



# Potentials and limitations for estimating daytime ecosystem respiration by combining tower-based remote sensing and carbon flux measurements



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## ABSTRACT

Vegetation carbon uptake and respiration constitute the largest carbon cycle of the planet with an annual turnover in the order of 120 GT. Currently, neither ecosystem carbon uptake (through photosynthesis) nor ecosystem carbon release (through respiration) can be measured directly during the daytime. Instead, flux-tower measurements rely on nighttime respiration based on the assumption of zero carbon uptake which are then projected to daytime using an exponential relationship to soil temperature at shallow soil depth. As an alternative to this approach,  $R$  could possibly also be determined from combining daytime eddy covariance measurements of net ecosystem production (NEP) and spectral observations of gross primary production (GPP). In previous work, we have shown that multi-angular observations can be used to determine GPP from the absorbed photosynthetically active radiation (APAR) and spectrally obtained observations of light-use efficiency ( $\epsilon$ ). The difference of NEP and GPP suggests that daytime respiration is greater and more dynamic than conventional estimates derived from nighttime flux values. Our findings also suggest that an accelerated ecosystem metabolism results in an exponential increase in respiration which eventually diminishes net ecosystem production. Respiration was also closely related to air and soil temperature. We conclude that tower-level spectral measurements provide considerable new insights into ecosystem fluxes as they allow independent yet complementary measurements of different aspects of the carbon and energy cycle.

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## 1. Introduction

Net ecosystem productivity (NEP) is the difference between gross primary production (GPP) and the sum of autotrophic and heterotrophic respiration ( $R$ ), also known as ecosystem respiration (Trumbore, 2006). As both GPP and  $R$  are much greater fluxes than NEP, comprehensive understanding of these components is essential for determining the response of ecosystems to global change and related carbon feedbacks (Janssens et al., 2001; Valentini et al., 2000). Currently, it is not possible to measure  $R$  directly in the presence of photosynthesis (Desai et al., 2008). Instead, most stand-level estimates of respiration rely on nighttime flux measurements of NEP, based on an assumption of zero GPP (Reichstein et al., 2005). These nighttime flux observations

are extrapolated to daytime measurements using relationships between nighttime  $R$  ( $R_N$ ) and various environmental drivers; most commonly, an exponential relation between  $R_N$  and soil temperature ( $T_s$ ) is used (Morgenstern et al., 2004):

$$R = R_{10} Q_{10}^{(T_s - 10)/10} \quad (1)$$

where  $R_{10}$  is the nocturnal ecosystem respiration ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) at a reference temperature of 10 °C,  $T_s$  is the soil temperature at a shallow depth (e.g. 5 cm) and  $Q_{10}$  is the factor by which  $R$  increases for a 10 °C increase in temperature (Lloyd & Taylor, 2014). Methods based on  $Q_{10}$  estimates of  $R_N$  are widely applied across different scales (Beer et al., 2010; Mahecha et al., 2010); but limitations have also been documented. First, low friction velocity ( $u_*$ ) during calm nocturnal periods can result in insufficient turbulent mixing (Van Gorsel et al., 2009) and, consequently, a systematic underestimation of fluxes has been observed during those times (Goulden, Munger, Fan, Daube, & Wofsy, 1996);

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Lavigne et al., 1997). Second, the use of the relationship between nighttime NEP versus temperature to calculate daytime  $R_D$  ignores the light inhibition of respiration (Janssens et al., 2001). Finally, different transport mechanisms of heat and momentum at leaf level (Belcher, Finnigan, & Harman, 2008) result in faster changes in the wind profile through the canopy than of the temperature profile (Van Gorsel et al., 2009). Reichstein et al. (2005) found a 25% difference in daytime  $R$  depending on whether observations were derived from short term or long term temperature sensitivities.

As a complementary approach to extrapolation of night time flux measurements, this paper explores the potentials and limitations for using remotely sensed estimates of GPP to obtain  $R_D$  by computing the difference between GPP and NEP derived from eddy covariance fluxes. Using a flux-tower based, automated, multi-angle spectro-radiometer (AMSPEC) (Hilker, Nesic, Coops, & Lessard, 2010), we have shown in previous work that stand-level GPP may be obtained from multi-angle reflectance as product of the fraction of absorbed PAR intercepted by the canopy (APAR) and the photosynthetic light use efficiency,  $\epsilon$  (Monteith & Moss, 1977). GPP estimates based on this approach could potentially provide an independent method for determining stand-level respiration without having to resort to night-time fluxes. Estimates of APAR have long been derived from vegetation indices, and work by Chen, Rich, Gower, Norman, and Plummer (1997) and Ryu et al. (2011) has demonstrated that angular retrievals of spectral reflectance can help to account for canopy clumping of foliage elements (Chen, Cihlar, & Chen, 2000; Chen et al., 1997) and bi-directional reflectance effects (Los, North, Grey, & Barnsley, 2005).

In our previous work (Hall et al., 2008; Hilker, Hall, et al., 2010) we have demonstrated that  $\epsilon$  may be robustly inferred across ecosystems using the first derivative of the photochemical reflectance index (a xanthophyll sensitive spectral index, Gamon, Peñuelas, & Field, 1992), with respect to shadow fractions ( $\alpha_s$ ) (PRI'). The relationship between PRI' and  $\epsilon$  is based on first principles, as  $\epsilon$  is closely linked to the xanthophyll cycle, a biochemical mechanism to balance light-use and absorption in leaves (Demmig-Adams & Adams, 1996). Hall, Hilker, and Coops (2011) described the theoretical foundations of this relationship and its form based on the assumption that  $PRI' = 0$  for  $\epsilon = \epsilon_{\max}$  and  $PRI' \rightarrow \infty$  for  $\epsilon \rightarrow 0$ : In cases where GPP is limited by factors other than light ( $\epsilon < \epsilon_{\max}$ ),  $\epsilon$  is closely related to canopy  $\alpha_s$  as sunlit leaves are more likely to be exposed to excess radiation levels than shaded leaves (Hall et al., 2008). This relationship however, disappears under conditions where light is limiting GPP ( $\epsilon = \epsilon_{\max}$ ), as in this case, photosynthesis will, by definition, not be down-regulated in either sunlit or shaded leaves (Hilker, Hall, et al., 2010).

The daytime footprints between EC-flux observations and AMSPEC measurements are similar (Hilker et al., 2008), and as a result, AMSPEC observations may provide new opportunities to estimate and

validate  $R_D$  by combining tower-based remote sensing and eddy flux observations.

The objective of this work is to investigate and compare the temporal dynamics, similarities and differences of the described method as opposed to deriving  $R_D$  conventionally as a ( $Q_{10}$ ) function of  $T_S$ . Based on results from five different forest sites spanning a range of biophysical and spectral characteristics, we conclude that tower-based spectral observations can be a vital tool for improving estimates of carbon fluxes in terrestrial ecosystems, and provide new opportunities to scale estimates of carbon fluxes in space and time.

## 2. Methods

### 2.1. Site description

Five research sites were selected to cover a variety of temperate and sub-arctic forest stands; including a coastal Douglas-fir (*Pseudotsuga menziesii* var *menziesii* (Mirb.)) dominated stand on Vancouver Island (DF49), an Aspen (*Populus tremuloides* Michx.) dominated forest in Central Saskatchewan (SOA) and three mountain pine beetle (*Dendroctonus ponderosae* Hopk.) affected lodgepole pine (*Pinus contorta* Dougl. ex Loud var. *latifolia* Engl.) stands in Northern British Columbia. Table 1 contains an overview, references and site description for each individual stand and the dates that the spectral data were acquired.

### 2.2. Eddy covariance measurements

Simultaneous flux measurements and multi-angular spectral data were acquired as part of the Canadian Carbon Program. Net ecosystem exchange (NEE) was determined as the sum of the half-hourly EC fluxes of  $CO_2$  and the rate of change in  $CO_2$  storage in the air column between ground and EC-measurement height. At DF49 and SOA, EC fluxes were measured using a three-axis sonic anemometer–thermometer (Model R3, Gill Instruments Ltd., Lymington, UK) and a closed-path  $CO_2/H_2O$  infrared gas analyzer (IRGA) (LI-6262 or LI-7000, LI-COR Inc., Lincoln, NE, USA) (Barr et al., 2004; Jassal et al., 2007). At the Northern BC sites, a three-axis sonic anemometer–thermometer (Model CSAT3, Campbell Scientific Inc, Logan UT, USA) and an open-path  $CO_2/H_2O$  IRGA (Model LI-7500, LI-COR Inc.) were used (Brown et al., 2010). The rate of change in  $CO_2$  storage in the air column was calculated from the half-hour average  $CO_2$  concentrations obtained at EC measurement height (Morgenstern et al., 2004). Incident and reflected PAR [ $\mu mol m^{-2} s^{-1}$ ] was measured using upward and downward looking quantum sensors (model 190 SZ and 190 SA, LI-COR Inc.) above and below the canopy and  $f_{PAR}$  was derived at each site from the incident and reflected total PAR measured above and below the canopy, leaf area index, and the solar zenith angle ( $\theta$ ) at the time of measurement

**Table 1**  
Study site descriptions and acquisition dates.

Site, reference	Lat (°)/long (°)	Elev (m)	Dominant species	LAI	Age (years)	Height (m)	Annual mean temp. (°C)	Data acquisition dates
Campbell River (DF49) (Morgenstern et al., 2004)	–125.334 49.867	340	<i>Pseudotsuga menziesii</i> , <i>Thuja plicata</i> , <i>Tsuga heterophylla</i>	7.1	60	35	8.1	2006/04/01– 2007/03/31 2008/03/17– 2008/10/21 2009/05/14– 2009/10/20
Kennedy Siding (MPB-06) (Brown et al., 2010; Hilker et al., 2009)	–122.840 55.112	750	<i>Pinus contorta</i> , <i>Abies lasiocarpa</i> , <i>Picea glauca</i> Understorey: <i>Alnus tenuifolia</i> , <i>Salix</i> spp., <i>Vaccinium</i> spp.	1.3	80	15	–2.3	2007/04/25– 2004/10/18
Crooked River (MPB-03) (Brown et al., 2010)	–122.713 54.473	710	<i>Pinus contorta</i> , <i>Abies lasiocarpa</i> , <i>Picea glauca</i> Understorey: <i>Salix</i> spp., <i>Vaccinium</i> spp.	0.9	110	17	–2.3	2010/07/10– 2010/08/24
Summit Lake (MPB-09)	–122.614 54.224	800	<i>Picea mariana</i> , <i>Picea engelmannii</i> x <i>glauca</i> , <i>Abies lasiocarpa</i>	0.5	70	16	–2.3	2010/07/10– 2010/08/24
Southern Old Aspen (SOA) (Barr et al., 2004)	106.198–52.629	600	<i>Populus tremuloides</i> Understorey: <i>Corylus cornuta</i>	2.1	83	22	0.4	2009/05/26– 2009/11/04

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