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Seasonal variation of source contributions to eddy-covariance CO_2 measurements in a mixed hardwood-conifer forest

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ABSTRACT

Net ecosystem exchange (NEE) measurements using the eddy covariance technique have been widely used for calibration and evaluation of carbon flux estimates from terrestrial ecosystem models as well as for remote sensing-based estimates across various spatial and temporal scales. Therefore, it is vital to fully understand the land surface characteristics within the area contributing to these flux measurements (i.e. source area) when upscaling plot-scale tower measurements to regional-scale ecosystem estimates, especially in heterogeneous landscapes, such as mixed forests. We estimated the source area of a flux tower at a mixed forest (Harvard Forest in US) using a footprint model, and analyzed the spatial representativeness of the source area for the vegetation characteristics (density variation and magnitude) within the surrounding 1- and 1.5-km grid cells during two decades (1993–2011). Semi-variogram and window size analyses using 19 years of Landsat-retrieved enhanced vegetation index (EVI) confirmed that spatial heterogeneity within the 1-km grid cell has been gradually increasing for leaf-on periods. The overall prevailing source areas lay toward the southwest, yet there were considerable variations in the extents and the directions of the source areas. The source areas generally cover a large enough area to adequately represent the vegetation density magnitude and variation during both daytime and nighttime. We show that the variation in the daytime NEE during peak growing season should be more attributed to variations in the deciduous forest contribution within the source areas rather than the vegetation density. This study highlights the importance of taking account of the land cover variation within the source areas into gap-filling and upscaling procedures.

1. Introduction

Our understanding of the interactive dynamics between climate change and terrestrial ecosystem processes (Cao and Woodward, 1998; Finzi et al., 2011; Keenan et al., 2014; Nemani et al., 2003) has been remarkably progressed through the use of tower-based eddy covariance (EC) flux measurements (Baldocchi, 2003; Baldocchi et al., 1988; Falge et al., 2002; Law et al., 2002; Schmid et al., 2000). As unique *in-situ* and semi-continuous measurements, these flux tower data have been applied to a wide range of studies, such as statistical analysis for a single site or across multiple biomes (Keenan et al., 2013; Urbanski et al., 2007), and for correlation analysis with other biophysical attributes and processes (Davidson et al., 2006).These tower data have also been used for calibration and validation of mechanical ecosystem models and remote sensing-based estimates at various spatial resolutions (e.g., the Moderate Resolution Imaging Spectrometer (MODIS) gross primary productivity (GPP) product at a 1-km resolution (Heinsch et al., 2006; Schwalm et al., 2010; Verma et al., 2015). The number of flux towers in the FLUXNET network (http://fluxnet.ornl.gov/) has increased rapidly, including about 846 sites as of November 2016. Mixed forests are some of the most common land covers in which flux towers have been set up (https://fluxnet.ornl.gov/site_list/IGBPLU/5). Several of the flux towers with the longest records, therefore the towers most frequently used in studies, are located in mixed forests such as Harvard Forest, MA, US (FLUXNET Site ID: US-Ha1, since 1991), Howland Forest, ME, US (US-Ho1,2,3, since 1995,1999, 2001), Morgan-Monroe State Forest, IN, US (US-MMS, since 1998), ON-Borden Mixed wood, Ontario, Canada (CA-Cbo, since 1995), Brasschaat, Belgium (BE-Bra, since 1996), and more.

Multiple factors have to be considered to determine whether the

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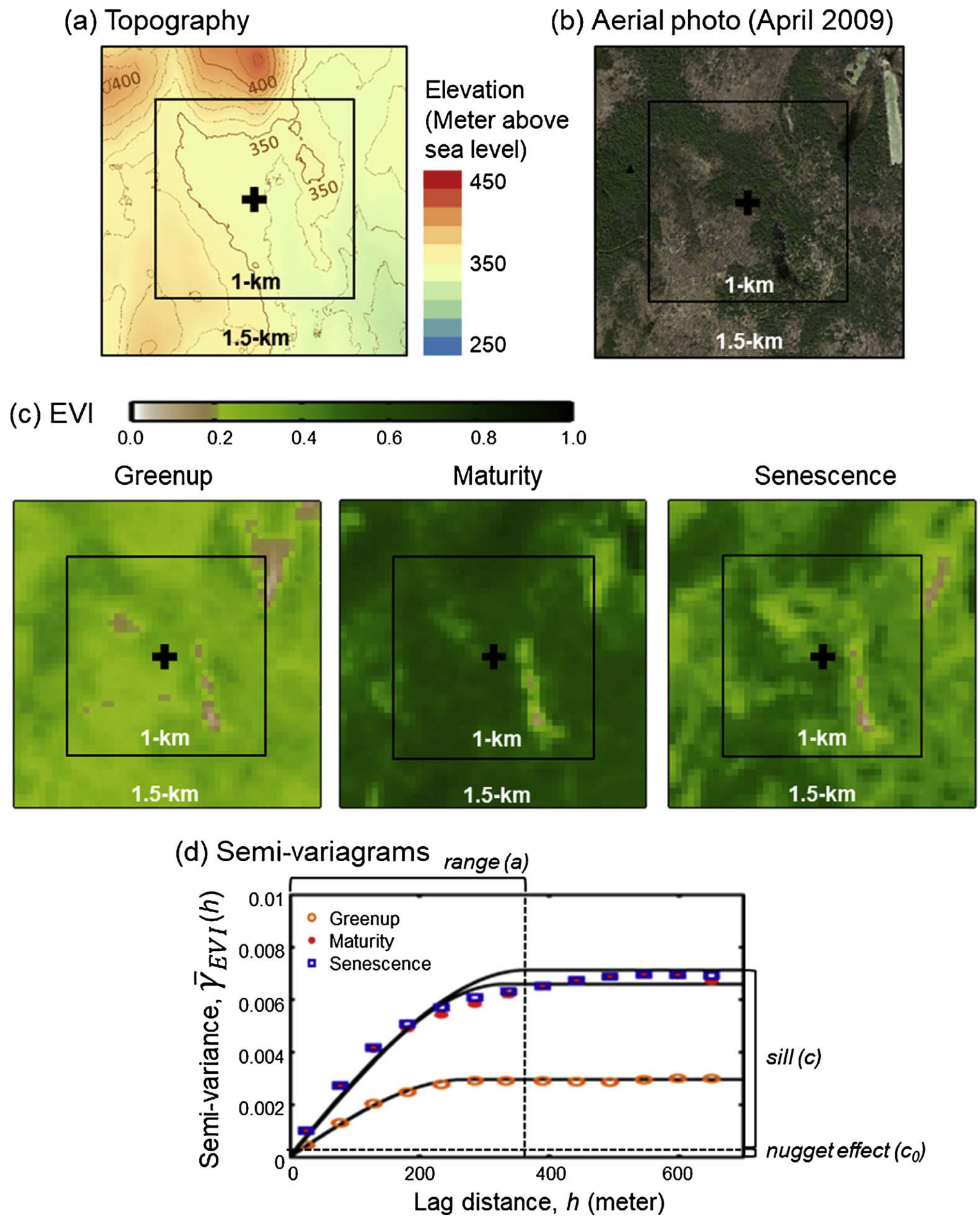

Fig. 1. (a) Topography of the surrounding area of the study tower (black cross). Elevation above sea level was retrieved from a LiDAR terrain file (accuracy of 5–35 cm; MassGIS: http://www.mass.gov/) (b) Aerial photo taken on April 2009 (30 cm resolution; MassGIS: http://www.mass.gov/) before the emergence of leaves on deciduous trees. (c) Enhanced vegetation index (EVI; Eq. (2)) maps retrieved from Landsat TM/ETM + scenes at each phenological stage: greenup (5/27/2008), maturity (8/31/2008) and senescence (10/18/2008). Details of the phenological stages are described in the data overview. (d) Schematic diagram of the semi-variogram estimators ($\overline{\gamma}_{EVI}(h)$) calculated from the EVI maps in (c) (orange circle, red dot, and blue square for greenup, maturity, and senescence stages, respectively), and the fitted isotropic spherical variogram models (black solid line), and *ranges* (dashed vertical lines in colors) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

upwind land surface measured by a flux tower ("*source area*") adequately describes the characteristics of the surrounding ecosystem ("*spatial representativeness*"; Román et al., 2009; Schmid, 1997). This is especially critical in mixed forests, where temporally varying wind direction and atmospheric stability can change the source weight distribution of fluxes measured at a tower considerably over the heterogeneous land covers, resulting in a large degree of variations in the source area characteristics and therefore in the measured flux (Wehr and Saleska, 2015). This inevitable source area variability has long been recognized as one of the major uncertainties in flux measurements (Baldocchi, 2003). To understand and reduce this uncertainty, a number of studies have focused on developing a source weight function ("*footprint*"; Hsieh et al., 2000; Kljun et al., 2002, 2004; Kormann and Meixner, 2001; Schmid, 1994; van Ulden, 1978) and applying these footprint models for the uncertainty analysis of flux measurements and also for ground-biometric sampling schemes (Amiro, 1998; Chasmer et al., 2011; Griebel et al., 2016; Novick et al., 2014; Oishi et al., 2008; Stoy et al., 2006; Xu et al., 2017). There are also ongoing efforts to standardize the source area estimation at the network levels (Menzer et al., 2015, 2014). However, as of yet, most studies of mixed forests have not fully considered the temporal variations in source areas, but instead have only approximated a fixed area (Turner et al., 2003; Verma et al., 2015) or simply rejected some flux data solely based on wind direction (Daley et al., 2007; Phillips et al., 2010). Such wind-direction based filtering schemes sometimes leave only 25% of the total data deemed as appropriate for further analysis (Hadley & Schedlbauer, 2002; Stoy et al., 2006), yet still leaves questions about the representativeness of the flux data for large-scale applications.