Agricultural and Forest Meteorology 250–251 (2018) 90–101

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

A novel correction for biases in forest eddy covariance carbon balance

Matthew N. Hayek[a,*], Richard Wehr[b], Marcos Longo[c], Lucy R. Hutyra[d], Kenia Wiedemann[a], J. William Munger[a], Damien Bonal[e], Scott R. Saleska[b], David R. Fitzjarrald[f], Steven C. Wofsy[a]

[a] Faculty of Arts and Sciences, Harvard University, Cambridge, MA, 02138, USA
[b] Department of Ecology and Evolutionary Biology, University of Arizona, Tucson, AZ, 85721, USA
[c] Embrapa Agricultural Informatics, Campinas, SP, Brazil
[d] Department of Earth and Environment, Boston University, Boston, MA, 02215, USA
[e] INRA, UMR EEF Université de Lorraine, INRA, 54280 Champenoux, France
[f] Atmospheric Sciences Research Center, SUNY Albany, Albany, NY, USA

ARTICLE INFO

Keywords:
Carbon dioxide
Amazon
Eddy covariance
Forest carbon flux
Respiration
Friction velocity

ABSTRACT

Systematic biases in eddy covariance measurements of net ecosystem-atmosphere carbon dioxide exchange (NEE) are ubiquitous in forests when turbulence is low at night. We propose an alternative to the conventional bias correction, the friction velocity (u_*) filter, by hypothesizing that these biases have two separate, concurrent causes: (1) a subcanopy CO_2 storage pool that eludes typical storage measurements, creating a turbulence-dependent bias, and (2) advective divergence loss of CO_2, creating a turbulence-independent bias. We correct for (1) using a simple parametric model of missing storage (MS). Prior experiments have inferred (2) directly from atmospheric measurements (DRAINO). For sites at which DRAINO experiments have not been performed or are infeasible, we estimate (2) empirically using a PAR-extrapolated advective respiration loss (PEARL) approach. We compare u_* filter estimates of advection and NEE to MS-PEARL estimates at one temperate forest and two tropical forest sites.

We find that for tropical forests, u_* filters can produce a range of extreme NEE estimates, from long-term forest carbon emission to sequestration, that diverge from independent assessments and are not physically sustainable. Our MS model eliminates the dependence of nighttime NEE on u_*, consistent with findings from DRAINO studies that nighttime advective losses of CO_2 are often not dependent on the strength of turbulence. Our PEARL estimates of mean advective loss agree with available DRAINO measurements. The MS-PEARL correction to long-term NEE produces better agreement with forest inventories at all three sites. Moreover, the correction retains all nighttime eddy covariance data and is therefore more widely applicable than the u_* filter approach, which rejects substantial nighttime data—up to 93% at one of the tropical sites. The full MS-PEARL NEE correction is therefore an equally defensible and more practical alternative to the u_* filter, but leads to different conclusions about the resulting carbon balance. Our results therefore highlight the need to investigate which approach's underlying hypotheses are more physically realistic.

1. Introduction

The terrestrial CO_2 sink, which mitigates approximately one quarter of anthropogenic emissions, is due to an imbalance between photosynthesis, termed gross ecosystem productivity (GEP), and ecosystem respiration (R). Globally, the net ecosystem-atmosphere exchange of CO_2 (NEE) is less than 1% of the two gross fluxes (IPCC, 2013), with global forests representing the majority of this quantity. Much of our process-based knowledge of forest NEE is derived from eddy covariance carbon dioxide flux measurements. However, eddy covariance estimates of NEE during the nighttime (nocturnal carbon efflux or NCE)—which represent R because photosynthesis is inactive at night—are prone to underestimation in the form of a selective systematic error (Moncrieff et al., 1996), causing an erroneous shift in the net balance towards uptake (Miller et al., 2004). Such biases in forest eddy covariance NCE therefore accumulate in the long-term ecosystem carbon balance.

The predominant explanation for the systematic low bias in NCE is that mean advective flows remove some CO_2 from the subcanopy airspace (Lee, 1998; Sun et al., 1998; Aubinet et al., 2003). This advective divergence loss can be caused by radiative cooling resulting in negative buoyancy, which can move cool CO_2-rich air down slight slopes and

---

[*] Corresponding author at: 24 Oxford St, Cambridge, MA 02143, USA.
E-mail addresses: mhayek@fas.harvard.edu, nassif.hayek@gmail.com (M.N. Hayek).

https://doi.org/10.1016/j.agrformet.2017.12.186
Received 17 July 2017; Received in revised form 11 November 2017; Accepted 7 December 2017

into the valleys (Grace et al., 1996) below eddy covariance measurement towers, which are typically placed on plateaus. These mean divergent flows violate the assumption of horizontal heterogeneity upon which the measurements rely.

Based on the assumption that calm, low-turbulence conditions facilitate the advective loss, the now ubiquitous approach to correcting NCE has been to discard nighttime eddy flux measurements when turbulence is low (Wofsy et al., 1993; Goulden et al., 1996; Gu et al., 2005; Reichstein et al., 2005; Papale et al., 2006; Barr et al., 2013). Typically, turbulence is quantified by the friction velocity (u_*) and measurements are discarded when u_* falls below a threshold (u_*^{Th}) below which NCE is observed to decline with u_* and above which NCE is independent of u_*. This method is referred to as the u_* filter approach.

A number of findings, however, cast doubt on the assumption that only calm, low-turbulence conditions facilitate advective divergence loss. Advective losses have been associated with negative buoyancy from thermal gradients, present even when the canopy air is turbulently mixed (Staebler and Fitzjarrald, 2005). Explicit measurements of subcanopy airflow indicate that horizontal advective divergence still occurs when u_* is much higher than the typically applied thresholds (Staebler and Fitzjarrald, 2004; Tóta et al., 2008). Furthermore, such subcanopy measurements also demonstrate that these horizontal advective fluxes do not account for the NEE correlations with u_*, and sometimes even exacerbate them (Aubinet et al., 2010). An alternative explanation for u_* –dependent biases in NCE is needed.

We propose an alternative set of hypotheses to explain the concurrent phenomena of the apparent u_*-dependence of NCE and the selective systematic error in NEE that leads to underestimation of the long-term carbon budget. The hypotheses are as follows. (1) Hidden CO_2 storage pools below the canopy are underestimated or unobserved by classical concentration profile measurements. The flux from the filling and emptying of these pools is dependent on u_*, and therefore accounts for turbulent-dependent biases, but cannot account for the long-term selective systematic NEE bias towards uptake. (2) Advective loss is independent of u_* but persistently occurs at night and is near zero during the day, and therefore accounts for the long-term selective systematic NEE bias towards uptake. (3) In order to estimate advective loss without explicit measurements of the phenomenon, we further hypothesize that at sunset, both nocturnal advection and photosynthesis are near zero, so eddy flux observations at this time, corrected for storage in both measured and unmeasured pools, are representative of the true *R*. The difference between *R* at sunset and *R* during the rest of the night therefore provides an estimate of advective loss.

Because both our hypotheses and those of the traditional u_* filter are speculative, we intend to highlight that our novel approach results in eddy flux-derived carbon fluxes that are closer to independent assessments of both advective loss and aboveground biomass changes. First, we highlight the problem by demonstrating the traditional technique of correcting NCE biases using a consistent u_* filter method across three sites (two tropical and one temperate forest). Next, we correct for a turbulence-dependent bias in NCE by modeling hypothesis (1) using a simple linear box model to compensate for effects of unmeasured CO_2 storage pools, which are filled or flushed depending on turbulence, but do not add or remove CO_2 from the system on daily or longer timescales. We then add the mean advective loss of hypothesis (2) using prior measurements of subcanopy advection and CO_2 gradients at two of our three sites (Staebler and Fitzjarrald, 2004; Tóta et al., 2008). We also model the advective loss using hypothesis (3), intended for sites lacking measurements of subcanopy flow, and validate the model against the aforementioned measurements. Our approach does not discard any data and consists only of two simple, first-order data corrections, added to observations of forest NEE in sequence, that we hope will ultimately allow for accurate estimates of whole-ecosystem net CO_2 fluxes.

2. Methods

2.1. Measurements of carbon dioxide and aboveground woody carbon fluxes

We compared eddy flux measurements of NEE to censuses of aboveground woody increment (AGWI) at three sites: (1) the Tapajós National Forest (TNF) km67 in Pará, Brazil (Rice et al., 2004; Hutyra et al., 2007; Pyle et al., 2009), (2) Guyaflux in Paracou, French Guiana (Bonal et al., 2008; Rowland et al., 2014), and (3) the Harvard Forest in Petersham, Massachusetts, USA (Wofsy et al., 1993; Urbanski et al., 2007). Eddy flux records covered: (1) January 2002-January 2006 and August 2008-December 2011 at TNF km67, (2) 2005–2014 at Guyaflux, and (3) 1992–2013 at the Harvard Forest.

The NEE data were quality-controlled half-hourly or hourly values, calculated as the sum of the eddy flux and the measured storage flux (i.e. the rate of storage of CO_2 in air spaces in the subcanopy and canopy, below the eddy flux sensor height). Half-hourly values were averaged to an hourly timestep in order to have uniform minimum time steps across all three sites. The hourly NEE observations are herein referred to as NEE_{obs}, to distinguish them from subsequent bias-corrected values. The nighttime subset of hourly NEE_{obs} is referred to as NCE_{obs}.

To calculate yearly and longer-timescale sums of both NEE_{obs} and bias-corrected NEE, hourly data were gap-filled using parametric relationships of daytime NEE with photosynthetically active radiation (PAR) and air temperature (Falge et al., 2001; Dunn et al., 2007; Urbanski et al., 2007). Gap-filling was performed with independent parameters for the following seasons: wet and dry seasons at TNF km67 and Guyaflux, with each year treated independently, and 8 seasons at the Harvard Forest, with each decade treated independently. Gap-filled data were only used to produce long-term total and annual mean NEE; non-gap-filled NEE_{obs} were used for the rest of the analysis. We estimated 95% confidence intervals due to random measurement errors for annual and total mean NEE by bootstrapping, i.e. randomly resampling (with replacement) hourly NEE_{obs} from similar seasons, years, and PAR and temperature conditions.

Biometry censuses covered (1) 1999, 2001, 2005, and 2008–2011 for TNF km67, once per year in the early dry season, (2) 2004, 2006, 2008, and 2013 for Guyaflux, once per year in March, and (3) 1993 and 1998–2013 for the Harvard Forest, once in July 1993 and four times per year in 1998–2013. At all sites, AGWI was calculated as the annual increase in aboveground woody biomass (AGWB) in trees with diameter at breast height (DBH) ≥ 10 cm, plus additions from recruitment minus losses from mortality. AGWI 95% confidence intervals were produced by bootstrapping, i.e. randomly resampling yearly subplot-based subtotal AGWB with replacement in the case of TNF km67 and Guyaflux, and randomly resampling yearly total AGWI with replacement in the case of the Harvard Forest.

2.2. Change-point detection for a conventional u_* filter approach

We applied a conventional u_* filter to NCE_{obs} (nighttime-only NEE_{obs}) and quantified the resulting net carbon balance in annual and long-term sums of u_* filtered NEE_{obs}. We used the change-point detection method (CPD) for selecting u_*^{Th} due to its insensitivity to noise in the NCE vs. u_* relationship and its prior validation at a suite of 38 North American forest eddy covariance sites (Barr et al., 2013). The CPD method consists of two steps: (1) binning the NCE_{obs} and u_* data into n_B equally sized u_* classes and (2) modeling the response of binned NCE_{obs} vs. u_* as two intersecting linear regressions, with their intersection representing the threshold, u_*^{Th}, below which data are discarded.

For each site, we modified step (1) from the original CPD method by binning NCE_{obs} and u_* for all years, instead of each individual year. Results were robust to a large range of values for n_B, but we selected a value of $n_B = 500$ for every site to allow our binning to include