Agricultural and Forest Meteorology 233 (2017) 110–121

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Carbon neutral or a sink? Uncertainty caused by gap-filling long-term flux measurements for an old-growth boreal black spruce forest

Ashley D. Soloway[a], Brian D. Amiro[a,*], Allison L. Dunn[b], Steve C. Wofsy[c]

[a] Department of Soil Science, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada
[b] Department of Earth, Environment, and Physics, Worcester State University, Worcester, MA, 01602, USA
[c] School of Engineering and Applied Science/Department of Earth and Planetary Science, Harvard University, Cambridge, MA, 02138, USA

ARTICLE INFO

Article history:
Received 16 June 2016
Received in revised form 3 November 2016
Accepted 8 November 2016
Available online 21 November 2016

Keywords:
Boreal forest
NEE
NEP
Respiration
Photosynthesis
Canada
Eddy covariance
Flux tower
Net ecosystem exchange
Net ecosystem production
Carbon

ABSTRACT

Old-growth (>100 years old) boreal forests are recognized as having accumulated large inventories of terrestrial carbon, but the magnitude of annual net exchange is not well established. Eddy covariance measurements of carbon dioxide exchange were made at a flux tower at the Northern Old Black Spruce forest in Manitoba, Canada, from 1994 to 2008. We evaluated the uncertainty in estimates of annual net ecosystem production by comparing four methods of filling missing measurement periods. Three of the methods were previously developed by groups at Harvard University, the Fluxnet Canada Research Network, and the Max Planck Institute of Biogeochemistry; and the fourth method used the mean of measurements from the dataset selected for the same time and day. Two methods showed carbon losses near the beginning of the period but all four methods estimated carbon gains in the later years. Individual years and methods ranged $\pm 90\,\mathrm{g\,C\,m^{-2}\,y^{-1}}$, demonstrating a wide range of estimates if data had been available from only a single year and a single method. When averaged over multiple years, the mean and standard error among methods gave a net forest carbon sink of $29 \pm 10\,\mathrm{g\,C\,m^{-2}\,y^{-1}}$, ranging from 4 to $48\,\mathrm{g\,C\,m^{-2}\,y^{-1}}$. Only the upper (Mean Data and Max Planck Institute of Biogeochemistry methods) and lower (Harvard method) estimates were significantly different, with the Fluxnet Canada Research Network method being the same as all other methods. There was no difference among methods for the January to August period, or for daytime periods. All methods were statistically different from a carbon-neutral forest suggesting that the Northern Old Black Spruce forest was likely a small carbon sink. Methods that estimated high ecosystem respiration also estimated high gross ecosystem production, and the small net differences could not be easily attributed to differences in flux partitioning. For forests that are close to carbon neutral, the use of several gap-filling methods: increases confidence in conclusions regarding the ecosystem carbon balance.

1. Introduction

The circumpolar boreal forest is of global importance because of its large size and inventory of carbon in excess of 500 Pg (e.g., Dixon et al., 1994). In Canada, analyses using a combination of inventory data and models indicate that the managed part of the boreal forest (1.45 million $\mathrm{km^2}$) has been a carbon sink of about $28\,\mathrm{Tg\,C\,y^{-1}}$ for the 1990 to 2008 period (Kurz et al., 2013). However, the data for the unmanaged forest (1.25 million $\mathrm{km^2}$), mostly in northern Canada, is very poor, and it is difficult to estimate the carbon budget for this area. The boreal forest is dominated by frequent disturbance, such as fire and insect infestation, causing the landscape to be a mosaic of different stand ages and species composition. Net ecosystem exchange (NEE) of carbon dioxide (CO_2) measured by eddy covariance flux towers in North American boreal forests have shown a general pattern of carbon loss following a stand-renewing disturbance for perhaps one to two decades, followed by net carbon uptake for several decades (Goulden et al., 2011; Amiro et al., 2010; Coursolle et al., 2012). Patterns of carbon exchange in old-growth boreal forests tend to be less clear. For example, multi-year flux tower measurements in mature black spruce (*Picea mariana*) forests in both Alaska (Ueyama et al., 2014) and Manitoba (Dunn et al., 2007) have shown that the forest can be a sink in some years and a source in others. A soil moisture effect on ecosystem respiration has been suggested as the driver for these changes in the annual carbon budget. These sites were close to carbon neutral over about a decade of measurements. In contrast, Krishnan et al.

---

* Corresponding author.
E-mail address: Brian.Amiro@UManitoba.ca (B.D. Amiro).

http://dx.doi.org/10.1016/j.agrformet.2016.11.005
0168-1923/

(2008) measured consistent carbon uptake in a black spruce forest in Saskatchewan, averaging about 56 g C m^{-2} y^{-1} over eight years.

Annual NEE estimates from flux towers have uncertainties caused by flux measurement error, criteria used for excluding measurements in low-turbulence conditions, and the choice of methods to fill gaps in missing data. An additional bias is the inability to close the energy balance, likely causing a systematic underestimation of the turbulent flux terms (e.g., Wilson et al., 2002). Of these uncertainties, gap-filling is usually the largest because many long-term sites experience missing data for perhaps 40 to 60% of the time period (Falge et al., 2001; Dragoni et al., 2007). Annual NEE often has an uncertainty of the range of ± 25 to 50 g C m^{-2} y^{-1} (Moffat et al., 2007; Baldocchi, 2008), but some sites report much greater uncertainties, and this can scale with the magnitude of the flux. There have been many developments in the choice of gap-fill methods for long-term NEE estimates. The most common methods use mean diurnal variations based on nearby days, look-up tables for similar conditions, regression analyses based on environmental drivers (e.g., temperature), neural networks or other simulated values (e.g., Falge et al., 2001; Hui et al., 2004; Ooba et al., 2006; Desai et al., 2008). A uniform gap-fill method would aid comparisons among sites because this would reduce the inter-site variability caused by the choice of method (Falge et al., 2001; Barr et al., 2002; Papale et al., 2006; Moffat et al., 2007; Desai et al., 2008). However, employing several gap-fill methods allows for additional uncertainty to be evaluated, especially when analysing long-term datasets for a single site. This assumes that the diversity of methods are equally well-suited to fill the gaps.

In the current study, we evaluated the net carbon exchange of one of the longest available boreal forest flux datasets spanning almost 15 years with four different gap-fill methods. Data were collected at the Northern Old Black Spruce (NOBS) forest from 1994 to 2008, initiated as part of NASA's Boreal Ecosystem-Atmosphere Study (BOREAS; Sellers et al., 1995). Our objective was to determine the variability imposed by gap-fill method on the estimated annual net ecosystem production (NEP) of the NOBS forest, with an aim to increase confidence in conclusions about the forest carbon budget. We selected four gap-fill methods, the Fluxnet Canada Research Network (FCRN) method (Barr et al., 2004), the Harvard method (Dunn et al., 2007), the method developed by the Max Planck Institute (MPI) of Biogeochemistry (Reichstein et al., 2005), and finally a method using dataset means to fill gaps, the Mean Data method. Both the FCRN and MPI methods have been intercompared and shown to perform similarly against test data sets (Moffat et al., 2007.) However, the diversity among gap-fill methods has the potential to arrive at different ecological conclusions, given that flux data from the NOBS forest have been filled with the FCRN method (e.g., Bergeron et al., 2007; Grant et al., 2009), the MPI method (e.g., Melaas et al., 2013; Xiao et al., 2014), and the Harvard method (Dunn et al., 2007) to assess components of the carbon budget, often with comparison to other forest sites. Given this diversity of choice, we hypothesized that there would be no differences in annual NEP among methods, which would allow us to conclude that a single method would be adequate for long-term carbon budgets at this site, which has very small annual net fluxes. Further, we used the four models to test a null hypothesis that the site was carbon neutral, an ecologically important question for the role of northern forests in the global carbon budget.

2. Methods

2.1. Site description

The NOBS site is located in the Canadian Shield close to the northern limit of the boreal forest; located at 55.88° N, 98.48° W in central Manitoba, Canada, about 40 km from the nearest city of Thompson, MB. Discontinuous permafrost underlies the soils, which were deposited by glacial Lake Agassiz. The soils are mainly clay and silt sediments and are peat rich, containing deep organic layers. Most of the landscape is flat but slight topographical changes create uplands and veneer bogs. The last recorded fire in the area was over 170 years ago (Gower et al., 1997). The uplands are well-drained and vegetation consists mainly of black spruce trees (*Picea mariana*) averaging 10 m tall, and feathermoss (*Pleurozium* and *Hylocomium*) ground cover. At lower elevations, the wetter, more poorly drained veneer bogs consist primarily of 1–6 m spruce and tamarack (*Larix laricina*) along with *Sphagnum* spp. The upland understory consists mainly of wild rose (*Rosa* spp.), and the veneer bog's understory consists of bog birch (*Betula glandulosa* var *hallii*), blueberry (*Vaccinium* spp.) and willow (*Salix* spp.), with Labrador tea (*Ledum groenlandicum*) common throughout. Average stem density was 5450 tree ha^{-1} with a basal area of 35.6 m^2 ha^{-1} and leaf area index of 4.2 in 1994 (Gower et al., 1997). Surrounding the tower, within a 500 m radius, 50% of vegetation was classified as poorly drained characterized by veneer bogs (both feathermoss and *Sphagnum*), 25% were the moderately drained upland forests, and the final 25% very poorly drained fens (both *Sphagnum* and brown moss) (Harden et al., 1997).

2.2. Flux measurements

Flux data were downloaded from Fluxnet archived datasets (ftp://daac.ornl.gov/data/fluxnet/fluxnet_canada/data/MB-NOldBlackSpruce/). The eddy covariance technique was used to calculate CO_2 turbulent fluxes on a half-hourly basis. The measurements were taken from a 31-m-tall flux tower, triangular in shape, each side measuring 30 cm. Data recording equipment was kept in a hut 20 m away from the tower. Primary and back-up power sources were provided to the site by two diesel generators 300 m east of the tower. Data were recovered weekly.

Three-dimensional wind speed and virtual temperature were recorded at 4 Hz with a sonic anemometer/thermometer (SATI/3 K, Applied Technologies Inc., Boulder, CO, USA) on the tower at 29 m. Mixing ratios of CO_2 and H_2O were also measured at 29 m at a rate of 20 L min^{-1} through a 50-m-long, 0.64 cm diameter Teflon PFA tube. A 4 L min^{-1} subsample was directed to a CO_2/H_2O infrared gas analyzer (IRGA; Model 6262, LI-COR Inc., Lincoln, NE, USA). The IRGA was calibrated for CO_2 every 3 h by a standard addition of 4% CO_2 at 40 and 80 mL min^{-1}. Every 3 h, an air sample through a CO_2 scrubber (soda lime) and desiccant ($Mg(ClO_4)_2$) was taken to determine the zero of the IRGA for CO_2 and H_2O, respectively. In order to determine canopy storage of CO_2, profile measurements of CO_2 were taken at 0.3, 1.5, 4.6, 8.4, 12.9 and 28.8 m sequentially at 0.5 Hz (half-hourly measurements) by a separate IRGA (Model 6262, LI-COR Inc.). Profile measurements were calibrated every 3 h using two CO_2 mixtures traceable to National Oceanic and Atmospheric Administration (NOAA)/Climate Monitoring and Diagnostic Laboratory (CMDL) standards.

The turbulent flux of CO_2 (F_c) was calculated as the 30-min covariance of the vertical wind velocity and CO_2 mixing ratio. NEE was then calculated as the sum of F_c and the air column storage (S_c).

$$\mathrm{NEE} = F_c + S_c \tag{1}$$

where S_c was determined as:

$$S_c = \int_0^{z_{ec}} \frac{\rho_a}{M_a} \frac{dC}{dt} dz \tag{2}$$