during dry or late-season conditions), the system remains at or near steady state throughout the day, where $\partial[\text{CO}_2]/\partial t \approx 0$ (e.g., August 28). Under steady state conditions, production of CO₂ ($k_A + k_H$) and transport ($-\frac{\partial}{\partial z}[D \frac{\partial[\text{CO}_2]}{\partial z}]$) are balanced and there is little or no hysteresis between T_S and soil [CO₂]. During wet conditions, production of CO₂ 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 $\partial[\text{CO}_2]/\partial t \neq 0$, hysteresis forms between soil [CO₂] and T_S . Soil [CO₂] increases when production of CO₂ exceeds transport, and decreases when transport exceeds production of CO₂. The rising limb of the daily hysteresis loop ($\partial[\text{CO}_2]/\partial t > 0$) occurs when autotrophic respiration is likely to dominate CO₂ production, whereas the falling limb ($\partial[\text{CO}_2]/\partial t < 0$) occurs when heterotrophic respiration is likely to dominate CO₂ 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 CO₂ production.

[10] In our study system, the time of daily maximum soil [CO₂] 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 CO₂ concentrations (soil [CO₂]) in the root zone, thereby excluding the time lag introduced by diffusive transport of CO₂ 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 [CO₂] and T_S , Figure 4a) generates a clockwise pattern of hysteresis between soil [CO₂] and T_S (Figure 4b). In the hypothetical absence of a *PAR* effect on soil [CO₂] (i.e., no contribution from k_A), clockwise hysteresis may not develop since daily maximum in soil [CO₂] 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 [CO₂] in those systems than in ours. By altering thermal diffusivity of the soil, θ 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

[11] During the early (wet) growing season ($\theta > 0.25 \text{ m}^3 \text{ m}^{-3}$), hysteresis has a strong effect on the relationship between soil [CO₂] and soil temperature. Although the relationship is highly organized, soil temperature alone is insufficient to explain changes in soil [CO₂]. The seasonality of soil water content introduces physical effects on soil CO₂ diffusivity and thermal diffusivity that must be considered to explain more fully the response of soil [CO₂] 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 [CO₂] and soil temperature (e.g. Q_{10} , Arrhenius) apply, except after isolated rainfall episodes. Based on chamber measurements at our site, a developed Q_{10} relationship overestimates CO₂ 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 [CO₂], the variability of soil moisture, and moisture-dependent diffusive transport of CO₂ through the soil column. Only under late-season dry conditions is the Q_{10} relationship able to predict CO₂ flux.

[12] These results have implications for quantitative assessment, process-based understanding, and modeling of production and efflux of CO₂ from soils subjected to strong diurnal and seasonal changes in temperature and moisture. In this study, we demonstrate that diurnal hysteresis between soil [CO₂] 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 [CO₂]-soil temperature relationship is an important indicator of the existence of concomitant, yet independent, autotrophic and heterotrophic soil [CO₂] processes. As such, the role of soil water content in controlling the relationship between soil [CO₂] 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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