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Research Paper

Quantifying and reducing the differences in forest CO_2-fluxes estimated by eddy covariance, biometric and chamber methods: A global synthesis

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ABSTRACT

Carbon dioxide (CO_2) fluxes between terrestrial ecosystems and the atmosphere are primarily measured with eddy covariance (EC), biometric, and chamber methods However, it is unclear why the estimates of the CO_2-fluxes, when measured using different methods, converge at some sites but diverge at others. We synthesized a novel global dataset of forest CO_2-fluxes to evaluate the consistency between EC and biometric or chamber methods for quantifying the CO_2 budget in forest ecosystems. The EC approach, compared with the other two methods, overestimated net ecosystem production (NEP) by 25% (0.52 Mg C ha^{-1} yr^{-1}), and underestimated ecosystem respiration (Re) by 10% (1.39 Mg C ha^{-1} yr^{-1}) and gross primary production by 3% (0.48 Mg C ha^{-1} yr^{-1}). The differences between EC and the other methods were greater at the sites with complex topography and dense canopy than at the sites with flat topography and open canopy. Forest age also influenced the differences mainly through changes in leaf area index. Open-path EC system induced large positive bias in the NEP estimated by EC, presumably due to its surface-heating effect. These results suggest that EC method likely produce biased estimates of NEP and Re in forest ecosystems. A global extrapolation suggests that the differences in the forest CO_2-fluxes measured with different methods be consistent with the global overestimation of NEP and underestimation of Re by EC method. Accounting for these differences would substantially improve our estimates of the forest carbon budget. The uncertainties involved in each method were also discussed. To reduce uncertainty in quantifying both local and global carbon budgets, we recommend cross-validation of forest CO_2-fluxes measured by different methods with more accurate measurements and careful data processing strategies.

1. Introduction

The terrestrial carbon (C) cycle, compared with the atmospheric and oceanic components, remains the least constrained component of the global C budget (Houghton, 2007; Le Quéré et al., 2016). The accuracy of the global C budget and process-model predictions depends strongly upon reliable ecosystem-level measurements of carbon dioxide (CO_2) fluxes (Jung et al., 2011; Luyssaert et al., 2009). A variety of methods has been used to estimate terrestrial CO_2-fluxes, such as eddy covariance (EC), biometric, chamber methods, etc. However, a brief global review on estimates of the terrestrial C budget reveals large differences in terrestrial gross primary production (GPP), ecosystem respiration (Re), soil respiration (R_S), and net biome production estimated by different methods (Table S1). For example, the bottom-up estimates of Re by EC method (Re_{EC}) vary from 96 (Jung et al., 2011) to 103 Pg C yr^{-1} (Yuan et al., 2011), while those of GPP vary from 119 to 123 Pg C yr^{-1} by EC method (Beer et al., 2010; Jung et al., 2011) and even from 107 to 175 Pg C yr^{-1} by process models and inversions (Anav et al., 2015; Campbell et al., 2017; Welp et al., 2011). The direct estimates of global Re_{EC}, close to the chamber-estimated soil respiration (Bond-Lamberty and Thomson, 2010; Hashimoto et al., 2015), are ~10% less than the indirect estimates (112–117 Pg C yr^{-1} after accounting the fire emission) by the IPCC (Ciais et al., 2014). Therefore, quantifying differences in forest CO_2-fluxes estimated by different methods is critical for improving the accuracy of the global C budget and its predictions.

The EC method has been used to directly measure net ecosystem exchange of CO_2 (NEE) without disturbing the vegetation and soils (Aubinet et al., 2012; Baldocchi, 2003); and long-term EC measurements of NEE, GPP (GPP_{EC}) and Re_{EC} with a high temporal resolution (e.g., 30 min) can provide insights into the seasonality and interannual variations in CO_2-fluxes and their environmental controls (Baldocchi et al., 2017; Baldocchi et al., 2001). Conceptually, NEE and net ecosystem production (NEP) are equivalent in value, in that both constitute the difference between GPP and Re (Curtis et al., 2002), but opposite in

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Nomenclature

Symbols and abbreviations

CP	Closed-path
CPEC	Closed-path eddy covariance
DC	Dynamic soil chamber
ΔC	Change rate of the total ecosystem carbon pool
EC	Eddy covariance
GPP_{BM}	Gross primary production by summation of net primary production and autotrophic respiration
GPP_{CHM}	Gross primary production estimated by scaled chamber
GPP_{EC}	Gross primary production estimated by eddy covariance
IRGA	Infrared gas analyzer
LAI	Maximum canopy leaf area index
LI	Light inhibition of leaf respiration
MAP	Mean annual precipitation
MAT	Mean annual temperature
NEE	Net ecosystem exchange of CO_2
NEP	Net ecosystem production
NEP_{BM}	Net ecosystem production measured by biometric method
NEP_{CHM}	Net ecosystem production measured by scaled chamber
NEP_{EC}	Net ecosystem production measured by eddy covariance
$NEP_{EC(SH)}$	Surface-heating-corrected net ecosystem production measured by open-path eddy covariance
NEP_{NPP}	Net ecosystem production calculated as the difference between net primary production and heterotrophic respiration
$NEP_{\Delta C}$	Net ecosystem production calculated as the change rate of the total ecosystem carbon pool
NPP	Net primary production measured by biometric method
OP	Open-path
OPEC	Open-path eddy covariance
R_A	Autotrophic respiration
Re	Ecosystem respiration
Re_{CHM}	Ecosystem respiration measured by scaled chamber
Re_{EC}	Ecosystem respiration measured by eddy covariance
R_H	Heterotrophic respiration
R_L	Leaf respiration
R_R	Root or rhizospheric respiration
R_S	Soil respiration
R_W	Aboveground woody-tissue respiration
SH	Surface-heating effect

sign (Chapin et al., 2006). As EC towers have proliferated around the world during past two decades (Aubinet et al., 2012; Baldocchi, 2014), EC-flux data have been increasingly used to evaluate terrestrial models (e.g., Chuine et al., 2016; Keenan et al., 2012) and remote sensing products (e.g., Verma et al., 2014) of ecosystem productivity, which improves our understanding of large-scale biosphere–atmosphere interactions and climate change effects. However, EC has some weaknesses, such as surface energy imbalance (Leuning et al., 2012; Stoy et al., 2013) and missing advection fluxes (Aubinet, 2008), which may introduce potential errors (Desai et al., 2008) that are difficult to quantify without independent measurements (Speckman et al., 2015; Wehr et al., 2016).

Besides, two other methods have been widely used to measure forest CO_2-fluxes. First, biometric method is employed to measure net primary production (NPP; Clark et al., 2001), from which subtracting heterotrophic respiration (R_H) yields the biometric-based NEP (NEP_{BM}). Alternatively, NEP_{BM} can also be obtained by calculating the change rate of the total ecosystem C pool (ΔC, Curtis et al., 2002), equivalent to the net ecosystem C balance (Chapin et al., 2006). However, biometric method is limited in terms of replication (due to labor intensive) and time resolution (often performed over annual or longer time intervals) (Baldocchi, 2014). Second, chamber method is employed to measure gas exchanges of leaves, stems, roots, and soils (Ryan et al., 1997; Speckman et al., 2015) that are then up-scaled to obtain ecosystem-level Re (e.g., Lavigne et al., 1997) and GPP (e.g., Keith et al., 2009). The difference between chamber-based GPP (GPP_{CHM}) and Re (Re_{CHM}) is the chamber-derived NEP (NEP_{CHM}). The main challenges for chamber method are how to upscale such point-measurements to the ecosystem level (Baldocchi, 2014; Speckman et al., 2015) and make accurate and representative measurements of soil respiration (R_S) (Lavigne et al., 1997; Phillips et al., 2017).

Because biometric, chamber and EC methods are largely complementary in terms of their pros and cons, and EC approach is almost fully independent of the other two methods (Campioli et al., 2016; Curtis et al., 2002), comparing these methods is sometimes used to detect potential biases for each method at the site scale (Curtis et al., 2005; Gough et al., 2008; Lavigne et al., 1997; Speckman et al., 2015). However, few studies have investigated the consistency between methods for estimating forest C budgets across sites, or at the global scale (Campioli et al., 2016).

Previous studies have identified some of sources of error for EC. Re_{EC} tends to be underestimated compared with Re_{CHM} (Speckman et al., 2015) especially over dense-canopy forests and complex terrains (Lavigne et al., 1997; Speckman et al., 2015), probably because of insufficient nocturnal turbulence mixing and significant advection of CO_2 (Aubinet, 2008; Thomas et al., 2013). Instrumentation of EC is another source of error. The EC infrared gas analyzers (IRGAs) have open- (OP) or closed-path (CP), depending on whether the optical path of the beam is exposed to the air or not (Leuning and Juud, 1996). It has been well-demonstrated that the OP IRGA can introduce significant biases in CO_2-flux estimates due to surface-heating particularly in cold environments (Burba et al., 2008). Recently, Campioli et al. (2016) reported that the absolute difference in NEP between EC and biometric methods decreased from boreal to tropical forests, indicating a potential effect of surface-heating of OP IRGA. However, it is unclear how the surface-heating of OP system affects CO_2-flux estimates at larger scales.

Global comparisons show that NEP_{EC} tends to be moderately greater than NEP_{BM} (Campioli et al., 2016; Xu et al., 2014), while site-specific comparisons display even larger differences. For example, Barford et al. (2001) reported that the decadal mean annual NEP_{EC} was 0.40 Mg ha^{-1} yr^{-1} (25%) greater than the NEP_{BM} in the Harvard Forest. The NEP_{EC} was 3.25–5.42 Mg ha^{-1} yr^{-1} (129%–229%) greater than the NEP_{BM} in a forest at the Walker Branch (Curtis et al., 2002; Hanson et al., 2003). Nevertheless, even a convergence of NEP does not prove an agreement between methods, because this may be a result of cancellation of similar biases for the GPP and Re components. For instance, the NEP_{EC} and NEP_{BM} at the University of Michigan Biological Station converged to 1% over a 5-year period (Gough et al., 2008), but the Re_{EC} was 25% lower than the Re_{CHM} with a concomitant 23% lower GPP_{EC} (calculated from Curtis et al., 2005). It is still uncertain why the CO_2-fluxes estimated by different methods converge at some sites but diverge at others (Campioli et al., 2016). As multi-method data on forest CO_2-fluxes have progressively become available, we have an opportunity to evaluate differences in estimates by EC, biometric and chamber methods (Baldocchi, 2003) and their contributing factors.

In this study, we conducted an extensive literature survey and compiled a novel global database of forest CO_2-fluxes (i.e., NEP, GPP and Re) with the aims of (1) quantifying differences in forest CO_2-fluxes estimated by EC, biometric and chamber methods, and (2) exploring effects of biome, topography, stand characteristics, measuring methodology on the differences. We hypothesized that: (1) EC method overestimated NEP_{EC} globally, which mainly resulted from an