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Comparing ecosystem and soil respiration: Review and key challenges of tower-based and soil measurements

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ABSTRACT

The net ecosystem exchange (NEE) is the difference between ecosystem CO_2 assimilation and CO_2 losses to the atmosphere. Ecosystem respiration (R_{eco}), the efflux of CO_2 from the ecosystem to the atmosphere, includes the soil-to-atmosphere carbon flux (i.e., soil respiration; R_{soil}) and aboveground plant respiration. Therefore, R_{soil} is a fraction of R_{eco} and theoretically has to be smaller than R_{eco} at daily, seasonal, and annual scales. However, several studies estimating R_{eco} with the eddy covariance technique and measuring R_{soil} within the footprint of the tower have reported higher R_{soil} than R_{eco} at different time scales. Here, we compare four different and contrasting ecosystems (from forest to grasslands, and from boreal to semiarid) to test if measurements of R_{eco} are consistently higher than R_{soil}. In general, both fluxes showed similar temporal patterns, but R_{eco} was not consistently higher than R_{soil} from daily to annual scales across sites. We identified several issues that apply for measuring NEE and measuring/upscaling R_{soil} that could result in an underestimation of R_{eco} and/or an overestimation of R_{soil}. These issues are discussed based on (a) nighttime measurements of NEE, (b) R_{soil} measurements, and (c) the interpretation of the functional relationships of these fluxes with temperature (i.e., Q_{10}). We highlight that there is still a need for better integration of R_{soil} with eddy covariance measurements to address challenges related to the spatial and temporal variability of R_{eco} and R_{soil}.

1. Introduction

The net ecosystem exchange (NEE) is the difference between atmospheric carbon dioxide (CO_2) assimilation through photosynthesis (gross primary production; GPP) and the efflux of CO_2 released back to the atmosphere through respiration processes (ecosystem respiration; R_{eco}) (Baldocchi, 2003). R_{eco} is a composite of different complex biological and non-biological sources. These include aboveground respiration, mainly from leaves (R_L) and woody tissues (R_w) (Brüggemann et al., 2011), and belowground respiration, derived from soil respiration (R_{soil}, the sum of both autotrophic and heterotrophic processes) (Ryan and Law, 2005), carbonate weathering (CW) (Mörner and Etiope, 2002; Rey, 2014), subterranean ventilation (SV) (Sanchez-Cañete et al., 2011), or photo-degradation (PD) (Austin and Vivanco, 2006). Therefore, R_{eco} can be defined as:

$$R_{eco} = R_{soil} + R_L + R_w + CW + SV + PD \qquad (1)$$

R_{soil} is expected to be the largest component of R_{eco} (Davidson et al., 2006), but it is still a fraction and theoretically has to be smaller than R_{eco} (i.e., $R_{eco} > R_{soil}$) at annual, seasonal, daily, or sub-daily scales.

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Nonetheless, several studies have found discrepancies between measurements of R_{eco} and R_{soil}, with R_{soil} being higher than R_{eco} (Barron-Gafford et al., 2011; Phillips et al., 2016; Speckman et al., 2015; Van Gorsel et al., 2007; Wang et al., 2010). These studies have combined ecosystem-scale measurements of CO_2 fluxes, using the eddy covariance (EC) technique, with independent site-specific automated R_{soil} measurements within the footprint of an EC tower. Studies performed across deciduous and temperate forests, managed meadows, semiarid grasslands, and rainforests have shown that R_{eco} could be between 27% and 50% lower than R_{soil} (Van Gorsel et al., 2007; Wang et al., 2010). Thus, it is critical to identify discrepancies between these two fluxes, and examine measurements of R_{soil} and estimates of R_{eco} as inconsistencies could lead to biased local to global carbon budgets and partitioning of ecosystem fluxes. A recent review has identified this topic as one of the three major challenges for interpreting respiration processes in ecosystems (Phillips et al., 2016).

The EC technique allows a direct estimate of NEE, using micrometeorological theory to quantify the covariance between turbulent fluctuations of the vertical wind speed and CO_2 (Aubinet et al., 1999; Baldocchi, 2003). The EC technique has been used to measure NEE at the ecosystem scale with more than 650 EC towers distributed in a wide variety of ecosystems (Baldocchi, 2014), improving our knowledge of the exchange of energy and matter between ecosystems and the atmosphere around the world (Beer et al., 2010; Jung et al., 2010; Mahecha et al., 2010).

As with any technique, the EC approach comes with some limitations. Several studies have discussed these challenges (Finnigan, 2008; Massman and Lee, 2002; Schimel et al., 2008) or how to quantify errors in measurements (Goulden et al., 1996; Hollinger and Richardson, 2005; Loescher et al., 2006; Moncrieff et al., 1996). Arguably, the largest limitation of EC CO_2 flux measurements comes from low atmospheric mixing at night (Aubinet, 2008; Burba and Anderson, 2010; Gu et al., 2005). During calm and stable night conditions, advection may be predominant (Cooper et al., 2006; Gu et al., 2005; Horst and Doran, 1986; Massman and Lee, 2002; Van Gorsel et al., 2007); thus, CO_2 produced near the ground can be transported laterally, and not measured by the EC tower (Aubinet et al., 2003; Baldocchi et al., 2000; Feigenwinter et al., 2008; Finnigan, 1999; Lee, 1998; Roland et al., 2015; Speckman et al., 2015). In contrast, during daytime, convective mixing often minimizes advection (Galvagno et al., 2017), creating appropriate micrometeorological conditions to apply the EC technique. Finally, since NEE is the difference between GPP and R_{eco} there are two general ways to estimate R_{eco} from EC (Desai et al., 2008): 1) estimating GPP using light-response curves fitted to daytime NEE (NEE_{Day}) to estimate daytime R_{eco} as the difference of GPP and NEE (Lasslop et al., 2010); and 2) estimating R_{eco} using nighttime NEE (NEE_{Night}) to fit an exponential relationship with air or soil temperature (Arrhenius, 1889) and extrapolating to daytime (thus, assuming that temperature functional relationship is the same for night and daytime); consequently, GPP is derived by adding NEE and R_{eco} (Reichstein et al., 2005). For both approaches, a bias in the estimation of one component may result in an over- or under-estimation of the other component. Previous studies have argued that both partitioning approaches result in similar cross-site results and are widely used across studies (Desai et al., 2008; Falge et al., 2001; Lasslop et al., 2010; Moffat et al., 2007).

R_{soil} has been commonly measured using static (non-) steady-state, (non-) through-flow chambers (Livingston and Hutchinson, 1995; Pumpanen et al., 2004), and most recently with the soil gradient method (Hirano et al., 2003; Tang et al., 2003), making continuous automated measurements of R_{soil} possible (Vargas et al., 2011). Previous studies have provided intercomparisons among different instruments designs and techniques to measure R_{soil} suggesting comparable results (Görres et al., 2016; Pumpanen et al., 2004; Pumpanen et al., 2003; Riveros-Iregui et al., 2008). However, high-temporal frequency measurements of R_{soil} have pitfalls due to the lack of spatial representation and the small area of the measurements (i.e., single point-measurements (Savage and Davidson, 2003)). Such measurements are usually performed at a few locations assumed to be representative of the whole ecosystem (in both patterns and magnitudes), but may underrepresent the spatial variability of R_{soil} (Barba et al., 2013), especially in those ecosystems where hotspots and high flux events are present (Jenerette et al., 2008; Leon et al., 2014). Thus, a scientific challenge is to properly represent R_{soil} spatial heterogeneity to capture spatial and temporal trends that are representative at the ecosystem scale.

The main goal of this study is to bring attention to issues and challenges related to discrepancies between R_{eco} and R_{soil} and, in light of the 20th anniversary of the AmeriFlux network, encourage new research to improve our understanding of respiration processes at the ecosystem scale. To this end we take advantage of four contrasting ecosystems (from forests to grasslands, and from boreal to semiarid ecosystems) to analyze how R_{eco}, estimated using the EC technique, compares with site-specific continuous measurements of R_{soil}. We hypothesize that 1) nighttime NEE (NEE_{Night}) should be similar to nighttime estimates of R_{eco} ($R_{ecoNight}$); 2) the temperature sensitivity (i.e., Q_{10}) of $R_{soilNight}$ and $R_{soilDay}$ should be similar, thus justifying the use of nighttime functional relations to estimate daytime fluxes; 3) the temperature sensitivity and temporal patterns of R_{eco} and R_{soil} should be similar within each study site, since R_{soil} is the main component of R_{eco}; but 4) R_{eco} should be higher than R_{soil} at annual, seasonal and daily scales at each site. We conclude with a review about issues influencing nighttime measurements of NEE, R_{soil} measurements, and the interpretation of the functional relationships between R_{soil} and R_{eco} with temperature.

2. Material and methods

2.1. Study sites

We consider four contrasting experimental sites with NEE measurements using the EC technique, and R_{soil} measurements collected within the footprint of the EC tower. The study sites include: a boreal evergreen forest, a temperate broadleaf forest, a temperate grassland, and a semiarid savanna.

The first site is a boreal evergreen forest (FI-Hyy, also known as SMEARII), located nearby the Hyytiälä Forestry Field Station, Finland. The vegetation is characterized by ~52 yr old boreal coniferous forest dominated by Scots pine (*Pinus sylvestris* L.). The soil type is a Haplic podzol. The EC system is composed by a three-dimensional sonic anemometer (R3IA; Gill Instruments Ltd) and a closed-path CO_2/H_2O infrared gas analyzer (LI6262; Li-Cor Inc.) installed above the forest canopy at a height of 23 m. R_{soil} was measured using automatic chambers based on the closed dynamic chamber technique (Pumpanen et al., 2015). R_{soil} could not be measured when soils were covered by snow (135 days of the year). FI-Hyy data used in this study were measured during 2008. Environmental conditions during the study period are shown in Sup. Fig. 1. We refer to specific bibliography for further information on instrumentation and characteristics of this study site (Bäck et al., 2012; Hari and Kulmala, 2005; Vesala et al., 2005).

The second site is a temperate grassland (AT-Neu), located in a meadow in the vicinity of the village Neustift in the Stubai Valley, Austria. The vegetation consists mainly of a few dominant graminoids (*Dactylis glomerata L., Festuca pratensis Huds., Phleum pratensis L., Trisetum flavescens (L.) Beauv.),* and forbs (*Ranunculus acris L., Taraxacum officinale G.H. Weber ex Wiggers, Trifolium pretense L., Trifolium repens L., Carum carvi L.)*. The soil type is a Gleyic fluvisol. The EC system included a three-dimensional sonic anemometer (R3IA; Gill Instruments) and a closed-path CO_2/H_2O infrared gas analyzer (LI6262; Li-Cor Inc.) installed above the grassland at a height of 3 m (Wohlfahrt et al., 2008). R_{soil} was measured using solid-state CO_2 sensors installed at 5 and 10 cm depth, employing the gradient flux method and located within the footprint of the flux tower (Vargas et al., 2011). AT-Neu data