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Advances in upscaling of eddy covariance measurements of carbon and water fluxes

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[1] Eddy covariance flux towers provide continuous measurements of ecosystem-level net exchange of carbon, water, energy, and other trace gases between land surface and the atmosphere. The upscaling of flux observations from towers to broad regions provides a new and independent approach for quantifying these fluxes over regions, continents, or the globe. The seven contributions of this special section reflect the most recent advances in the upscaling of fluxes from towers to these broad regions. The section mainly stems from presentations at the recent North American Carbon Program (NACP), FLUXNET, and AGU meetings. These studies focus on different aspects of upscaling: (1) assessing the representativeness of flux networks; (2) upscaling fluxes from towers to broad spatial scales; (3) examining the magnitude, distribution, and interannual variability of fluxes over regions, continents, or the globe; and (4) evaluating the impacts of spatial heterogeneity and parameter variability on flux estimates. Collectively, this special issue provides a timely update on upscaling science and also generates gridded flux data that can be used for model evaluations. Future upscaling studies are expected to advance toward incorporating the impacts of disturbance on ecosystem carbon dynamics, quantifying uncertainties associated with gridded flux estimates, and comparing various upscaling methods and the resulting gridded flux fields.

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1. Introduction

[2] Accurate quantification of ecosystem carbon and water fluxes over regions, continents, or the globe is essential for understanding the feedbacks between the terrestrial biosphere and the atmosphere in the context of global change and climate policy-making. Several techniques have been widely used to estimate the net exchange of fluxes between terrestrial ecosystems and the atmosphere, including inventory approaches [e.g., *U.S. Climate Change Science Program*, 2007], ecosystem modeling [e.g., *Xiao et al.*, 2009], and atmospheric inverse modeling [e.g., *Butler et al.*, 2010]. The upscaling of flux observations from eddy covariance towers provides an alternative and independent approach to quantify carbon and water exchange between the terrestrial biosphere and the atmosphere at regional, continental, and global scales [*Xiao et al.*, 2008].

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[3] Eddy covariance flux towers can provide continuous measurements of ecosystem-level exchanges of carbon, water, and energy at diurnal, synoptic, seasonal, and interannual scales. Flux towers have been established in different ecosystems and climate zones since the early 1990s [*Wofsy et al.*, 1993]. These towers directly measure net ecosystem exchange (NEE), evapotranspiration (ET), and other trace gases. The continuous NEE measurements are routinely partitioned to gross primary productivity (GPP) and ecosystem respiration (ER).

[4] At present, over 500 flux towers are operating on a long-term and continuous basis around the world (FLUXNET, http://daac.ornl.gov/FLUXNET). Many flux towers are affiliated with regional flux networks (e.g., AmeriFlux, Fluxnet-Canada, CarbEurope-IP, and USCCC) that coordinate regional analyses of flux observations. These flux networks have been making significant progress in making flux data available to the scientific community. For instance, flux data can be downloaded for a number of AmeriFlux sites (http://public.ornl.gov/ameriflux/) with various levels of processing and time steps (e.g., half-hourly, daily, 8-day, and monthly). In particular, the Level 4 product consists of flux data processed with consistent procedures and has been widely used for model validation, cross-site comparisons, and upscaling.

[5] The FLUXNET is the global network of regional flux networks [*Baldocchi et al.*, 2001]. Globally, the FLUXNET synthesis data set (a.k.a., the LaThuile database) provides flux data from 253 flux sites affiliated with FLUXNET

(Figure 1). Similarly, the LaThuile database is based on a standard data format for convenient manipulation and comparison of data from different instruments and among different regions. This database harmonizes, standardizes, and gap-fills the raw 30-min data records of carbon dioxide, water vapor, and energy fluxes submitted by members of regional networks from around the world.

[6] Despite the relatively large number of flux towers across the globe, the tower measurements only represent fluxes at the scale of the tower footprint (i.e., ecosystem level) with longitudinal dimensions ranging from a few hundred meters to several kilometers. To quantify the net exchange of fluxes between the terrestrial biosphere and the atmosphere, these tower fluxes need to be upscaled to regions, continents, or the globe [*Xiao et al.*, 2008]. Considerable advances have been made in upscaling during recent years [e.g., *Xiao et al.*, 2008, 2010, 2011a; *Jung et al.*, 2009]. Many studies on this topic have been reported at recent AmeriFlux, FLUXNET, and AGU meetings. Advances in the upscaling of flux observations were also summarized in plenary talks led by Jingfeng Xiao at the 2nd North American Carbon Program (NACP) All-Investigators Meeting in San Diego, California (February 2009) and the AmeriFlux Science Meeting & 3rd NACP All-Investigators Meeting in New Orleans, Louisiana (31 January to 4 February 2011).

[7] This special section reflects the most recent advances in the upscaling of flux observations from towers to broad regions. Several research groups from different countries (e.g., Canada, China, Germany, Italy, and USA) participated in this synthesis effort. This special section consists of seven articles on different topics of upscaling science: (1) assessing the representativeness of flux networks; (2) upscaling fluxes from towers to broad regions; (3) examining the magnitude, distribution, and interannual variability of fluxes at regional to global scales; and (4) evaluating the impacts of spatial heterogeneity and parameter variability on flux estimates.

2. Upscaling Methods, Data Products, and Findings

[8] The flux sites within FLUXNET appear to be fairly representative of the major climate types and also involve a variety of ecosystem types (e.g., forests, shrublands, savannas, grasslands, croplands, and wetlands). However, these sites are not evenly distributed across the globe. Some regions such as North America and Europe are more densely instrumented than other regions (e.g., Central Asia, Africa, South America, and Australia). In addition, for each biome, the total number of sites is not proportional to its total land area. The representativeness of flux networks will influence the accuracy of the gridded flux estimates derived from tower fluxes through upscaling. One contribution of this special section [*Sulkava et al.*, 2011] uses a cluster-based tool for quantitative network design to assess the representativeness of an existing flux network or to suggest the best network for a defined number of sites. This methodology was applied to the current CarbEurope-IP network to assess its representativeness. *Sulkava et al.* [2011] also conclude that the quantitative network design could improve the predictive ability of future data-driven upscaling methods but the optimized networks have poor capacity for the representation of the spatial variability of fluxes.

[9] The following four contributions focus on how to upscale fluxes from towers to broad regions. *Xiao et al.* [2011b] use a network of 17 flux towers deployed across the Upper Midwest region of northern Wisconsin and Michigan and a simple diagnostic carbon flux model (DCFM) to upscale fluxes from towers to the regional scale. This heterogeneous, densely instrumented region provides a unique test bed for regional upscaling. *Zhang et al.* [2011] map carbon fluxes for the U.S. Great Plains using fluxes from 15 grassland towers. *Sun et al.* [2011] use a water-centric ecosystem model to upscale carbon and water fluxes from the AmeriFlux database to the national scale and estimates fluxes for each large watershed across the conterminous U.S. *Jung et al.* [2011] upscale FLUXNET observations of carbon, water, and energy fluxes to the global scale using an ensemble of regression trees and generated gridded fluxes at 0.5 degree spatial resolution.

[10] Upscaling methods can be classified to data-driven and data-assimilation approaches. Data-driven approaches [e.g., *Xiao et al.*, 2008] are based on empirical, statistical models and are trained with flux observations and various explanatory variables such as land cover, enhanced vegetation index (EVI), photosynthetically active radiation (PAR), and land surface temperature. These predictive models are often rule-based models, each of which is a set of conditions associated with a multivariate linear submodel. For spatial prediction of fluxes, the explanatory variables are usually derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) data streams and/or climate reanalysis data. *Jung et al.* [2011], *Sun et al.* [2011], and *Zhang et al.* [2011] use data-driven methods in their upscaling exercises. Data-assimilation approaches [e.g., *Xiao et al.*, 2011b] are often based on simple ecosystem models and parameter estimation techniques. In this type of methods, flux observations are used to optimize the parameters of the models, and the optimized models are then used for the estimation of fluxes over broad regions. *Desai* [2010] and *Xiao et al.* [2011b] use Markov chain Monte Carlo (MCMC) and differential evolution (DE) methods in their regional upscaling efforts, respectively.

[11] Three of the studies use the resulting gridded flux estimates to assess the spatiotemporal patterns, magnitudes, and year-to-year variations of fluxes. *Zhang et al.* [2011] suggest that the Great Plains was a net carbon sink, and the size of the sink was reduced by severe droughts. *Sun et al.* [2011] examine the carbon sink capacity and fresh water yield of U.S. terrestrial ecosystems, and shows that both carbon and water fluxes exhibited large spatial and temporal variability. *Jung et al.* [2011] assess the magnitude and spatiotemporal patterns of carbon fluxes at the global scale and suggest that GPP had a larger impact on the interannual variability in NEE than ecosystem respiration.

[12] Three contributions of this special section examine the impacts of spatial heterogeneity on the upscaling of fluxes. *Desai* [2010] uses a simple ecosystem model and flux observations to examine the interannual variation of carbon fluxes for five different forest ecosystems in the temperate-boreal transition zones of the Upper Great Lakes region, USA, and shows that coarse spatial resolution carbon-climate models could likely specify climate-phenological relationships at grid scales on order of 100 km without significantly sacrificing the ability to model interannual

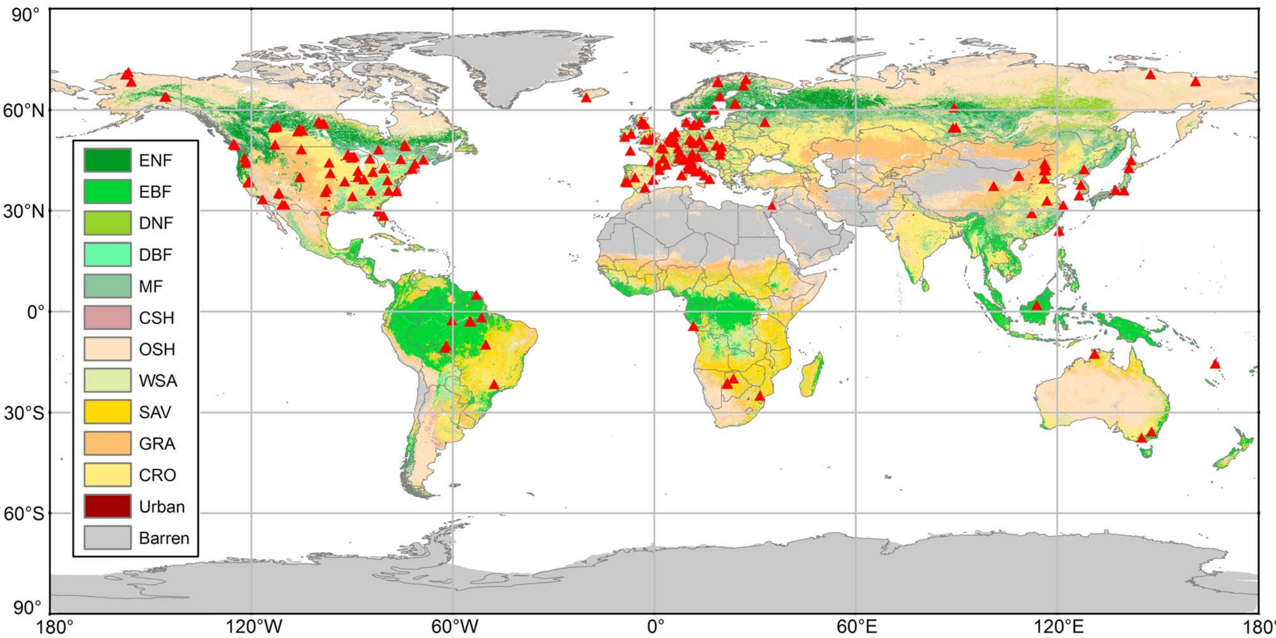

Figure 1. The location and distribution of eddy covariance flux towers involved in the FLUXNET synthesis database (also known as the LaThuile database). The symbols stand for flux towers. The base map is the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover map, and the dominant land cover types include evergreen needle-leaf forests (ENF), evergreen broadleaf forests (EBF), deciduous needle-leaf forests (DNF), deciduous broadleaf forests (DBF), mixed forests (MF), closed shrublands (CSH), open shrublands (OSH), woody savannas (WSA), savannas (SAV), grasslands (GRA), croplands (CRO), urban and built-up (urban), and barren or sparsely vegetated (barren).

variability of carbon fluxes. *Chasmer et al.* [2011] integrate structural vegetation and topographic attributes derived from airborne scanning light detection and ranging (lidar) and footprints originating from prevailing wind directions to assess eddy covariance sampling within homogenous and heterogeneous mature boreal aspen stands and the validity of pixel GPP estimated from MODIS. They report that Southern Old Aspen and heterogeneous Upland Aspen sites were more representative of a 1 km radius area surrounding the tower than a 4 × 4 km area; GPP estimates for MODIS pixels identified using a Boolean approach had a greater correspondence to tower estimates than estimates for pixels proximal to the tower [*Chasmer et al.*, 2011]. *Xiao et al.* [2011b] show that land cover representation including land cover heterogeneity and the spatial resolution and accuracy of land cover maps can lead to substantial uncertainty in regional flux estimates. In heterogeneous, complex regions, detailed and accurate land cover maps are essential for accurate estimation of regional fluxes [*Xiao et al.*, 2011b].

[13] The availability of flux observations from multiple towers provides the opportunity to examine the variability of parameters. *Xiao et al.* [2011b] use flux observations and a data assimilation approach to estimate the parameters of a simple DCFM and assessed the variability of parameters both within and across plant functional types (PFTs). The results show that (1) model parameters vary not only within PFTs but also across PFTs; (2) cross-site (or joint) optimization based on flux observations from multiple sites encompassing a range of site and climate conditions can improve the representativeness and robustness of parameter estimates; and (3) parameter variability can lead to significant uncertainty in regional flux estimates.

3. Summary

[14] The contributions of this special section reflect the most recent advances in the upscaling of flux observations from towers to broad spatial scales. These studies focus on various aspects of upscaling such as assessing the representativeness of flux networks, generating grid flux fields at regional, continental, or global scales, examining the magnitude, distribution, and interannual variability of carbon and water fluxes, and evaluating the impacts of spatial heterogeneity and parameter variability on flux estimates. Collectively, this special issue provides a timely update on upscaling science and generates gridded flux fields that can be used to evaluate the simulations of ecosystem models and atmospheric inversions. Future upscaling studies should advance toward explicitly incorporating the impacts of disturbance on ecosystem carbon exchange [e.g., *Amiro et al.*, 2010; *Liu et al.*, 2011], quantifying uncertainties associated with gridded flux estimates, and expanding our efforts to include other gases such as CH_4 and N_2O. Future upscaling efforts will also benefit from the intercomparison of multiple upscaling methods (data-driven and data assimilation approaches) and the resulting flux fields. The juxtaposition of flux estimates resulting from different upscaling approaches as well as comparison of these approaches to other methods such as atmospheric inversions, biomass inventories, and more traditional ecosystem models can provide complementary information for the diagnostics

of ecosystem carbon exchange at regional, continental and global scales and valuable information for future improvement of these approaches.

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