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Does day and night sampling reduce spurious correlation between canopy photosynthesis and ecosystem respiration?

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ABSTRACT

It is necessary to partition eddy covariance measurements of carbon dioxide exchange into its offsetting gross fluxes, canopy photosynthesis, and ecosystem respiration, to understand the biophysical controls on the net fluxes. And independent estimates of canopy photosynthesis (G) and ecosystem respiration (R) are needed to validate and parametrize carbon cycle models that are coupled with climate and ecosystem dynamics models. Yet there is a concern that carbon flux partitioning methods may suffer from spurious correlation because derived values of canopy photosynthesis and ecosystem respiration both contain common information on net carbon fluxes at annual time scales.

We hypothesized that spurious correlation among canopy photosynthesis and ecosystem respiration can be minimized using day–night conditional sampling of CO_2 exchange; daytime fluxes are dominated by photosynthesis and nighttime fluxes are dominated by respiration. To test this hypothesis, we derived explicit equations that quantify the degree of spurious correlation between photosynthesis and respiration. Theoretically, day and night samples of net carbon exchange share a different common variable, daytime ecosystem respiration, and the degree of spurious correlation depends upon the variance of this shared variable.

We then applied this theory to ideal measurements of carbon exchange of over a vigorous, irrigated, and frequently harvested alfalfa field in the sunny and windy region of California, the Sacramento-San Joaquin Delta, where soil CO_2 efflux is strong. In this case, we found that the correlation coefficient between canopy photosynthesis and ecosystem respiration was −0.79. This relatively high correlation between canopy photosynthesis and respiration was mostly real as the degree of spurious correlation was only −0.32.

We then expanded this analysis to the FLUXNET database that spans a spectrum of climate and plant functional types. We found, on average, that the correlation between gross photosynthesis and ecosystem respiration, using day–night sampling, was close to minus one (−0.828 ± 0.130). For perspective, a large fraction of this correlation was real, as the degree of spurious correlation (Eq. (22)) was −0.526. We conclude that the potential for spurious correlation between canopy photosynthesis and ecosystem respiration across the FLUXNET database was moderate. Looking across the database, we found that the least negative spurious correlations coefficients (>−0.3) were associated with seasonal deciduous forests. The most negative spurious correlations coefficients (<−0.7) were associated with evergreen forests found in boreal climates.

1. Introduction

Our ability to simulate ecosystem scale photosynthesis remains poor, despite over 50 years of research on this topic (Dietze et al., 2011; Schaefer et al., 2012; Vargas et al., 2013). Yet trustworthy measurements of gross CO_2 exchange between vegetation and the atmosphere are needed to improve, and parameterize, the suite of extant ecosystem models that predict gross carbon fluxes (Alton, 2011; Loew et al., 2014; Williams et al., 2009) and couple these fluxes with the climate system (Cox et al., 2000; Friedlingstein et al., 2006).

Eddy covariance measurements of CO_2 exchange between an ecosystem and the atmosphere are direct and represent the net difference between uptake by plant photosynthesis and losses by ecosystem respiration. To understand and diagnose how and why those fluxes vary with time and environmental conditions, prac-

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titioners have attempted to partition the net flux into its two, offsetting gross components, canopy photosynthesis, and ecosystem respiration (Falge et al., 2002; Lasslop et al., 2010b; Papale et al., 2006; Reichstein et al., 2005).

Several approaches are popular for flux partitioning. One approach estimates canopy photosynthesis by subtracting empirical estimates of daytime respiration from daytime measurements of net carbon dioxide exchange (Reichstein et al., 2005). An empirical function describing the relationship between ecosystem respiration and environmental drivers, like temperature and soil moisture, is derived using nighttime eddy covariance flux measurements. There are limitations and uncertainties toward using nocturnal eddy flux measurements of CO_2 exchange to derive this empirical model for daytime respiration. Better models incorporate a seasonal component to a baseline efflux (Reichstein et al., 2005; Xu and Baldocchi, 2004). The other issue revolves around the accuracy and representativeness of nocturnal efflux measurements, when atmospheric turbulence is often low and the atmosphere is stably stratified (Barr et al., 2013; Gu et al., 2005). Under calm, stable conditions, insufficient mixing of the air can occur. This results in either substantial storage of CO_2 in the underlying air space or the pooling and draining of air, which prevent it from crossing the canopy-atmosphere interface. In other circumstances the stable boundary layer causes winds aloft to be decoupled from flow in the surface layer. This condition is untenable and leads to sporadic turbulent transfer (Lee, 2000; Mahrt, 2014; Nappo, 1991). Bursts in CO_2 efflux are non-local in time, as they vent air that was stored in the air space during the preceding calm period. Together, these processes can cause a bias in the eddy covariance flux density measured across the canopy-atmosphere interface (Acevedo et al., 2007; Barr et al., 2013; Finnigan, 2006; Gu et al., 2005).

The second approach derives information on ecosystem respiration from the better-mixed conditions of daytime carbon flux measurements. In one situation, the estimate of ecosystem respiration is produced by extrapolation of the response curve between canopy photosynthesis and light to its zero intercept (Falge et al., 2002; Xu and Baldocchi, 2004). Strength of this method revolves around the fact that it infers night respiration from daytime measurements, when turbulent mixing is greater. A weakness of this approach is the fact it relies on flux measurements during the sunrise and sunset transition periods when the atmosphere is not stationary and atmospheric storage can be great; the constant flux layer, upon which eddy covariance theory relies on, depends on the assumption of steady-state conditions (Baldocchi, 2003; Foken and Wichura, 1996).

A third approach exploits the fact the respiratory effluxes are relatively capped, when measured a few hours after sundown; then mixing remains relatively vigorous and measurement biases are assumed small (van Gorsel et al., 2009).

Recently there has been constructive criticism about deriving canopy photosynthesis and ecosystem respiration from measurements of net ecosystem carbon exchange. This approach suffers from the closure problem that involves deriving two pieces of information (canopy photosynthesis and ecosystem repiration) from one equation. We acknowledge that efforts are underway to assess canopy photosynthesis with independent proxies like carbonyl sulfide (COS) (Asaf et al., 2013; Berry et al., 2013; Blonquist et al., 2011), with simultaneous fluxes of stable carbon isotopes (^{12}C and ^{13}C) (Bowling et al., 2001; Griffis, 2013), as differences between above and below canopy flux systems (Baldocchi et al., 1987; Baldocchi et al., 1997) and with sun induced fluorescence (Frankenberg et al., 2011; Guanter et al., 2014). But none of these alternative methods produce measurements of gross canopy photosynthesis, year round, quasi-continuously, and with as few assumptions as direct eddy covariance measurements.

Others have reported on how the partitioning of ecosystem respiration (R) and canopy photosynthesis (G) may suffer from the pitfalls of spurious correlation (Kenney, 1982; Lasslop et al., 2010a; Vickers et al., 2009). Concern rises because estimates of canopy photosynthesis and ecosystem respiration both contain information on net ecosystem carbon exchange (NEE). Additional concern revolves on how well estimates of daytime ecosystem respiration can be represented as a function of temperature, time, and soil moisture. A growing number of studies are finding that recent photosynthesis primes soils respiration (Kuzyakov, 2010; Tang et al., 2005). While others have shown an inhibition of dark respiration in light by the so-called Kok-effect (Amthor, 1994; Heskel et al., 2013). Consequently, daytime ecosystem respiration, at a given temperature, may be different than nighttime respiration at the same temperature.

The topic of spurious correlation has a long history. The eminent statistician, Karl Pearson (Pearson, 1896), was probably the first researcher to caution about spurious correlations among three inter-related variables. He showed that a correlation between two independent datasets, x and y, would exist if they were divided by another independent variable, z, and the ratios were regressed against with one another. To quantify this measure of spurious correlation, he developed an index:

$$\rho = \frac{(\sigma_z/\bar{z})^2}{\sqrt{(\sigma_x/\bar{x})^2 + (\sigma_z/\bar{z})^2}\sqrt{(\sigma_y/\bar{y})^2 + (\sigma_z/\bar{z})^2}} \quad (1)$$

In micrometeorology, examples of spurious correlation include the relationships between standard deviations in vertical velocity (σ_w/u_*) and Monin-Obukhov length scale $L = \frac{u_*^3\theta_v}{kgw'\theta'}$ (Hicks, 1978) and the relationship between nocturnal CO_2 effluxes and friction velocity; in these situations both variables contain information on the standard deviation in vertical velocity.

While we acknowledge the claim of spurious correlation between canopy photosynthesis and ecosystem respiration can be true, we advocate that the problem is more nuanced with respect to the partitioning of net CO_2 exchange. For example, it is important to ask and answer: what is the degree of spurious correlation?

We hypothesize that the degree of spurious correlation depends on the sampling method and time scale upon which the data are summed and integrated (day/night vs. 24 h vs. annual). And we aim to show that spurious correlation can be minimized if we use conditional sampling of daytime and nighttime flux measurements to construct sums at daily and annual scales. For example, canopy photosynthesis is populated by daytime flux measurements and ecosystem respiration is populated by nighttime measurements. In the case of annual sums, many of the ecosystem respiration measurements are populated with winter-time samples when photosynthesis is nil. Consequently, conditional sampling at these time scales can yield relatively independent measurements of photosynthesis and ecosystem respiration, producing a degree of spurious correlation that may not be as large as previously claimed (Vickers et al., 2009).

In this paper, we derive new theory to examine spurious correlation among day and night measurements of CO_2 exchange, as applied to partitioning net ecosystem carbon exchange into canopy photosynthesis and ecosystem respiration. We use the theory to determine which conditions are most and least prone to spurious correlation. Next, the theory is tested with new measurements over an ideal site; an irrigated alfalfa field, growing in an extremely windy portion of northern California, where the adjustments for lack of wind at night are essentially nil. Finally, we expand the analysis to the larger FLUXNET database and evaluate the degree of spurious correlation that may occur between canopy photosynthesis and ecosystem respiration across a spectrum of climate, plant