AGRICULTURAL AND FOREST METEOROLOGY 148 (2008) 1266–1279

available at www.sciencedirect.com

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

Resolving systematic errors in estimates of net ecosystem exchange of CO_2 and ecosystem respiration in a tropical forest biome

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ARTICLE INFO

Article history:
Received 1 April 2007
Received in revised form
7 November 2007
Accepted 10 March 2008

Keywords:
Carbon
Eddy correlation
LBA
Respiration
Amazon
Tropical rainforest

ABSTRACT

The controls on uptake and release of CO_2 by tropical rainforests, and the responses to a changing climate, are major uncertainties in global climate change models. Eddy-covariance measurements potentially provide detailed data on CO_2 exchange and responses to the environment in these forests, but accurate estimates of the net ecosystem exchange of CO_2 (NEE) and ecosystem respiration (R_{eco}) require careful analysis of data representativity, treatment of data gaps, and correction for systematic errors. This study uses the comprehensive data from our study site in an old-growth tropical rainforest near Santarem, Brazil, to examine the biases in NEE and R_{eco} potentially associated with the two most important sources of systematic error in Eddy-covariance data: lost nighttime flux and missing canopy storage measurements. We present multiple estimates for the net carbon balance and R_{eco} at our site, including the conventional "u^* filter", a detailed bottom-up budget for respiration, estimates by similarity with ^{222}Rn, and an independent estimate of respiration by extrapolation of daytime Eddy flux data to zero light. Eddy-covariance measurements between 2002 and 2006 showed a mean net ecosystem carbon loss of $0.25 \pm 0.04\ \mu mol\ m^{-2}\ s^{-1}$, with a mean respiration rate of $8.60 \pm 0.11\ \mu mol\ m^{-2}\ s^{-1}$ at our site. We found that lost nocturnal flux can potentially introduce significant bias into these results. We develop robust approaches to correct for these biases, showing that, where appropriate, a site-specific u^* threshold can be used to avoid systematic bias in estimates of carbon exchange. Because of the presence of gaps in the data and the day–night asymmetry between storage and turbulence, inclusion of canopy storage is essential to accurate assessments of NEE. We found that short-term measurements of storage may be adequate to accurately model storage for use in obtaining ecosystem carbon balance, at sites where storage is not routinely measured. The analytical framework utilized in this study can be applied to other Eddy-covariance sites to help correct and validate measurements of the carbon cycle and its components.

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0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2008.03.007

1. Introduction

Tropical rainforests contain large stores of biomass and rapidly cycle carbon through photosynthesis and respiration, giving these ecosystems significant leverage on the global carbon cycle and rate of atmospheric CO_2 increase. Determining the net carbon balance in tropical rainforests is critical for quantifying the global carbon cycle, to understand the component processes of ecosystem respiration (R_{eco}) and photosynthesis, and to define responses of forests to environmental change.

Current research has not adequately constrained the magnitude, or even the sign, of the net carbon balance of tropical rainforests. Plot-level biometric measurements in undisturbed tropical rainforests have observed both significant carbon uptake (Phillips et al., 1998; Baker et al., 2004) and carbon emission (Rice et al., 2004; Miller et al., 2004). Analysis of Eddy-covariance measurements in the Amazon, which integrate carbon exchange over several square kilometers, have similarly observed a range of net ecosystem exchange (NEE) in primary forest sites from net uptake (Grace et al., 1995; Malhi et al., 1998), neutral (Miller et al., 2004), to small net release of carbon to the atmosphere (Hutyra et al., 2007; Saleska et al., 2003). Many modeling studies have predicted net uptake of CO_2 in the wet season and emission in the dry season, driven by temperature and water effects on R_{eco} and photosynthesis (respectively), but the opposite seasonality in NEE has been observed at some tropical forests (Saleska et al., 2003). Models predict divergent future scenarios in a changed climate, including collapse of the Amazon forest (Cox et al., 2004) and possible feedbacks between warming, reduced forest cover, and increased aridity (Oyama and Nobre, 2003; Hutyra et al., 2005).

Photosynthesis and its response to primary drivers (temperature and light) are relatively well understood at the leaf level and in environmental chambers (Farquhar and Sharkey, 1982). However, given the very high leaf area and significant variability in vertical and horizontal light interception within tropical ecosystem, it is a significant challenge to scale up leaf level results to the entire forest canopy. R_{eco} is a less understood process in tropical forests, integrating both aboveground and belowground plant and microbial processes, each driven by different ecosystem processes and responding differently to environmental drivers (Davidson et al., 2006; Trumbore, 2006).

Measurements from flux towers are a powerful tool for understanding the exchange of CO_2 between the atmosphere and biosphere at the ecosystem scale. The Eddy-covariance technique has been particularly useful for making direct, long-term measurements of CO_2 exchange in forests (e.g. Wofsy et al., 1993; Urbanski et al., 2007). Observed NEE (the sum of Eddy-covariance flux and changes in canopy CO_2 storage) represents the small residual difference between carbon uptake by photosynthesis and carbon loss through respiration.

During the daytime hours, NEE measures the combination of photosynthesis and autotrophic (roots, stem, leaves) and heterotrophic (microorganisms) respiration. In the nighttime, NEE represents R_{eco} because photosynthesis is zero. However, calm and stable atmospheric conditions complicate the interpretation of nighttime fluxes, with potentially significant affects on the computed ecosystem carbon budget (Papale et al., 2006; Falge et al., 2001). Eddy-covariance methods fail to measure NEE when turbulence is absent. Canopy storage, the change in average concentration below the Eddy sensor, in principle should account for respiratory CO_2 that is not transported from the canopy by turbulent exchange, but in practice, some CO_2 flux is 'lost' from the system by transport processes that cannot be measured at a single point (e.g. Staebler and Fitzjarrald, 2004; Aubinet et al., 2002). Considerable prior work has been done to understand and quantify the consequences of periods of low nighttime turbulence and storage measurements. Many investigators have concluded that not correcting for low nighttime turbulence can constitute a selective, systematic error, which can result in an overestimate of carbon sequestration (Goulden et al., 2006; Miller et al., 2004; Aubinet et al., 2002; Moncrieff et al., 1996; Goulden et al., 1996). Not correctly accounting for nighttime storage can also result in a double counting of fluxes (Papale et al., 2006; Gu et al., 2005; Aubinet et al., 2002; Falge et al., 2001). The importance of advection and storage processes are related to instrumentation, site characteristics (heterogeneity, topography, canopy conditions, etc.) and meteorology (Massman and Lee, 2002).

Data gaps exist in all Eddy-covariance data sets; average data coverage has been reported to be only 65% (Falge et al., 2001). Canopy storage measurements are unavailable for long time periods at many flux towers in the Amazon because of the remote locations, challenging environmental conditions, and sustained instrument failures (Iwata et al., 2005), making the assessment of NEE in Amazonian rainforests particularly challenging and error prone. Numerous efforts to standardize methods and protocols of data processing and gap filling have been undertaken (e.g. Papale et al., 2006; Gu et al., 2005; Falge et al., 2001), but local differences in site characteristics, meteorology, and instrumentation have made it difficult to apply them uniformly across the hundreds of flux sites currently in operation. Estimates of integrated annual carbon balance may vary by several Mg C ha^{-1} $year^{-1}$ depending on the treatment of flux measurements made under calm conditions (Miller et al., 2004; Papale et al., 2006). The consequent carbon-balance problem is particularly significant in the tropics, because the R_{eco} fluxes are large throughout the year and constitute a greater fraction of the annual NEE observations, relative to temperate zones.

Biometric data provide another measure of ecosystem carbon dynamics. Repeated measurement of forest structure (biomass, growth, mortality, and recruitment) document changes in aboveground carbon stocks. These data have the potential to elucidate the ecological mechanisms controlling longer term (years to decades) ecosystem carbon balance. Biometric data can also provide an important independent check on flux tower measurements on the time scale of several years (Barford et al., 2001; Curtis et al., 2002; Saleska et al., 2003). Finer scale measurements of respiration (soil, coarse woody debris, etc.) can quantify the efflux rates for different forest components and provide an independent estimate of R_{eco}, to check estimates based on Eddy-covariance data (Law et al., 1999; Falge et al., 2001; Chambers et al., 2004).