Agricultural and Forest Meteorology 173 (2013) 14–27

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

# Toward biologically meaningful net carbon exchange estimates for tall, dense canopies: Multi-level eddy covariance observations and canopy coupling regimes in a mature Douglas-fir forest in Oregon

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ARTICLE INFO

*Article history:*
Received 18 June 2012
Received in revised form 6 November 2012
Accepted 7 January 2013

*Keywords:*
Net ecosystem exchange
Ecosystem respiration
Advection
Eddy covariance
U-star correction
Canopy flow
Douglas-fir
Turbulence

ABSTRACT

We sought to improve net ecosystem exchange (NEE) estimates for a tall, dense, mature Douglas-fir forest in the Oregon Coast range characterized by weak flows, systematic wind directional shear, and limited turbulent mixing throughout the diurnal period. We used eddy covariance (EC) observations at two levels and concurrent biological measurements of carbon and water fluxes collected over a period of 6 years (2006–2011) to develop and test a conceptual framework to (i) reduce uncertainty by retaining more measurements for the computation of annual NEE sums and (ii) produce defendable and biologically meaningful estimates by accounting for the missing sub-canopy respiration. The framework assumes that (a) the scalar exchange between vertical layers can be categorized into discrete canopy coupling regimes and (b) advection leads to a systematic loss of scalar from the observational volume that can indirectly be estimated and accounted for as sub-canopy respiration flux when canopy layers are decoupled.

Periods with a decoupled sub-canopy layer dominated and occupied 65 and 88% of the day- and nighttime periods, respectively. Annual NEE derived from the new framework was estimated as $480\,gC\,m^{-2}\,year^{-1}$, which was reduced by $620\,gC\,m^{-2}\,year^{-1}$ compared to traditional estimates from single-level EC data filtered using a critical friction velocity. The reduced NEE was due to an enhanced ecosystem respiration (RE), while gross ecosystem productivity remained unchanged. Improved RE estimates agreed well with those from independent estimates based on soil, stem, and foliage respiration within 3%. Risks and limitations of the new framework are discussed. We conclude that concurrent above- and sub-canopy EC observations are essential to measure a meaningful carbon balance in tall, dense forests since they do no lend themselves to traditional, standardized processing. The new framework may help to include more tall and dense forests in global carbon cycle synthesis and modeling efforts.


## 1. Introduction

The net ecosystem exchange NEE is the single most important parameter describing the strength of the carbon sink or source of terrestrial ecosystems. Its estimation has received much attention in the literature and a commonly identified obstacle is the 'nighttime problem' when weak turbulent mixing becomes limiting and the computed NEE from a simplified mass balance approach may not reflect ecosystem functioning (see Goulden et al., 1996; Aubinet et al., 2000; Baldocchi, 2003; Papale et al., 2006, and references therein). The simplified mass balance approach defines NEE as the sum of the turbulent vertical carbon dioxide or methane flux observed above the canopy and the temporal change in storage term from profile observations. In contrast, during the day when mixing is enhanced through stronger flows and significant heat flux, estimates of NEE are typically assumed to reflect ecosystem response to environmental drivers such as light, nutrients, and water independent of the strength of the turbulent transport. Global NEE estimates are modeled based on continental observational networks representing the major biomes, but the selection of individual sites within the networks may be biased toward short vegetation such as grass, open shrubland, and forest. In these canopies, mixing of the scalar sinks and sources can sufficiently well be estimated using variety of mixing indicators. Quantities that have been proposed as a proxy for the turbulent mixing strength include the standard deviation of the vertical velocity

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http://dx.doi.org/10.1016/j.agrformet.2013.01.001

variance $\sigma_w$ (e.g., Acevedo et al., 2009), the friction velocity $u_*$ (e.g., Goulden et al., 1996), their non-dimensional ratio $\sigma_w u_*^{-1}$ termed the integral turbulence characteristic (e.g., Foken and Wichura, 1996; Thomas and Foken, 2002), the mean wind speed $U$ (e.g., Suyker et al., 2003), and a modified turbulent kinetic energy scale $u_{TKE}$ (Wharton et al., 2009). The indicators are typically evaluated from eddy covariance (EC) measurements with a fixed perturbation time scale of 30 or 60 min taken at a single level above the main canopy. However, dense canopies pose additional challenges as they suffer from a night- and daytime problem, since the dense crown space with the maximum plant area index (PAI) presents a mechanical barrier and efficient momentum sink throughout the diurnal cycle leading to a frequent, persistent decoupling of the sub-canopy from the overstory and above-canopy layers (e.g., Thomas and Foken, 2007; Belcher et al., 2008). In contrast, short vegetation and open forests are only temporally limited by turbulent mixing when surface heating and the mean flow are weak, which typically occurs at night in the absence of significant synoptic meso-scale forcing. As a result, forests with high-PAI, closed canopies are often excluded from network syntheses for reasons of uncertain data quality and insufficient number of observations, since many measurements need to be discarded for the computation of seasonal and annual NEE because of the systematic turbulence limitations. However, these ecosystems may be very efficient carbon sinks as demonstrated by their high PAI, which can only be sustained in high productivity ecosystems. Hence, we identify a significant observational, modeling, and interpretational problem when assessing regional to global carbon balances and their dynamics without the inclusion of tall and dense forests.

In this study we seek to improve NEE estimates for a very dense mature Douglas-fir stand analyzing 6 years of concurrent EC flux observations at two levels, above the main canopy crown and in the clear bole space below the main canopy crown, with the following objectives:

- identify a simple and meaningful estimator for canopy mixing, coupling, and decoupling that reflects characteristics of the mean flow and the turbulent carbon, sensible and latent heat, and momentum fluxes;
- construct an alternative and practical theoretical framework for the evaluation of multi-level EC observations to estimate NEE;
- increase the fraction of sub-daily NEE estimates that are retained for the computation of seasonal and annual sums, which are assumed to reflect ecosystem behavior;
- compute an improved carbon balance by applying the proposed framework to the observations.

We do not expect this study to solve the problem of overestimating NEE by systematically missing ecosystem respiration, but it may be an important step toward producing defendable and biologically meaningful estimates for dense canopy sites. The ultimate goal is to include these ecologically important sites into network syntheses and global estimates. We further aim at demonstrating the utility of concurrent sub-canopy EC observations to better understand turbulent mixing and other micrometeorological processes in dense canopies. In the literature, only few studies exist that utilize sub-canopy EC observations with the intention of either incorporating their flux estimates into the carbon mass balance or partitioning net carbon fluxes into its components (e.g., Misson et al., 2007; Falk et al., 2008). A number of recent studies has focused on evaluating the advective terms directly using sensor networks and include their flux contributions to the mass balance (e.g., Feigenwinter et al., 2004; Staebler and Fitzjarrald, 2004; Aubinet et al., 2005), while the success of these efforts has recently been questioned (Aubinet et al., 2010).

## 2. Conceptual framework

Diagnosing the dynamics of the canopy flow and its turbulence is critical to connecting the biologically active surfaces such as the foliage, stems, and the soil with the micrometeorological sensors used to quantify the ecosystem scalar exchange. The conceptual framework presented here is based on two major assumptions: first, coupling between vertical layers of the soil–plant–air continuum and thus the exchange of scalar flux varies depending on the strength of the turbulent mixing, which can be diagnosed using multi-level turbulence statistics. Secondly, both vertical and horizontal advection is the main transport mechanism removing the scalar from the observational volume when layers are decoupled. The concept of vertical communication of air across the canopy profile is based on the exchange regimes proposed by Thomas and Foken (2007) for a tall, moderately dense spruce canopy with a PAI of 5.2. Their work differentiates between different conceptual vertical layers which together comprise most of the roughness sub-layer (Fig. 1): (i) the above-canopy layer between the top of the overstory and the upper EC observation height, (ii) the overstory where most of the PAI is concentrated, (iii) the sub-canopy layer or the clear bole space with minimum PAI, and (iv) the ground layer including the soil surface and understory including herbs and shrubs often comprising a secondary maximum in the PAI profile. For a typical EC setup located above the canopy at $zh_c^{-1} \approx 1.2$–$1.8$, where $z$ is the observation and $h_c$ the mean canopy height, to measure the entire ecosystem, i.e., integrate over all its vertically distributed scalar sources and sinks, one must assure that turbulent eddies communicate across all three interfaces between these four layers. In their approach horizontal heterogeneity and transport were originally neglected, but were investigated later by Serafimovich et al. (2011). Thomas and Foken (2007) proposed five exchange regimes with increasing degree of vertical communication between the layers using turbulence measurements at five observation levels to determine the penetration depth and flux contribution of mixing-layer type eddies. They demonstrated that the sub-canopy layer is often decoupled from the crown and free roughness sub-layers even during the day when the above-canopy flow and turbulent mixing are significant. A recent study by Foken et al. (2012) confirmed the utility of this concept when investigating the dynamics of ecosystem fluxes of volatile organic compounds, nitrous oxides, and ozone. The authors concluded that the observed concentration profiles and fluxes could only be explained when the cross-interface transport was diagnosed using the exchange regimes, while other simpler methods including the critical $u_*$ threshold approach (Goulden et al., 1996) failed.

Since extensive multi-level EC observations and complex post-processing are impractical and probably cost-prohibitive for long-term ecosystem studies targeting measuring NEE on annual and decadal time scales, we simplified the method. The method proposed here diagnoses the cross-interface transport based on only two observational heights located in the above- and sub-canopy layers while retaining the concept of exchange regimes and layers. We further added a concept originally proposed by Scanlon and Albertson (2001) to use scalar–scalar cross-correlations between perturbations in carbon dioxide and water vapor mixing ratios to partition scalar sinks and sources. Instead of partitioning, we here invert the original idea and apply it to diagnose the communication of air across the canopy profile by relating the scalar–scalar fingerprint to the turbulent mixing strength. The simplified conceptual framework differentiates between three exchange regimes:

- Fully coupled canopy (C): above-canopy EC fluxes fully integrate over all scalar sinks and sources and are representative of the entire ecosystem. This is the ideal state typically assumed for traditional EC analysis of NEE.