Assessing Ecosystem Carbon Balance: Problems and Prospects of the Eddy Covariance Technique

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ABSTRACT

The eddy covariance method, as it is applied to the case of ecosystem CO_2 exchange on short and long time scales and over ideal and non-ideal surfaces, is assessed. The eddy covariance method is most accurate when the atmosphere is steady and the vegetation is homogeneous and on flat terrain. When the eddy covariance method is applied over complex landscapes and non-steady conditions, the interpretation biosphere and atmosphere CO_2 exchange must include measurements of atmospheric storage, flux divergence and advection.

Measuring CO_2 flux measurements over long periods reduces random sampling error to small values. However, gaps are inevitable in long records. Filling data gaps with empirical estimates do not introduce significant bias errors as gaps are filled with algorithms derived from a large statistical population. Systematic bias errors are greatest when winds are light and intermittent, as at night. On an annual basis, the error of net ecosystem CO_2 exchange ranges between 30 and 200 gC m^{-2}.

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INTRODUCTION

A prime focus of ecological research is on carbon assimilation and respiration of ecosystems. The suite of traditional tools in an ecologist's tool box include leaf cuvettes (Field et al., 1982), whole-plant (Denmead et al., 1993) and soil (Goulden and Crill, 1997) chambers and biomass (Clark et al., 2000) and soil carbon inventories (Admundson et al., 1997). While each of the cited methods has a set of distinct strengths, they are limited with regards to their ability to measure net carbon dioxide exchange of the whole ecosystem across a variety of time scales.

For example, the manual dependency of translucent cuvettes limits the duration they can be applied and the number of leaves that can be measured across the domain of the canopy. Enshrouding groups of plants or trees in large transparent chambers diffuses light, alters the microclimate (Denmead et al., 1993) and suppresses soil respiration (Lund et al., 1999). Consequently, the response of whole canopy carbon exchange to environmental perturbations, as measured with a whole plant chamber system, differs from that detected with independent micrometeorological measurements (Denmead et al., 1993).

Biomass inventories produce indirect estimates of net primary productivity, as allometric relations are used to scale measurements of incremental changes in diameter at breast height to estimates of net primary production at plot and landscape scales (Clark et al., 2000; Barford et al., 2001). The coarse time resolution of biomass inventories prevents them from being used to address questions relating to the dynamics of ecosystem physiology. Bias errors can be introduced when allometric relationships ignore trees in small size classes, understorey vegetation, the amount of carbon that is allocated below ground (Clark et al., 2001) and when they do not represent the multi-aged and multi-species structure of forest stands (Carey et al., 2001).

Chamber-based measurements of CO_2 efflux from the soil are susceptible to bias errors introduced by perturbing local pressure, wind and CO_2 concentration fields and by altering the heat and water balance of the soil (Livingston and Hutchison, 1995). The areal extent of ground that is sampled by a chamber, or a set of chambers, is relatively small compared to the spatial variability of the CO_2 efflux from the ecosystem.

The eddy covariance technique provides an alternate and direct means of measuring net carbon dioxide exchange, at the canopy scale. In particular, it supplies investigators with a tool to study ecosystem physiology across a spectrum of times scales, ranging from hours to years (Wofsy et al., 1993; Baldocchi et al., 2001a) and across a relatively large spatial domain (Schmid, 1994).

The eddy covariance method has limitations, too. The method is most applicable over flat terrain when the environmental conditions are steady and the underlying vegetation upwind of the sensors is horizontally homogeneous for an extended distance of several hundred meters and the terrain is flat. Violation of these assumptions can cause systematic errors in the interpretation of the eddy covariance measurements and its integration over long time durations. In fact controversy has already occurred for this reason, as observed by criticisms from members of the ecological community when results deduced from eddy covariance measurements do not comply with established ecological concepts (Keller et al., 1996; Piovesan and Adams, 2001).

Use of the eddy covariance method by specialists and non-specialists has accelerated in recent years. A citation search of published papers that index the term ‘eddy covariance’ produced over 200 records and over 500 papers referred to the analogous term ‘eddy correlation’. The objective of this review is to discuss the merits and limitations of the eddy covariance method as a tool for examining CO_2 exchange between ecosystems and the atmosphere, for increasingly longer time scales. For reviews on the theoretical and technical aspects of micrometeorological flux measurements, the reader is referred to papers produced by Baldocchi et al. (1988), Verma (1990), Desjardins (1991), Lenschow (1995), Foken and Wichura (1995), Aubinet et al., (2000) and Massman and Lee (2002).

HISTORICAL DEVELOPMENT

Sir Osborne Reynolds (1895) is credited with devising the theoretical framework for the eddy covariance method. The first eddy covariance study occurred n 1926 and focused on momentum transfer (Scrase, 1930). The development of fast responding hot-wire anemometry and thermometry and digital computers, three decades later, led the next wave of eddy covariance studies (Swinbank, 1951; Kaimal and Wyngaard, 1990). Early micrometeorological studies focused on the structure of turbulence in the atmospheric boundary layer and the transfer of heat and momentum and they were conducted at locales with extremely level terrain, short vegetation and windy, sunny climes where atmospheric conditions were steady. Nevertheless, they are notable for laying the theoretical and experimental foundation for subsequent work on CO_2 exchange, that is of interest to the ecological community.

Initial studies on CO_2 exchange between plant canopies and the atmosphere relied on the flux-gradient method, rather than the eddy covariance technique. The first studies were performed over short agricultural crops during the late 1950’s and early 1960’s

(Inoue, 1958; Monteith and Szeicz, 1960; Lemon, 1962). A decade later, scientists started to apply the flux-gradient method to measure CO_2 exchange over forests (Denmead, 1969; Baumgartner, 1969; Jarvis et al., 1976) and over native ecosystems, such as tundra, grasslands and wetlands (Coyne and Kelley, 1975; Ripley and Redman, 1976; Houghton and Woodwell, 1980). Application of flux gradient theory over forests was found to be problematic at the onset (Raupach, 1979). Over tall forests eddy exchange coefficients are enhanced by turbulent transport in the roughness sublayer of forests and vertical gradients of CO_2 are small and difficult to resolve because turbulent mixing is efficient.

The first application of the eddy covariance method, towards measuring carbon dioxide exchange, occurred in the early 1970's (Desjardins, 1974; Desjardins and Lemon, 1974). Initial studies were performed over corn using a propeller anemometer and a modified, closed-path infrared gas analyzer, with a capacitance detector. The time constants of these sensors, however, were relatively slow—on the order of 0.5 s. These limitations prompted Garratt (1975) to critique the measurements of Desjardins and Lemon (1974) and conclude that they suffered from large errors (~40%).

The next wave of technological improvements came with the commercial availability of sonic anemometers and the development of rapid-responding, open path infrared gas analyzers (Jones et al., 1978; Bingham et al., 1978; Brach et al. 1981; Ohtaki and Matsui, 1982). Open-path CO_2 sensors, using solid-state, PbSe detectors, were able to sense CO_2 fluctuations as rapidly as ten times per second. Their open architecture enabled them to sample parcels of air without disturbing them. The earliest studies using the eddy covariance method to measure CO_2 exchange were conducted over agricultural crops include reports; instrumental papers include work by Anderson et al. (1984) over soybeans, Anderson and Verma (1986) over sorghum, Ohtaki (1984) over rice and Desjardins (1985) over corn. The earliest eddy covariance studies on CO_2 exchange over native ecosystems included studies by Wesely et al. (1983) and Verma et al (1986) over temperate deciduous forests, by Verma et al. (1989) and Kim and Verma (1990) over a prairie grassland, by Fan et al. (1990) over a tropical forest, and by Valentini et al. (1991) over Mediterranean macchia.

Prior to 1990, limitations in sensor performance and data acquisition systems restricted the duration of the eddy covariance studies to short campaigns during the heart of the growing season (Verma et al., 1986). Subsequent development and availability of commercial, stable and fast responding hygrometers and infrared spectrometers enabled scientists to conduct eddy covariance field studies 24 hours a day, seven days a week, 52 weeks a year. Wofsy et al. (1993) reported on the first application of the eddy covariance method towards measuring carbon dioxide exchange of a forest over the course of a year, starting in 1990. By 1993, a handful of other study sites were operating, continuously over forests in North America (Black et al., 1996; Goulden et al., 1996a, b; Greco and Baldocchi, 1996), Japan (Yamamoto et al., 1999), and Europe (Valentini et al., 1996). By 1997, regional networks of flux measurement sites were operating in Europe (Aubinet et al., 2000) and North America (Running et al., 1999). Currently, the eddy covariance method is being used at over 150 sites worldwide, as part of the FLUXNET program (Baldocchi et al, 2001) and regional networks in North America (AmeriFlux), Brazil, Europe (CarboEuroflux), Asia (AsiaFlux), Australia (OzFlux) and Africa.

PRINCIPLES AND CONCEPTS

The equation defining the conservation of mass provides the theoretical guide for utilizing the eddy covariance technique (Baldocchi et al., 1988; Paw U et al., 2000). For the case of CO_2, the conservation of mass states that the time rate of change of the CO_2 mixing ratio, *c*, is balanced by the sum of the flux divergence of CO_2 in the vertical (z), lateral (x) and longitudinal (y) directions and the biological source sink-strength (S_B):

$$\frac{dc}{dt} = -\left(\frac{\partial F_z}{\partial z} + \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + S_B(x,y,z)\right) \quad (1$$

The mixing ratio of CO_2, *c*, is defined as the ratio of mole density of CO_2 to the mole density of dry air, $c = \rho_c / \rho_a$. *F* denotes the flux density of CO_2 (μmol m^{-2} s^{-1}). Under ideal conditions, the atmosphere is steady and the underlying surface is horizontally homogeneous and on flat terrain. Based on these assumptions, the conservation equation simplifies to a balance between the vertical flux divergence of CO_2 and its biological source/sink strength, S_B:

$$\frac{\partial F_z}{\partial z} = -S_B(z) \quad (2$$

By integrating Equation 2 with respect to height, one derives an equality between the mean vertical flux density measured at some height, $F_c(h)$, and the net flux density of material in and out of the underlying soil, $F_c(0)$, and vegetation:

$$F_C(h) = F_C(0) - \int_0^h S_B(z)dz \quad (3$$

1. Evaluating the Flux Covariance

On the basis of physical principles and Reynolds' rules of averaging (Reynolds, 1895), the mean covariance between vertical velocity (*w*) and the CO_2 mixing ratio, *c*, produces a direct measure of the mean vertical flux density of CO_2:

$$F = \overline{\rho_a wc} \cong \overline{\rho_a} \cdot \overline{w'c'} \qquad (4$$

In Eq. 4, the overbars denote time averaging and primes represent fluctuations from the mean (e.g. $c' = c - \bar{c}$). A positively signed covariance represents net CO_2 transfer into the atmosphere and a negative value denotes the reverse.

Assessment of the flux covariance requires that we sample the spectrum of turbulent motions that exist in the atmosphere and contribute to the flux density of CO_2 between the surface and atmosphere (Garratt, 1975):

$$\overline{w'c'} = \int_0^\infty S_{wc}(\omega)d\omega \qquad (5$$

S_{wc} is cospectral density between w and c and ω is angular frequency, which is related to natural frequency, n, by a factor of 2π. Sampling rates on the order of 10 times per second are needed to sample the high frequency portion of the flux co-spectrum (Anderson et al., 1984, 1986; Goulden et al., 1996a). The sampling duration must be long enough to capture low frequency contribution to the flux covariance, but not too long to be affected by diurnal changes in CO_2. In general, sampling durations and averaging periods of 30 to 60 minutes are adequate during daylight hours (Anderson et al., 1984, 1986; Aubinet et al., 2000). Longer averaging times may be needed at night when atmosphere thermal stratification is stable and turbulence is intermittent (Lee et al. 1996; Massman and Lee, 2002).

In practice, CO_2 is measured with infrared spectrometers, which do not measure mixing ratio, c. Instead they sample molar density, ρ_c (moles per unit volume). In principle, changes in molar density can occur by adding or removing molecules in a controlled volume, or by changing the volume, as is done when pressure, temperature and humidity change in the atmosphere. By measuring the eddy flux covariance in terms of molar density, the net flux density of CO_2 across the atmosphere-biosphere interface is evaluated as:

$$F = \overline{\rho_a wc} = \overline{\rho_a} \cdot \overline{w'c'} = \overline{w\rho_c} = \overline{w'\rho_c'} + \overline{w}\,\overline{\rho_c} \qquad (6$$

The new term, on the right hand side of Eq. 6, is the product of the mean vertical velocity and CO_2 density. The mean vertical velocity arises from density fluctuations (Webb et al., 1980). Its magnitude is too small (< 1 mm s^{-1}) to be detected by anemometry, but it can be computed on the basis of temperature (T) and humidity density (ρ_v) fluctuations using the Webb-Pearman-Leuning (1980) algorithm:

$$F_c = \overline{w'\rho_c'} + \frac{m_a}{m_v}\frac{\overline{\rho_c}}{\overline{\overline{\rho_a}}}\overline{w'\rho_v'} + (1 + \frac{\overline{\rho_v} m_a}{\overline{\overline{\rho_a}} m_v})\frac{\overline{\rho_c}}{\overline{\overline{T}}}\overline{w'T'} \qquad (7$$

Undefined variables in Equation 7 are the molecular weights of air (m_a) and water vapor (m_v). The derivation of Equation 7 ignores effects of pressure fluctuations, which may be significant under high winds (Massman and Lee, 2002) and advection (Paw U et al., 2000); the reader is referred to a different formulation if one uses a density-weighted averaging scheme (Kramm et al., 1995). The validity of Equation 7 has been demonstrated by studying CO_2 exchange over a bare, dry field (Leuning et al., 1982)—without density corrections photosynthesis is 'detected' over a bare field.

Significant terms in Equation 7 depend on whether one uses an open or closed path infrared spectrometer. If one draws air down a heated tube in a turbulent state, as is needed to implement a closed-path sensor, temperature fluctuations will dampen and approach zero, thereby canceling the last term on the right hand side of Equation 7 (Leuning and Moncrieff, 1990; Leuning and Judd, 1996).

On paper, the assessment of an eddy covariance seems to be simple and straightforward. In practice, numerous instrument, sampling and turbulence issues influence how well it is measured. The *w-c* covariance, that is measured by a set of instruments, is a function of the true covariance, $S_{wc}(\omega)$, and a filter function, $H(\omega)$ (Moore, 1986; Leuning and Judd, 1996; Aubinet et al.,2000; Massman, 2000; Berger et al., 2001):

$$\overline{w'c'}_{measured} = \int_0^\infty H(\omega) S_{wc}(\omega) d\omega \quad (8$$

Correct sampling of the w and CO_2 signals will produce a –4/3 slope in the high frequency portion of the co-spectrum (Anderson et al., 1984, 1986). High pass filtering of the flux covariance, on the other hand, will cause a steeper slope, whereas white noise will produce a high frequency spectrum that has a slope of one. High pass filtering can be caused by slow sensor response time, a large sensor path, a slow sampling rate, and by instruments placed too far abreast from one another or too close to the ground (Moore, 1986; Massman, 2000; Aubinet et al., 2000). In addition, sampling air through a tube filters high frequency scalar fluctuations (Sukyer and Verma, 1993; Leuning and Judd, 1996; Massman, 2000).

Low pass filtering is imposed by the averaging method and the sampling duration (Moore, 1986; Massman, 2000; Aubinet et al., 2000). Low pass filtering is most severe during convective conditions, when the passage of a large convective cell may be incomplete during a conventional averaging period. Some investigators chose to detrend signals (Foken and Wichura, 1995) but Reynold's averaging rules do not consider detrending (Paw U et al.,2000). Plus, it is redundant to detrend turbulence signals and compensate for storage in the canopy air space (see below).

The options for making accurate eddy covariance measurements are either to design an eddy covariance system that minimizes cospectral filtering or to assess the spectral transfer function and correct one's measurements. Moore (1986) and Massman (2000) have produced theoretical transfer functions that can be applied to correct eddy covariance measurements. In general, spectral corrections factors range between 1.04 and 1.25 for CO_2 flux densities measured by systems employed by the Euroflux community (they use closed path gas analyzers) and the correction ranges between 1.06 and 1.35 for water vapor flux densities (Aubinet et al., 2000). Alternatively, Wofsy et al. (1993) and Goulden et al. (1996a, b) use an empirical approach. They correct the measured flux covariance by the ratio of a nearly 'perfect' measure of covariance, such as that between acoustic temperature and *w*, and its degraded value. The time constant of a low pass recursive filter is adjusted to degrade the 'perfect' signal until it mimics the measured CO_2 signal. This method does not rely on any assumptions about the functions describing turbulence spectra and transfer functions. On the other hand, it does not account for line averaging, which occurs because of the fixed distance of the anemometer path, and it fails when sensible heat flux density is near zero.

2. Interpreting Eddy Covariance Measurements

When the thermal stratification of the atmosphere is stable or turbulent mixing is weak, CO_2 exiting leaves and the soil may not reach the reference height, *h*. Under such conditions, the storage of CO_2 in the underlying airspace, $\overline{\rho_a}\int_0^h \frac{\partial \overline{c}}{\partial t} dt$, becomes significant. Its contribution must be added to the eddy covariance measurement if we expect to obtain a measure of the net flux of CO_2 flowing into and out of the soil and vegetation (Fan et al., 1990; Grace et al., 1996; Goulden et al., 1996; Moncrieff et al., 1996; Yang et al., 1999; Baldocchi et al., 2000; Aubinet et al., 2000). In practice, the storage term is an important quantity on an hour-by-hour basis. The storage term is greatest near sunrise when there is a break-up of the stable nocturnal boundary layer by the onset of convective turbulence (Grace et al., 1996; Moncrieff et al., 1996; Yang et al., 1999). To measure the storage term accurately, one must measure temporal changes in CO_2 above the canopy and, at least, two heights within the canopy (Yang et al., 1999). On daily and annual time scales the storage term is approximately zero (Anthoni et al., 1999; Baldocchi et al., 2000).

Over sloping terrain, the mean vertical velocity, with respect to the geopotential, will be non-zero because hills cause wind streamlines to converge and diverge (Finnigan, 1999). Classically, investigators apply a mathematical rotation to the wind coordinate system to compute flux covariances that are orthogonal to the mean streamlines flowing over the landscape (McMillen, 1988; Baldocchi et al., 1988; Foken and Wichura, 1995). If mesoscale circulations persist, it is inappropriate to rotate the coordinate system and force the mean vertical velocity to zero (Lee, 1998). A new reference for coordinate rotation must be defined and it depends on wind direction, instrument biases and the slope of the upwind terrain (Paw U et al., 2000). With this modification, the net ecosystem exchange of CO_2 (N_e) is now defined as the sum of the eddy covariance, measured at a reference height, the storage term and horizontal and vertical advection terms (Sun et al., 1998; Lee, 1998; Finnigan, 1999; Yi et al. 2000; Eugster and Siegrist, 2000; Paw U et al., 2000).

From a practical standpoint it is difficult to assess horizontal advection terms over tall forests. Motivated by this problem, Lee (1998) developed an equation that represents net ecoystem-atmosphere CO_2 exchange (N_e) that is a function of a one-dimensional, vertical advection term. General application of the model of Lee (1998) is still subject to debate, however. From a practical standpoint, the introduction of an additional term to the conservation budget introduces new sources of measurement error (Baldocchi et al., 2000). Theoretically, Finnigan (1999) argues that topography and spatial changes in surface roughness and CO_2 sources and sinks strengths, produces spatial variation in the scalar concentration and wind velocity fields that may not be accommodated by this one-dimensional relation.

Alternative approaches to assessing CO_2 advection include measuring flux divergence profiles over plant canopies (Lee et al. 1999; Baldocchi et al. 2000, Yi et al. 2001), measuring horizontal transects across landscapes (Baldocchi and Rao, 1995) or by assessing regional box budgets (Sun et al., 1998; Eugster and Siegrist, 2000). As a word of caution, observations of no flux divergence above a plant canopy do not prove that there is no advection occurring inside a canopy. Drainage flows may transport CO_2 from the vicinity of the eddy covariance measurement tower and vent it elsewhere (Sun et al., 1998).

EVALUATING DAILY AND ANNUAL CARBON FLUXES

1. The Influence of Random and Systematic Bias Errors

By our desire to sum eddy fluxes over very long durations, as is needed to address ecologically relevant questions, we face new challenges to the application of the eddy covariance method. In this section, we assess potential errors occur and discuss whether they are acceptable and if they cancel over longer integration times.

In practice, the accuracy of summing short-term eddy flux measurements on daily, seasonal and annual time scales depends upon the calibration and stability of instruments and how well one removes random and systematic bias errors that can arise from sampling and theoretical reasons (Moore, 1986; Foken and Wichura, 1995; Moncrief et al., 1996; Massman, 2000; Massman and Lee, 2002).

With proper system design and implementation random measurement errors of individual measurement periods are generally small. For example, calibration errors of infrared gas analyzers are on the order of 2 to 3% and errors in covariance calculations associated with time lags between velocity and scalar sensors are less than 2% (Berger et al. 2001). With the application of proper transfer functions, the covariance measurement error is less than 7% during the day and less than 12% at night (Berger et al, 2001; Soegaard et al., 2001). These values are much smaller than natural variability of turbulence, which is on the order of 10 to 20% (Wesely and Hart, 1985).

Long term averaging reduces random sampling errors to a value within +/- 5%, thereby increasing the precision of CO_2 flux measurements (Moncrieff et al., 1996; Goulden et al. 1996a). There is a practical limitation to making long-term measurements, however, which offsets its reduced sampling error. Gaps in the long-term data records will occur as sensors breakdown, when they are being calibration or when they go off-scale. Data are generally rejected when the wind is blowing through a tower or from an undesirable wind sector, when sensors are wet or when the measurements fail to meet pre-set acceptance criteria (Foken and Wichura, 1995). Typical data coverage, over the course of a year, ranges between 65 % and 75% for a large number of field studies (Falge et al., 2001).

Several methods are being employed by the research community to fill gaps. One approach fills missing flux data on the basis of empirically derived algorithms that are driven by easily measurement meteorological variables, such as sunlight, temperature and humidity (Goulden et al., 1996b; Aubinet et al., 2000; Falge et al., 2001). This approach, however, needs continual updating and tuning as seasonal changes in leaf area, soil moisture, photosynthetic capacity will alter any derived relation. Another approach involves interpolation between adjacent periods. This method may work well for small data gaps, but will have problems with gaps occurring over several hours and days. A third approach is to bin data by hour for a one to two week period, then use the time dependent mean to replace missing data (Moncrieff et al., 1996; Jarvis et al., 1997). Falge et al. (2001) compared various gap filling methods and found that they produced similar results and did not introduce any particular methodological bias. Furthermore, they report that rejecting up to 40% of data still produces repeatable annual sums, as there is still an adequate sampling of the population of data.

Two types of systematic bias errors continue to plague eddy covariance measurements. One is the widely observed lack of energy balance closure (Aubinet et al., 2000; Twine et al., 2000; Wilson et al, *in press*). The other is an underestimate of nocturnal ecosystem efflux during low wind conditions (Grace et al., 1996; Black et al., 1996; Goulden et al., 1996a; Moncrieff et al., 1996; Mahli et al., 1998; Aubinet et al., 2000; Baldocchi et al., 2000). Tests of surface energy balance closure suggest that turbulent fluxes at some sites are systematically 10% to 30% too small to close the energy budget, (Aubinet et al., 1999; Twine et al., 2000; Wilson et al. *in press*). These results raise the possibility that CO_2 fluxes are underestimated similarly. For investigators using open-path CO_2 sensors, errors in energy balance closure will translate into an additional source of errors in measuring CO_2 flux density as the Webb et al density corrections are a function of sensible and latent heat flux densities. Factors contributing to a lack of energy balance closure include: 1) filtering of low frequency flux contributions; 2) advection; and 3) different footprints viewed by the eddy flux and the available energy measurement systems (Twine et al., 2000; Yi et al., 2001; Wilson et al., *in press*).

Some scientists advocate adjusting CO_2 flux densities in proportion to the lack of energy balance closure (Twine et al. 2000). But this procedure places high levels of confidence on the accuracy and representativeness of the sensors measuring available energy; net radiometers and soil heat flux plates sample a small portion of the landscape near the tower, while eddy covariance measurements represent an area hundreds of meters square in area (Schmid, 1994). Furthermore, independent tests of evaporative fluxes, based on lysimeters and watershed water balances, are agreeing well with eddy covariance measurements (Barr et al., 2000; Wilson et al., 2001), which lends support to the accuracy of daytime eddy covariance measurements.

Insufficient turbulent mixing, incorrect measurement of the storage term of CO_2 in the air space and soil and the drainage of CO_2 out of the canopy volume at night have been posited as reasons why the eddy covariance method underestimates CO_2 flux densities at night (Black et al., 1996; Lindroth et al., 1998; Sun et al., 1998). Typically, intermittent turbulence at night causes much run-to-run variability in nocturnal CO_2 flux measurements (Lee et al., 1996; Aubinet et al., 2000). During a period with vigorous turbulence, CO_2 from the canopy will be flushed. But this CO_2 flux density will not represent CO_2 that was produced locally in time. The occurring CO_2 efflux density will be exaggerated due to the accumulation of CO_2 in the canopy airspace since the previous flushing event. And during the period following a flushing event, the reduction in turbulent mixing may cause an artificially low CO_2 flux density to be detected, as the canopy volume will start to refill with CO_2.

At present, several teams of investigators are applying an empirical correction to compensate for the underestimate of nighttime carbon flux measurements. Some investigators replace data with a temperature-dependent respiration function that is derived from soil chambers (Anthoni et al., 2001). Others correct CO_2 flux density measurements relative to measurements made during windy periods using a regression between CO_2 flux density and friction velocity (Black et al., 1996; Goulden et al., 1996a, b; Lindroth et al., 1998; Hollinger et al., 1999; Malhi et al., 1998; Aubinet et al., 2000; Falge et al., 2001; Lafleur et al., 2001). The critical friction velocity that produces 'good' nighttime CO_2 fluxes is not universal and can range from 0.1 to 0.6 m s^{-1}.

There are pro and cons to adjusting nocturnal CO_2 fluxes relative to values measured during well-mixed conditions. On the negative side, the regression statistics between F and friction velocity, u_*, tend to be poor; typically, the coefficient of variation is less than 0.2 (Aubinet et al., 2000). Longer averaging periods reduce the sampling error of individual data points (Sukyer and Verma, 2001), but uncertainty in the statistical regression between F_c and the independent variable, friction velocity, remains high because of the reduced number of samples (Aubinet et al., 2000, 2001).

Despite the problems cited above, several investigators have reported favorable comparisons between nocturnal respiration rates and independent estimates, as inferred by the intercept of the response curve between CO_2 flux and sunlight (Hollinger et al., 1999; Lee et al., 1999; Suyker and Verma, 2001). Comparing nocturnal eddy flux measurements with scaled estimates of ecosystem respiration components using soil, bole and plant chambers have produced mixed results. Law et al. (2001) report good agreement between the two methods for a young, ponderosa pine stand that was 4 m tall. In contrast, Lavigne et al. (1997), studying an array of boreal forest stands (10 to 15 m tall) and Law et al (1999) studying a 34 m ponderosa pine forest report poor agreement between the two methods. In the long run, validity of nocturnal flux measurements will depend whether or not they produce ecologically defensible ratios between net carbon gain and losses (Law et al., 1999; Falge et al., 2001) and if they produce Q_{10} respiration coefficients that are consistent with those determined with other techniques.

2. Error Bounds of Annual Carbon Flux Sums

Formal error analyzes on annual sum of net ecosystem CO_2 exchange have been produced by several groups of colleagues. Goulden et al. (1996a) concluded that the sampling error, with 90% uncertainty, was +/- 30 gC m^{-2} y^{-1} at Harvard forest. Similar values have been reported by Lee et al. (1999) for a temperate broadleaved forest (+/- 40 gC m^{-2} y^{-1}), by Yang et al. (1999) for a boreal aspen stand (+/- 30 gC m^{-2} y^{-1}) and by Lafleur et al. (2001) for a short bog (+/- 68 gC m^{-2} y^{-1}); all studies were on relatively on level terrain. Larger errors have been reported over less ideal sites. At Walker Branch Watershed, where I have conducted much of my research, the topography is a hilly and the site is near power plant plumes. We have bounded the annual sum of CO_2 exchange using soil chambers, biophysical model calculations and advection estimates. This procedure produced a range of carbon fluxes of +/- 130 gC m^{-2} y^{-1} (Baldocchi et al., 2000). At another topographically-challenged site, a ponderosa pine stand near a ridge, Anthoni et al (2000) report an error term of 180 gC m^{-2} y^{-1}.

Comparisons between annual estimates of net ecosystem carbon exchange using eddy covariance measurements and biometry have produced mixed results, so far. On the favorable side, eddy covariance measurements by Schmid et al. (2000) agreed within 5% of values determined using ecological biomass estimates, while those reported by Barford et al (2001) agree within 20% of biomass studies. Granier et al (2000), on the other hand, report a discrepancy of about 100% between measured NEP with the eddy covariance method and annual biomass increment of stand (a difference of about 200 gC m^{-2} $year^{-1}$). But they did not consider respiration of woody debris.

PROSPECTS

Much progress has been made in the application and interpretation of eddy covariance measurements for ecological problems. At present, annual carbon budgets, eddy covariance measurements are most trustworthy when they come from micrometeorologically ideal sites. Eddy covariance measurements from non-ideal sites have value, too. Such data can provide information on the inter-relationship between carbon fluxes and phenology, they can quantify how stand-scale carbon fluxes respond to environmental perturbations and quantifying year-to-year variability in carbon fluxes (e.g. Baldocchi et al. 2001b). A better understanding of bias errors due to advection and drainage will be needed to reduce uncertainties in annual carbon fluxes from between 100 to 200 gC m^{-2} $year^{-1}$ to less than 50 gC m^{-2} $year^{-1}$.

A new priority for eddy covariance research is to produce annual sums of carbon exchange that represents scenes viewed by satellites. To evaluate carbon fluxes over mosaics of vegetation we will need to consider how carbon fluxes, the underlying vegetation and the flux footprint vary with wind direction (Amiro, 1998; Schmid and Lloyd, 1999; Soegaard et al. 2000; Aubinet et al. 2001).

Confidence in long-term carbon flux measurements will come by using multiple constraints to interpret the annual sums. To meet this end, more collaborative studies among scientists working with the eddy covariance method, models, chambers and soil and biomass inventories will be needed.

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