AGRICULTURAL AND FOREST METEOROLOGY 148 (2008) 1894–1907

available at www.sciencedirect.com

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

Comparison of eddy covariance, chamber, and gradient methods of measuring soil CO_2 efflux in an annual semi-arid grass, *Bromus tectorum*

M.C. Myklebust [a,*], *L.E. Hipps* [b,1], *R.J. Ryel* [c,1]

[a] *Institut National de la Recherche Agronomique, Ecologie de Forêts Méditerranéennes, UR 629, F-84914 Avignon, France*
[b] *Department of Plants, Soils, and Climate, Utah State University, Logan, UT 84322-4820, USA*
[c] *Department of Wildland Resources, Utah State University, Logan, UT 84322-5230, USA*

ARTICLE INFO

Article history:
Received 4 February 2008
Received in revised form
26 June 2008
Accepted 30 June 2008

Keywords:
CO_2
Bromus tectorum
Eddy correlation
Grass land
Respiration
Nocturnal

ABSTRACT

Eddy covariance measures net ecosystem exchange of CO_2 (NEE) at a scale between chamber-based measurements of CO_2 exchange processes and large-scale models of CO_2 flux dynamics. As the intermediate, it represents a link between small and large-scale estimates of NEE. Accuracy is therefore critical. However, estimates of nighttime ecosystem respiration based on scaled-up measurements of soil and leaf CO_2 exchange are most often larger than from eddy covariance. Identifying the source of the discrepancy is difficult due to large measurement uncertainties associated with high variability of fluxes in complex ecosystems. This study compared measurements in a simple system that allowed for minimal uncertainty. We compared measurements of soil efflux using (1) soil chambers, (2) the soil CO_2 gradient technique and ecosystem respiration using the (3) the eddy covariance method from a surface that was covered with living vegetation, straw, and snow in turn through a year. Results showed general agreement among measurements in a range of conditions during canopy absence indicating that each measurement technique is theoretically sound. However, we found disagreement among measurements in specific conditions that indicated certain limitations with each method. Nighttime eddy covariance measurements of ecosystem respiration were below the uncertainty limits of soil respiration measurements during the period of active canopy growth (leaf area index from approx. 0.3–1.0 $m^2\ m^{-2}$. This raises questions about the accuracy of nocturnal eddy covariance measurements over more complex surfaces. There was indication that the chamber method estimates were unrepresentative of the footprint in certain conditions due to within collar surface treatment and due to collar interaction with the environment. Lastly, the gradient method failed to represent surface fluxes during summer rain. To measure soil efflux in all conditions typical of this site, a combination of all three methods is recommended. A combined NEE estimate for 2005 for soil efflux was $406 \pm 73\ g\ C\ m^{-2}$.

* *Corresponding author*. Tel.: +33 4 32 72 29 55; fax: +33 4 32 72 20 42.
E-mail addresses: may.myklebust@avignon.inra.fr (M.C. Myklebust), biomet@cc.usu.edu (L.E. Hipps), ron.ryel@usu.edu (R.J. Ryel).
[1] Ecology Center, Utah State University, Logan, UT 84322-5205, USA.
0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2008.06.016

1. Introduction

Net ecosystem exchange (NEE) of CO_2 between the atmosphere and biosphere is measured by eddy covariance at a scale of a few hectares to several square kilometers (Baldocchi, 2003). The processes that make up NEE, soil respiration and leaf gas exchange (photosynthesis and respiration), are typically measured at smaller scales by chambers (Davidson et al., 2002; Long et al., 1996) and scaled-up to match the eddy covariance footprint (Savage and Davidson, 2003; Law et al., 1999b). Together, these techniques should provide a high temporal resolution of spatially integrated CO_2 exchange processes. But the techniques are not often complementary because estimates of NEE usually disagree. Using the convention that photosynthesis is negative and respiration positive, chamber-based estimates tend to be higher than eddy covariance measurements (Curtis et al., 2005; Launiainen et al., 2005; Bolstad et al., 2004; Janssens et al., 2001; Law et al., 1999b; Norman et al., 1997; Goulden et al., 1996). The cause of this apparent bias is not understood though the general lack of energy balance closure suggests that eddy covariance may be underestimating NEE (Wison et al., 2002). However, due to the large uncertainties in scaled-up chamber measurements, underestimation by EC is not confirmed.

Eddy covariance measures net vertical turbulent CO_2 flux between the atmosphere and surface (vegetation and soil). This should represent the sum of photosynthesis and respiration in a fully adjusted boundary layer (the layer of atmosphere that is in equilibrium with mass and energy exchange with the surface). Turbulence is caused by buoyancy generated at the surface, and by shear forces propagated by momentum transfer toward the surface from above. In the day, turbulence is typically caused by both buoyancy and shear forces. At night, shear forces alone may cause turbulence. During calm conditions at night, atmospheric stability often occurs where cool, dense air near the soil surface resists mixing with air above (negative buoyancy). This decoupling of the atmosphere causes fluxes measured at the sensors to be unrepresentative of fluxes from the soil and canopy.

Daytime measurements of eddy covariance are corroborated by independent methods but corroboration of nighttime measurements is rare. Good agreement between daytime eddy covariance measurements and predictions of NEE based on environmental variables has been found at several sites (Falge et al., 2002; Goulden et al., 1996). In contrast, predictions of nighttime eddy covariance measurements have had very low r^2 values (Falge et al., 2002; Goulden et al., 1996). A process-based model for fluxes in a deciduous broadleaf forest found good agreement with daytime but not nighttime eddy flux values (Ito et al., 2007). In addition at a hardwood forest site, chamber-based estimates were within the limits of uncertainty of eddy covariance measurements in the day (Wofsy et al., 1993), but were higher at night even when the atmosphere was expected to be well mixed due to turbulence (Goulden et al., 1996). Similar discrepancies during nights with high turbulence have been shown for six coniferous boreal forest sites (Lavigne et al., 1997), a mature ponderosa pine forest (Law et al., 1999b), and a temperate deciduous (Kutsch et al., in press) and a mixed (Aubinet et al., 2002) forest. However, there is evidence of good agreement with chamber-based estimates during turbulent nights in a young ponderosa pine plantation (Law et al., 1999a), a eucalypt forest (Van Gorsel et al., 2007), and over bare soil (Reth et al., 2005). The reason for the agreement inconsistency is not clear.

Uncertainties in the eddy covariance technique vary with differences in sampling design, data treatment (Baldocchi, 2003), data cleaning protocol (Papale et al., 2006; Gu et al., 2005; Wohlfahrt et al., 2005), and gap-filling techniques (Falge et al., 2001). Uncertainties also vary with differences in site characteristics such as canopy heterogeneity (Aubinet et al., 2002), LAI (Yi, 2008), topography (Katul et al., 2006), and patterns of advection (Feigenwinter et al., 2008; Aubinet et al., 2005). Many of the uncertainties can be reduced by measuring over an extensive horizontally homogeneous surface on flat terrain and with a steady atmosphere (Baldocchi, 2003). In addition, a short canopy (Baldocchi et al., 2001) with relatively low LAI (Yi, 2008) will maximize canopy air mixing in turbulent conditions.

The chamber technique calculates rates of photosynthesis and respiration by measuring the rate of change of CO_2 concentration inside a chamber. Accurate measurements depend on accounting for all gains and losses of CO_2 in the chamber. They also depend on simulating ambient conditions inside the chamber to prevent altering fluxes. Detailed reviews covered uncertainties in measurement in leaf (Long et al., 1996) and soil chamber (Davidson et al., 2002) techniques. Subsequently, leaks across gaskets have been found to cause overestimates in leaf respiration and corrections were established (Pons and Welschen, 2002). Also, underestimation of soil efflux were found when collars are inserted so deeply into the soil as to cut roots (Wang et al., 2005) and vented chambers could cause an over-estimate in soil during windy conditions (Bain et al., 2005) unless the vents were correctly designed (Xu et al., 2006). Because closed (unvented) chambers have been most commonly used, vent design does not explain why soil chambers tend to measure higher values than eddy covariance. Closed chambers actually have a tendency to underestimate (Davidson et al., 2002), so underestimates rather than overestimates likely predominate the literature. Uncertainties associated with scaling up to the eddy covariance footprint may be very large because of propagation of small measurement error, spatial and temporal heterogeneity in fluxes, and the difficulty in estimating the total area of the gas exchange surface (Bolstad et al., 2004). However, scaled-up estimates may result in over- or underestimates of actual fluxes and so do not explain the preponderance for over-estimation of chamber relative to eddy covariance-based estimates of respiration. Uncertainties in chamber-based estimates are reduced when spatial and temporal heterogeneity of fluxes are minimized and when plant structure is simple.

A problem with comparing values from two techniques is the difficulty of determining which is more accurate when they disagree. One approach is to use three independent measurement techniques to help identify errors in measurements. Soil efflux can be measured three ways: from gradients of CO_2 in the soil (gradient method), at the surface using soil CO_2 chambers (chamber method) and from eddy covariance measurements above the canopy within the fully adjusted