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Spatial representativeness and uncertainty of eddy covariance carbon flux measurements for upscaling net ecosystem productivity to the grid scale

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ABSTRACT

Eddy covariance (EC) measurements are often used to validate net ecosystem productivity (NEP) estimated from satellite remote sensing data and biogeochemical models. However, EC measurements represent an integrated flux over their footprint area, which usually differs from respective model grids or remote sensing pixels. Quantifying the uncertainties of scale mismatch associated with gridded flux estimates by upscaling single EC tower NEP measurements to the grid scale is an important but not yet fully investigated issue due to limited data availability as well as knowledge of flux variability at the grid scale. The Heihe Watershed Allied Telemetry Experimental Research (HiWATER) Multi-Scale Observation Experiment on Evapotranspiration (MUSOEXE) built a flux observation matrix that includes 17 EC towers within a 5 km × 5 km area in a heterogeneous agricultural landscape in northwestern China, providing an unprecedented opportunity to evaluate the uncertainty of upscaling due to spatial representative differences at the grid scale. Based on the HiWATER-MUSOEXE data, this study evaluated the spatial representativeness and uncertainty of EC CO_2 flux measurements for upscaling to the grid scale using a scheme that combines a footprint model and a model-data fusion method. The results revealed the large spatial variability of gross primary productivity (GPP), ecosystem respiration (Re), and NEP within the study site during the growing season from 10 June to 14 September 2012. The variability of fluxes led to high variability in the representativeness of single EC towers for grid-scale NEP. The systematic underestimations of a single EC tower may reach 92(±11)%, 30(±11)%, and 165(±150)% and the overestimations may reach 25(±14)%, 20(±13)%, and 40(±33)% for GPP, Re, and NEP, respectively. This finding suggests that remotely sensed NEP at the global scale (e.g., MODIS products) should not be validated against single EC tower data in the case of heterogeneous surfaces. Any systematic bias should be addressed before upscaling EC data to grid scale. Otherwise, most of the systematic bias may be propagated to grid scale due to the scale dependence of model parameters. A systematic bias greater than 20% of the EC measurements can be corrected effectively using four indicators proposed in this study. These results will contribute to the understanding of spatial representativeness of EC towers within a heterogeneous landscape, to upscaling carbon fluxes from the footprint to the grid scale, to the selection of the location of EC towers, and to the reduction in the bias of NEP products by using an improved parameterization scheme of remote-sensing driven models, such as VPRM.

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1. Introduction

Carbon dioxide, as an important greenhouse gas, plays a vital role in regulating the Earth's surface temperature through radiative forcing and the greenhouse effect. Atmosphere carbon dioxide has increased by ~40% since 1750 (Ballantyne et al., 2012), with a pronounced increase in the past ten years (IPCC, 2013). Vegetation productivity is one of the main sinks of atmospheric CO_2. Net ecosystem production (NEP) is the net rate of carbon accumulation within an ecosystem. It is defined as the difference between the amount of carbon (C) removed from the atmosphere in the form of carbon dioxide through photosynthesis and the loss of carbon through the respiration of vegetation and soil. The quantification of NEP indicates whether an ecosystem is a net sink or source of atmospheric CO_2. Positive NEP indicates the ecosystem is a carbon sink, while negative NEP indicates the ecosystem is a carbon source.

Eddy covariance (EC) instruments, remote sensing-based models, and biogeochemical models are three main methods to quantify the NEP of terrestrial ecosystems. The EC technique is considered one of the most direct and appropriate ways to measure and calculate turbulent fluxes of CO_2 on a local scale (Burba, 2013; Wang et al., 2015). Remote sensing-based models, on the other hand, provide quantitative estimates of spatially continuous NEP, which can be used to evaluate the spatial patterns and seasonal to inter-annual variability of carbon sources/sinks (Kimball et al., 2009; Sasai et al., 2011). However, remote sensing is an indirect measurement and is associated with large uncertainty (Chasmer et al., 2009; Coops et al., 2007; Kwon and Larsen, 2012; Turner et al., 2006; Zhang et al., 2012). Biogeochemical models use process understanding obtained from past measurements within ecosystems to predict future ecosystem dynamics given a range of different driving mechanisms and contributing factors. Model uncertainty often varies as a result of model structure, boundary conditions, and parameterization schemes (Huntzinger et al., 2012; Mitchell et al., 2009; Randerson et al., 2009). Currently, EC measurements are important for both the calibration and validation of NEP estimated using biogeochemical models and those driven using remote sensing data (Heinsch et al., 2006; Luo et al., 2011; Raupach et al., 2005; Verma et al., 2014; Wang et al., 2009; Weng et al., 2011). However, EC measurements represent an integrated flux over their footprint area, which may not match the scale of the respective model grids or remote sensing pixels. It is therefore important to address the potential uncertainty related to spatial and temporal scaling as this may significantly alter the suitability of EC tower data for the evaluation and calibration of estimates derived from remotely sensed data and biogeochemical models (Göckede et al., 2008, 2010).

Errors in EC observations can be decomposed into measurement error and representativeness error (Lasslop et al., 2008; Li, 2014; Raupach et al., 2005). In general, part of measurement errors can be minimized by calibrating instruments and by data processing techniques such as averaging flux values (Wang et al., 2015), while representativeness error may be dominant at a grid scale (Chasmer et al., 2009; Raupach et al., 2005). We therefore focus on representativeness error in this study. Here, the representativeness error of the EC measurements is relative to the grid scale. The representativeness error is affected by measurement height, surface roughness and thermal stability associated with the heterogeneity of vegetation structural and disturbance patterns (Burba, 2001; Chasmer et al., 2011; Chen et al., 2009; Göckede et al., 2010; Raupach et al., 2005). EC systems are usually set up within relatively homogeneous ecosystems, where the spatial variability of the vegetation structural characteristics is minimal to reduce uncertainty. However, heterogeneity is inevitable within complex and fragmented landscapes, such as those found in semi-arid agro-ecosystems in western China.

The spatial representativeness of EC flux measurements at the grid scale in complex and fragmented landscapes is still not completely understood, mainly due to limited available EC data within the grid area. The related studies are rather limited and most of them are based on single tower data. For example, Barcza et al. (2009) quantified the spatial representativeness of tall tower-based EC measurements at a height of 82 m within a heterogeneous landscape by combining footprint analysis and land cover classification. These authors found that the source region distribution of fluxes was very similar from year to year. This means that the spatial representativeness is temporally stable. Chasmer et al. (2009) proposed a method to derive the spatial representativeness of EC measurements relative to a 1-km resolution from the Moderate Resolution Imaging Spectroradiometer (MODIS) pixel using a structure-based gross primary production (GPP) model. In addition, Chasmer et al. (2011) examined the relationship between the spatial frequency of the 3-D vegetation attributes within the MODIS pixel and the EC footprint, and found that the comparability of the flux data obtained from the EC measurements and the MODIS pixel may depend on the relationship of the vegetation structure. Further, Xiao et al. (2011) estimated parameters for upscaling the EC flux to a regional scale using a single EC tower and found that the model parameters estimated from a single site are not representative of the parameter values for a given plant functional type. This means that parameter heterogeneity exists within plant functional types defined at a coarse scale. Consequently, plant functional types need to be defined at a fine resolution, and the associated spatial representativeness of EC flux measurements should be evaluated. The above-mentioned studies have touched on some key aspects for evaluating the spatial representativeness or representativeness error of EC flux measurements, and provide an important basis for more detailed research. Their main limitation is that they are based on strong underlying assumptions and few measurements, which reduces the reliability of the conclusions drawn.

An extensive grid-based flux matrix was constructed in a fragmented agro-ecosystem in western China as part of the Heihe Watershed Allied Telemetry Experimental Research (HiWATER)—Multi-Scale Observation Experiment on Evapotranspiration (MUSOEXE) over a heterogeneous land surface (Li et al., 2013; Liu et al., 2016). This constitutes a component of the integrated study of the water-ecosystem-economy in the Heihe River Basin (Cheng et al., 2014). Compared with previous campaigns, such as BOREAS (Boreal Ecosystem-Atmosphere Study) (Sellers et al., 1995), CASES-99 (Cooperative Atmosphere-Surface Exchange Study-1999) (Poulos et al., 2002), SGP97 (Southern Great Plains-1997) (Twine et al., 2000), IHOP 2002 (International H2O Project) (Weckwerth et al., 2004), LITFASS-2003 (Lindenberg Inhomogeneous Terrain-Fluxes between Atmosphere and Surface: a long-term study) (Beyrich and Mengelkamp, 2006), and BEAREX-08 (Bushland Evapotranspiration and Agricultural Remote Sensing Experiment-2008) (Anderson et al., 2012), the flux matrix of HiWATER-MUSOEXE includes 17 EC towers within a 5 km × 5 km area and thus provides the first opportunity to evaluate the representativeness of the towers with respect to grid-scale carbon fluxes. The grid-based tower setup can be used to reveal the spatial heterogeneities of carbon fluxes, to determine scaling effects and to provide ground truth data for the improvement of remote sensing-based models and scaling approaches for carbon fluxes over heterogeneous land surfaces.

The goals of this study are to use an EC grid-based deployment methodology to quantify the uncertainty of grid-scale NEP estimation resulting from the representativeness of a single EC tower and to explore the tools that can reduce this uncertainty. The specific objectives are to (1) evaluate the representativeness of single tower data for long-term grid-scale carbon flux estimates; (2) assess the influence of the representativeness of a heterogeneous vegetation