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Data-driven diagnostics of terrestrial carbon dynamics over North America

Jingfeng Xiao[a,*], Scott V. Ollinger[a], Steve Frolking[a], George C. Hurtt[b], David Y. Hollinger[c], Kenneth J. Davis[d], Yude Pan[e], Xiaoyang Zhang[f], Feng Deng[g], Jiquan Chen[h], Dennis D. Baldocchi[i], Bevery E. Law[j], M. Altaf Arain[k], Ankur R. Desai[l], Andrew D. Richardson[m], Ge Sun[n], Brian Amiro[o], Hank Margolis[p], Lianhong Gu[q], Russell L. Scott[r], Peter D. Blanken[s], Andrew E. Suyker[t]

[a] Earth Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA
[b] Center for Global Change & Earth Observations, Department of Geography, Michigan State University, East Lansing, MI 48823, USA
[c] USDA Forest Service, Northern Research Station, Durham, NH 03824, USA
[d] Department of Meteorology, Pennsylvania State University, University Park, PA 16802, USA
[e] U.S. Department of Agriculture Forest Service, Newtown Square, PA 19073, USA
[f] Geospatial Sciences Center of Excellence, South Dakota State University, Brookings, SD 57007, USA
[g] Department of Physics, University of Toronto, Canada
[h] Department of Environmental Sciences, University of Toledo, Toledo, OH 43606, USA
[i] Ecosystem Science Division, Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720, USA
[j] Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331, USA
[k] McMaster Centre for Climate Change and School of Geography and Earth Sciences, McMaster University, Hamilton, Ontario, Canada
[l] Department of Atmospheric & Oceanic Sciences, University of Wisconsin, Madison, WI 53706, USA
[m] Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA 02138, USA
[n] Eastern Forest Environmental Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, NC 27606, USA
[o] Department of Soil Science, University of Manitoba, Winnipeg, Manitoba, Canada
[p] Centre d'Étude de la Forêt, Faculté de Foresterie, de Géographie et de Géomatique, Université Laval, Québec G1V 0A6, Canada
[q] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[r] USDA-ARS Southwest Watershed Research Center, Tucson, AZ 85719, USA
[s] Department of Geography, University of Colorado at Boulder, Boulder, CO 80309, USA
[t] School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68583, USA

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ABSTRACT

The exchange of carbon dioxide is a key measure of ecosystem metabolism and a critical intersection between the terrestrial biosphere and the Earth's climate. Despite the general agreement that the terrestrial ecosystems in North America provide a sizeable carbon sink, the size and distribution of the sink remain uncertain. We use a data-driven approach to upscale eddy covariance flux observations from towers to the continental scale by integrating flux observations, meteorology, stand age, aboveground biomass, and a proxy for canopy nitrogen concentrations from AmeriFlux and Fluxnet-Canada Research Network as well as a variety of satellite data streams from the MODIS sensors. We then use the resulting gridded flux estimates from March 2000 to December 2012 to assess the magnitude, distribution, and interannual variability of carbon fluxes for the U.S. and Canada. The mean annual gross primary productivity (GPP), ecosystem respiration (ER), and net ecosystem productivity (NEP) of the U.S. over the period 2001–2012 were 6.84, 5.31, and 1.10 Pg C yr^{-1}, respectively; the mean annual GPP, ER, and NEP of Canada over the same 12-year period were 3.91, 3.26, and 0.60 Pg C yr^{-1}, respectively. The mean nationwide annual NEP of natural ecosystems over the period 2001–2012 was 0.53 Pg C yr^{-1} for the U.S. and 0.49 Pg C yr^{-1} for the conterminous U.S. Our estimate of the carbon sink for the conterminous U.S. was almost identical with the estimate of the First State of the Carbon Cycle Report (SOCCR). The carbon fluxes exhibited relatively large interannual variability over the study period. The main sources of the interannual variability in carbon fluxes included drought and disturbance. The annual GPP and NEP were strongly related to annual evapotranspiration (ET) for both

* Corresponding author. Tel.: +1 603 862 1873; fax: +1 603 862 0188.
E-mail address: j.xiao@unh.edu (J. Xiao).

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the U.S. and Canada, showing that the carbon and water cycles were closely coupled. Our gridded flux estimates provided an independent, alternative perspective on ecosystem carbon exchange over North America.

1. Introduction

The net exchange of carbon dioxide (CO_2) is a key measure of ecosystem metabolism and a critical intersection between the terrestrial biosphere and the Earth's climate. Although there is general agreement that North American ecosystems provide a large carbon sink (Goodale et al., 2002; Gurney et al., 2002; Deng et al., 2007; Xiao et al., 2011a), the size and distribution of this sink are not well quantified and there are large uncertainties related to sources of variability over space and time. Extreme climate events (Ciais et al., 2005; Xiao et al., 2009; Zhao and Running, 2010) and disturbances such as fire (Bowman et al., 2009), hurricanes (Chambers et al., 2007; Xiao et al., 2011a), wind storms (McCarthy et al., 2006; Lindroth et al., 2009), and insect outbreaks (Kurz et al., 2008) can substantially alter ecosystem structure and function in ways that cause significant year-to-year variation in carbon budgets. In light of these factors, improved understanding of the variability in carbon dynamics over North America and quantification of associated uncertainties are essential for improving projections of the Earth's carbon-climate system under future climate conditions (IPCC, 2007).

To date, terrestrial carbon dynamics over North America have been most widely examined through use of ecosystem models (Schimel et al., 2000; Nemani et al., 2002) or inventory approaches (SOCCR, 2007; Pan et al., 2011a). The North American Carbon Program (NACP) Regional Interim Synthesis recently conducted a model intercomparison study and compared carbon simulations over North America over the period 2000–2005 from 22 ecosystem models. The model intercomparison showed that carbon fluxes exhibited enormous variability among these models for both spatial and temporal domains (Huntzinger et al., 2012; Raczka et al., 2013). This underscores the fact that, despite the substantial advances in ecosystem modeling, large uncertainties still exist in the spatial and temporal variability of carbon fluxes. Although inventory approaches can constrain this variability to some degree, these surveys capture only some of the relevant fluxes and at time scales that are too coarse for resolving important ecophysiological processes or their underlying drivers (Baldocchi et al., 2001).

In contrast, the eddy covariance (EC) technique provides an alternative approach to estimate net ecosystem exchange (NEE) through direct ecosystem-level measurements (Baldocchi et al., 2001; Baldocchi, 2008). NEE is routinely partitioned into gross primary productivity (GPP) and ecosystem respiration (ER). EC techniques provide quasi-continuous, high-frequency measurements of whole-ecosystem CO_2, water, and energy fluxes that can be used to examine ecosystem response to climate variability and disturbance over a range of time scales (Amiro et al., 2010; Schwalm et al., 2010). Tower-based estimates, however, sample an up-wind distance of a few kilometers, and thus represent a relatively small portion of the landscapes. These observations provide useful information over larger scales only when combined with rigorous methods of upscaling. To date, significant advances have been made in the upscaling of EC flux observations (Xiao et al., 2012). A number of studies have upscaled EC flux observations to large regions using satellite remote sensing data and modeling approaches (Xiao et al., 2008, 2010, 2011a,b; Jung et al., 2009; Ryu et al., 2011), and some of these studies have also used the resulting flux estimates to assess regional terrestrial carbon and water budgets (Sun et al., 2011; Xiao et al., 2010, 2011a,b; Zhang et al., 2014).

In our own work with the AmeriFlux network of flux measurement sites across the U.S. (Xiao et al., 2008, 2010, 2011a), we integrated EC flux data with satellite observations to produce continuous GPP and NEE estimates (as opposed to single annual snapshots) for the conterminous U.S., and assessed the magnitude, distribution, and interannual variability of the U.S. terrestrial carbon sink. Compared to inventory approaches and conventional ecological modeling, upscaling methods that explicitly integrate EC flux data and remote observations have the advantage of combining the high-temporal resolution afforded by towers with the broad spatial coverage provided by satellites (Xiao et al., 2008). The use of satellite data in this capacity is logical because remote platforms provide the only means of viewing large portions of the Earth's surface at regular intervals and the selective absorption and reflectance of light by plants allows orbital sensors to gather large amounts of information relevant to ecosystem functioning.

Despite the growing number of studies in upscaling EC flux observations, the effects of disturbance, stand age and nitrogen availability on ecosystem carbon dynamics have not been explicitly considered. Disturbance and stand age are important drivers of forest structure and function (Chapin et al., 2011), and are known to influence terrestrial carbon budgets (Liu et al., 2011; Deng et al., 2013). Similarly, the availability of nitrogen (N) is widely recognized as an important constraint on canopy photosynthesis (Field and Mooney, 1986; Wright et al., 2005) as well as whole-ecosystem carbon gain (Oren et al., 2001; Ainsworth and Long, 2005; Reich et al., 2006; Magnani et al., 2007; LeBauer and Treseder, 2008). In spite of growing scientific understanding of the roles of disturbance and canopy nitrogen in ecosystems, application to continental-scale analyses has lagged because of limited mapping of disturbance (Kennedy et al., 2010; Masek et al., 2013) and canopy nitrogen concentrations (Ollinger et al., 2008) over large regions.

In this study, we used EC flux observations from 94 sites across the U.S. and Canada, in combination with satellite data streams and new ecological data including stand age and aboveground biomass to generate gridded flux estimates for North America over the period 2000–2012. Our new flux estimates could partly account for the effects of disturbance and nitrogen limitation. The objectives of this study are: (1) to upscale flux observations from EC flux sites to the continental scale and to generate gridded flux estimates; (2) to examine the magnitude and spatial patterns of carbon fluxes; (3) to assess the interannual variability of carbon fluxes at the continental scale; and (4) to evaluate the responses of these fluxes to extreme climate events and large disturbance.

2. Data and methods

2.1. Flux observations

We used the EC flux observations from 68 sites in the U.S. and 26 sites in Canada (Fig. 1; See Supplementary Table S1). This network of EC sites across North America is broadly representative of environmental and climate space with the exception of the far northern (tundra) regions. Hargrove et al. (2003) conducted a multivariate analysis of environmental "data space" and concluded that the central, Midwestern, and northeastern U.S. were well represented