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Improving the CO_2 storage measurements with a single profile system in a tall-dense-canopy temperate forest

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ABSTRACT

The CO_2 storage (F_s) measurement can contribute significantly to the estimation of the net ecosystem exchange of CO_2 (NEE) especially in tall-canopy forest ecosystems. The F_s is often measured with a profile of CO_2 concentration or with an eddy covariance system at the tower top, but few studies investigated potential errors in the F_s measurements. We assessed the errors in F_s relevant to the vertical distribution of sampling levels and window sizes of averaging time of CO_2 mixing ratio and their effects on NEE in a temperate deciduous forest site in Northeast China using the standardized major axis method. The CO_2 storage per unit height typically decreased with the height increasing, suggesting that the below-canopy layer need a higher spatial resolution. CO_2 storage could be underestimated by up to one third based only on the tower-top measurement. The uncertainty (standard deviation) of the F_s decreased with the length of the averaging time window increasing. However, taking time averaging of CO_2 mixing ratio caused significant underestimate of F_s, and consequently led to significant underestimates of CO_2 uptake and release at a 30-min time scale. Our results highlight that appropriately combining spatial resolution and temporal resolution (response time for a whole sampling of all levels) is essential to improving the F_s estimates with the existing CO_2 profile systems in forest ecosystems. Since the systematic bias and random error in F_s estimate with a single profile system are irreconcilable, there is an urgent need to develop a fast response planar-averaging profile or measure the instantaneous vertical-mean concentration to improve the accuracy of F_s measurement.

1. Introduction

Rapid development of the FLUXNET network (Baldocchi et al., 2001) has greatly improved our understanding of carbon and water fluxes in terrestrial ecosystems in recent years (Papale et al., 2015). The eddy covariance (EC) method provides direct flux measurements of trace gas and energy across the atmosphere–ecosystem interface without disturbing the vegetation and the soil (Aubinet et al., 2012). There are more than 600 active sites globally (Papale et al., 2015), among which dozens have more than a decade of the duration of the time series (Baldocchi, 2014). Generally, the net ecosystem exchange of CO_2 (NEE) can be estimated by summing the vertical eddy flux (F_c), the advection term, and the storage term (F_s) (Aubinet et al., 2005). The F_c can be a close estimation of NEE under ideal conditions (horizontal homogeneity, enough footprint, flat terrain or after appropriate axis choice, strong turbulent mixing, and steady state conditions) (Aubinet et al., 2012; Baldocchi, 2003). However, the conditions in field are rarely ideal, which leads to frequent underestimation of NEE due to ignoring considerable contributions of the advection and F_s especially in tall-canopy forest ecosystems (Papale et al., 2006; Yang et al., 2007).

Great efforts have been made on improving the accuracy of F_c and advection (Aubinet et al., 2012), but few studies investigated the errors of F_s. The F_s can be significant at short time periods such as half-hours, particularly around sunrise, sunset, or at night (e.g., Dolman et al., 2002; Finnigan, 2006; Yang et al., 2007). Therefore, the F_s should be taken into account because of potential error propagation in the gap-filling processing for annual NEE estimation (Papale et al., 2006). As long as the F_s is properly tackled, potential underestimations of NEE on calm nights can be greatly reduced after the critical friction velocity filtering (Papale et al., 2006; Yang et al., 2007) or by using the data in the early evening period (van Gorsel et al., 2007).

The first objective of this study is to assess the effect of vertical configuration of a CO_2 profile system on F_s estimates. An essential issue of F_s is the uncertainty caused by the spatial and temporal

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Nomenclature

χ_c	Molar mixing ratio of CO_2 (μmol mol^{-1})
c_c	Molar fraction of CO_2 (μmol mol^{-1})
c_v	Molar fraction of water vapor (mmol mol^{-1})
ρ_a	Moist air molar density (mol m^{-3})
ρ_c	CO_2 density (mg m^{-3})
ρ_{dz}	Molar density of dry air at 36 m (mol m^{-3})
$\Delta\chi_c/\Delta t$	Time derivative of CO_2 mixing ratio
$\Delta\chi_{cz}$	Change of the molar mixing ratio of CO_2 at the EC height (μmol mol^{-1})
Δt	Time interval between the two samplings (1800 s)
EC	Eddy covariance
F_c	Vertical eddy flux (μmol m^{-2} s^{-1})
F_s	Storage term (μmol m^{-2} s^{-1} or μmol m^{-3} s^{-1})
F_{s_EC}	Storage term by the tower-top method (μmol m^{-2} s^{-1})
F_{s_p}	Storage term by the eight-level profile system (μmol m^{-2} s^{-1})
F_{s_p36m}	Storage term by the top level of the profile system (μmol m^{-2} s^{-1})
H	Height of the EC system (36 m)
IRGA	Infrared gas analyzer
LAI	Leaf area index (m^2 m^{-2})
M	Number of time windows for averaging of CO_2 mixing ratio in a flux averaging period (30 min)
M_c	Molar mass of CO_2
N	Number of sampling levels of a profile system
NEE	Net ecosystem exchange of CO_2 (μmol m^{-2} s^{-1})
OLS	Ordinary least square
P	Length of the window (min)
SD	Standard deviation
SMA	Standardized major axis

variability in CO_2 concentration. The F_s for a single flux tower design is often estimated from a single vertical profile of CO_2 concentration (Finnigan, 2006). A literature review highlighted that there were substantial differences in sampling designs of CO_2 concentration profile systems, e.g., the number and vertical distribution of sampling levels, time needed for a complete profile measurement, and the percentage of the effective measurement time (Table S1). The simplest method for estimating F_s is based on the change in CO_2 density (or molar mixing ratio) measured by the EC system (the tower-top method) if a profile is not available. Some researchers assume that estimates of F_s based on tower-top and profile measurements are interchangeable (Carrara et al., 2003; Hollinger et al., 1994; Knohl et al., 2003), thus the tower-top method is widely used when profile measurements are not available. However, others report that the tower-top method substantially underestimates F_s compared with the profile system (Gu et al., 2012; Iwata et al., 2005; Yang et al., 2007, 1999). Then how many measurement levels are required to accurately quantify the CO_2 mixing ratio profile may depend on canopy complexity and height (Munger et al., 2012). For example, Yang et al. (2007) reported that more sampling levels were needed at the Missouri Ozark flux site in order to achieve the same level of accuracy as at a boreal aspen site (Yang et al., 1999), perhaps because of the difference in their canopy complexity (vertical complex vs. simple) (Yang et al., 2007). But it is not clear whether the difference in topography (e.g., the top of a ridge vs. flat terrain) contributes to it. In this study, we investigated the vertical configuration of an eight-level profile in a temperate forest at the Maoershan flux tower site in Northeast China with vertical complex canopy structure over the toe slope in a small valley. We will examine the relative importance of the complexity in canopy structure and topography on determination of the number of sampling levels and their vertical distribution.

Our second objective is to quantify the uncertainty (random error) in F_s due to discrete measurements for each level by a single infrared gas analyzer (IRGA). Many researchers use the design of single-IRGA with multiple inlets for CO_2 concentration gradient to remove the systematic errors between IRGAs (Table S1; Munger et al., 2012). The air from each inlet (height level) is sequentially flowed through a manifold and measured with an IRGA (Munger et al., 2012; Xu et al., 1999). The actual measurement from each inlet is thus discrete, and the effective measurement time for each height is much shorter than the averaging period (varying from 8% to 80% for single profile systems, Table S1). Because of the wavelike fluctuation of CO_2 concentration, the instantaneous or small time-window averaged CO_2 concentration may introduce large uncertainty in F_s (Heinesch et al., 2007; Marcolla et al., 2014; van Gorsel et al., 2011). van Gorsel et al. (2011) reported that the uncertainty caused by the wavelike motion of CO_2 concentration and discrete measurement was approximately 0.9 μmol m^{-2} s^{-1} in an open-canopy forest, which was large compared to the F_s of 0.3 μmol m^{-2} s^{-1}. Compared to the open-canopy forest, we will quantify the uncertainty of F_s measured with a profile system in our dense-canopy forest.

The third objective is to test whether time averaging of CO_2 concentration underestimates the F_s and consequently NEE. Theoretically, the F_s is the change rate of the instantaneous CO_2 concentration integrated in the control volume (Finnigan, 2006). For a single flux tower, it is the difference between instantaneous CO_2 concentration profiles at the tower measured at the beginning and end of the flux-averaging period, divided by the length of this period (Finnigan, 2006; Xu et al., 1999). The instantaneous CO_2 concentration profile for a single tower can be very noisy due to wind gusts and may not represent the average concentration of the whole control volume. To reduce the random error caused by insufficient spatial sampling, researchers adopt the strategy of replacing the spatial averaging by time-averaging (Finnigan, 2006). However, Finnigan (2006) inferred that the time-averaging procedure can underestimate F_s by at least 50% in most conditions because of filtering high frequency information. Using the single-point high-frequency CO_2 density measurement by the EC system, Yang et al. (2007) qualitatively verified the theoretical inference by Finnigan (2006). In contrast, Ohkubo et al. (2008) augured that the difference in F_s calculated based on a profile system by different sizes of time-averaging window was negligible. Whether the discrepancy is caused by the difference between single-point and profile measurements needs further studies. We will explore how the time averaging of CO_2 concentration influences the F_s and NEE.

In this study, we extended the work conducted by Yang et al. (1999) and Yang et al. (2007), and conducted our study in a temperate broad leaved deciduous forest at the Maoershan Forest Ecosystem Research Station in Northeast China. The fast cycling (one cycle of sequential measurements over the eight levels is completed in 2 min) eight-level profile (AP100, Campbell Scientific Inc., Logan, UT, USA) (Table S1; Wang et al., 2013b) provides us an opportunity to quantify uncertainty due to the discrete measurement and time averaging of CO_2 concentration. The hilly terrain and wind regime are common properties in forest ecosystems. A classic mountain-valley wind system over forest canopy was previously found at the Maoershan site (Wang et al., 2015). The F_s also had a typical diurnal variation in the forest ecosystem, with the negative peak occurring in the early morning and the positive maximum in the early evening (Wang et al., 2013b). Therefore, assessing the effects of sampling strategy and time averaging of the profile system on estimating F_s at the Maoershan site is of importance for assessing the NEE of forest ecosystems in Northeast China, and also has implications for other forest sites. We calculated the