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Revisiting the choice of the driving temperature for eddy covariance CO_2 flux partitioning

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ABSTRACT

So-called CO_2 flux partitioning algorithms are widely used to partition the net ecosystem CO_2 exchange into the two component fluxes, gross primary productivity and ecosystem respiration. Common CO_2 flux partitioning algorithms conceptualise ecosystem respiration to originate from a single source, requiring the choice of a corresponding driving temperature. Using a conceptual dual-source respiration model, consisting of an above- and a below-ground respiration source each driven by a corresponding temperature, we demonstrate that the typical phase shift between air and soil temperature gives rise to a hysteresis relationship between ecosystem respiration and temperature. The hysteresis proceeds in a clockwise fashion if soil temperature is used to drive ecosystem respiration, while a counter-clockwise response is observed when ecosystem respiration is related to air temperature. As a consequence, nighttime ecosystem respiration is smaller than daytime ecosystem respiration when referenced to soil temperature, while the reverse is true for air temperature. We confirm these qualitative modelling results using measurements of day and night ecosystem respiration made with opaque chambers in a short-statured mountain grassland. Inferring daytime from nighttime ecosystem respiration or *vice versa*, as attempted by CO_2 flux partitioning algorithms, using a single-source respiration model is thus an over-simplification resulting in biased estimates of ecosystem respiration. We discuss the likely magnitude of the bias, options for minimizing it and conclude by emphasizing that the systematic uncertainty of gross primary productivity and ecosystem respiration inferred through CO_2 flux partitioning needs to be better quantified and reported.

1. Introduction

Gross primary productivity (GPP; for a recent discussion on the definition of this term see Wohlfahrt and Gu, 2015) and ecosystem respiration (R_{eco}) are key concepts and terms in carbon cycle science (Chapin et al., 2006) and their magnitude determines the sign of the net ecosystem CO_2 exchange, *i.e.* NEE = GPP + R_{eco} (here and in the following we employ a sign convention according to which negative fluxes represent a net uptake of CO_2 by the underlying surface). Since GPP and R_{eco} mask each other in the NEE during daytime conditions, it is difficult, or even impossible, to directly quantify GPP and daily sums of R_{eco} and thus various methods, with quite different theoretical backgrounds, have emerged to indirectly disentangle GPP and R_{eco}: Partitioning based on (i) flux variance similarity theory (Scanlon and Sahu, 2008; Sulman et al., 2016), (ii) the isotopes of CO_2 (*e.g.* Bowling et al., 2001; Ogée et al., 2003; Wehr and Saleska, 2015), (iii) carbonyl sulfide (COS) exchange (*e.g.* Asaf et al., 2013; Commane et al., 2015), (iv) sun-induced fluorescence (SIF; *e.g.* Parazoo et al., 2014) and (v) the photo-chemical reflectance index (PRI; Hilker et al., 2014). The most widely applied method, however, are the so-called CO_2 flux partitioning algorithms (Lasslop et al., 2010; Reichstein et al., 2005), which within the FLUXNET project are applied in a consistent fashion globally at +500 sites (*e.g.* Papale et al., 2006; Tramontana et al., 2016).

CO_2 flux partitioning algorithms exploit, in one way or the other, the contrasting sign of nighttime (positive – net CO_2 release) and daytime (negative – net CO_2 uptake) NEE. The nighttime approach put forward by Reichstein et al. (2005) uses nighttime NEE measurements to parametrise a temperature-dependent model of R_{eco}. GPP is then inferred by extrapolating R_{eco} to daytime temperatures and by subtracting the latter term from NEE. The daytime approach by Lasslop et al. (2010) uses nighttime NEE measurements to parameterise the temperature sensitivity of R_{eco}, but then

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uses a light- and temperature-driven model to infer both GPP and R_{eco} from daytime data only.

While being simple and appealing in principle, CO_2 flux partitioning approaches have not escaped criticism. Methodological problems discussed are related to uncertainties associated with nighttime eddy covariance flux estimates (*e.g.* Aubinet, 2008; Speckman et al., 2015) and approaches of minimizing these (*e.g.* Gu et al., 2005), different day and nighttime flux footprints and associated bias in R_{eco} (Wehr and Saleska, 2015) and possible artificial correlations between inferred GPP and R_{eco} (*e.g.* Baldocchi et al., 2015; Vickers et al., 2009). From a more process-oriented perspective, issues which have been discussed include short- *versus* longer-term temperature sensitivities of R_{eco} (Reichstein et al., 2005), the overestimation of R_{eco} during daytime conditions due to leaf mitochondrial respiration being lower in the light compared to darkness (Heskel et al., 2013; Wehr et al., 2016; Wohlfahrt et al., 2005b) and temperature-independent diurnal variations in ecosystem respiration components (*e.g.* Bahn et al., 2009).

Another issue, first addressed in a synthetic fashion by Lasslop et al. (2012), is related to the fact that both CO_2 flux partitioning algorithms conceptualise R_{eco} to result from a single source, requiring a corresponding driving temperature being chosen. While Lasslop et al. (2012) showed that differences in the correlations between various driving temperatures and nighttime NEE were minor, the authors also found that the choice of the driving temperature affected inferred GPP and R_{eco} estimates and that the time lag between air and soil temperature was the best indicator for these differences.

The main objective of the present paper is to revisit the effects related to the choice of the driving temperature on inferred GPP and R_{eco}. In particular we aim to (i) clarify the consequences of the phase shift between air and soil temperature using a simple dual-source model of ecosystem respiration, (ii) confirm the qualitative model predictions with day and night R_{eco} measurements from a mountain grassland made with opaque chambers, and (iii) discuss the implications of our findings for eddy covariance CO_2 flux partitioning.

2. Material and methods

2.1. Conceptual dual-source ecosystem respiration model

In order to analyse how differences in phase and amplitude of above- and below-ground temperature and differences in the associated respiration components affect the extrapolation of nighttime R_{eco} to daytime conditions (and *vice versa*) we used a simple conceptual model representing R_{eco} as the sum of an above- (R_{ag}) and below-ground (R_{bg}) respiration component, driven by the two corresponding temperatures (Wohlfahrt et al., 2005a):

$$R_{eco} = R_{ag} + R_{bg} \text{and} \tag{1}$$

$$R_x = R_x@T_{ref}\, e^{E_{o\_x}\left(T_x - T_{ref}\right)}. \tag{2}$$

Here $R_x@T_{ref}$ refers to the above-ground (R_{ag}) or below-ground (R_{bg}) respiration ($\mu mol\, m^{-2}\, s^{-1}$) at the reference temperature ($T_{ref} = 283.15$ K), E_{o_x} to the temperature sensitivity (K^{-1}) and T_x either to air (T_a) or soil temperature (T_s) (K).

The diurnal course of above- and below-ground temperature was simulated according to Campbell and Norman (1998) using a sinusoidal model:

$$T = T_{avg} + A_o e^{-z/D} sin\left[\pi/12\,(t - t_o) - z/d\right], \tag{3}$$

where T_{avg} is the average daily temperature (K), A_o the daily temperature amplitude (K), t_o a phase-shift parameter ($t_o = 8$), z the soil depth (m), D the soil damping depth (m) and t represents time (hours). In order to simulate the temperature of the above-ground respiration component, the soil depth (z) was set to zero.

2.2. Study site

Direct measurements of nighttime and daytime dark ecosystem respiration were conducted at the FLUXNET site Torgnon (IT-Tor), a subalpine grassland located in the northwestern Italian Alps at 2160 m asl (45°50′40″ N, 7°34′4″E). The mean annual temperature is 3.1 °C and annual precipitation 880 mm. The site is typically covered by a continuous snow cover from the end of October to late May. Vegetation is mainly composed by matgrass (*Nardus stricta*) with other graminoids and forbs as co-dominant species (*e.g. Arnica montana*, *Trifolium alpinum* and *Carex sempervirens*) and the soil was classified as Cambisol (FAO). The peak value of leaf area index and canopy height is on average 2.2 $m^2\, m^{-2}$ and 20 cm, respectively. Additional information on the study site can be found in Galvagno et al. (2013).

2.3. Ecosystem respiration chamber measurements, data processing and analysis

The low stature of the vegetation allowed direct measurements of ecosystem respiration without the need for upscaling different respiration components. Chamber measurements were conducted from mid-June to mid-October 2010, *i.e.* during most of the snow-free period, with four automated opaque CO_2 flux chambers (model 8100-104, LI-COR, USA) connected to a LI-8100/8150 multiplexer system (LI-COR, USA). The four chambers measured consecutively with an observation length of 120 s and a deadband (the time interval before steady mixing is established) of 30 s. A delay time and purging period was also set between two sequential measurements to avoid contamination between chambers. Each chamber was sampled twice in a measurement cycle and the resulting fluxes were aggregated to half-hourly values. CO_2 fluxes were calculated with the manufacturer software as the time rate of change of CO_2 mixing ratio in the measurement chamber. Due to high and low turbulent mixing during day and night respectively, post-field adjustments of the deadband duration were applied to optimise the reliability of flux calculations (Brændholt et al., 2016).

Basic meteorological parameters were regularly measured at the study site. Air temperature was measured with a Pt1000 thermometer (HMP45, Vaisala, Finland) at 1.5 m above the ground and soil temperature with thermistors (Therm107, Campbell Scientific, USA) installed at different depths below ground (0.02, 0.10, 0.25 and 0.35 m). An infrared radiometer sensor (SI111, Apogee Instruments, USA) was installed to infer surface temperature.

Because measurements were made with opaque chambers, *i.e.* in darkness also during daytime, our daytime R_{eco} estimates do not include the reduction in leaf mitochondrial respiration in light (Heskel et al., 2013) and thus allow to directly compare nighttime with daytime R_{eco} without the associated complications (Wohlfahrt et al., 2005b; Wohlfahrt and Gu, 2015). This was confirmed experimentally by comparing measurements of chambers that had been dark-adapted for longer periods (up to one hour) with normally operating chambers (data not shown).

Night and daytime data were distinguished based on a threshold of calculated (after Ham, 2005) potential incident radiation of 20 $W\, m^{-2}$. The following analyses were carried out both with air temperature and the average soil temperature at 0.02 and 0.1 m soil depth. Preliminary analysis with the radiometrically inferred surface temperature and soil temperatures at 0.02 and 0.1 m depth showed that the results obtained with the two chosen driving temperatures were quantitatively and qualitatively representative (data not shown).