Global Change Biology (2003) **9**, 479–492

REVIEW

Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future

DENNIS D. BALDOCCHI
Ecosystem Science Division, Department of Environmental Science, Policy and Management, 151 Hilgard Hall, University of California, Berkeley, Berkeley, CA 94720-3110, USA

Abstract

The eddy covariance technique ascertains the exchange rate of CO_2 across the interface between the atmosphere and a plant canopy by measuring the covariance between fluctuations in vertical wind velocity and CO_2 mixing ratio. Two decades ago, the method was employed to study CO_2 exchange of agricultural crops under ideal conditions during short field campaigns. During the past decade the eddy covariance method has emerged as an important tool for evaluating fluxes of carbon dioxide between terrestrial ecosystems and the atmosphere over the course of a year, and more. At present, the method is being applied in a nearly continuous mode to study carbon dioxide and water vapor exchange at over a hundred and eighty field sites, worldwide. The objective of this review is to assess the eddy covariance method as it is being applied by the global change community on increasingly longer time scales and over less than ideal surfaces.

The eddy covariance method is most accurate when the atmospheric conditions (wind, temperature, humidity, CO_2) are steady, the underlying vegetation is homogeneous and it is situated on flat terrain for an extended distance upwind. When the eddy covariance method is applied over natural and complex landscapes or during atmospheric conditions that vary with time, the quantification of CO_2 exchange between the biosphere and atmosphere must include measurements of atmospheric storage, flux divergence and advection.

Averaging CO_2 flux measurements over long periods (days to year) reduces random sampling error to relatively small values. Unfortunately, data gaps are inevitable when constructing long data records. Data gaps are generally filled with values produced from statistical and empirical models to produce daily and annual sums of CO_2 exchange. Filling data gaps with empirical estimates do not introduce significant bias errors because the empirical algorithms are derived from large statistical populations. On the other hand, flux measurement errors can be biased at night when winds are light and intermittent. Nighttime bias errors tend to produce an underestimate in the measurement of ecosystem respiration.

Despite the sources of errors associated with long-term eddy flux measurements, many investigators are producing defensible estimates of annual carbon exchange. When measurements come from nearly ideal sites the error bound on the net annual exchange of CO_2 is less than $\pm 50\,g\,C\,m^{-2}\,yr^{-1}$. Additional confidence in long-term measurements is growing because investigators are producing values of net ecosystem productivity that are converging with independent values produced by measuring changes in biomass and soil carbon, as long as the biomass inventory studies are conducted over multiple years.

Keywords: Biosphere–atmosphere interactions, carbon dioxide, ecosystem physiology, micrometeorology

Received 3 October 2002; revised version received and accepted 14 November 2002

Correspondence: D. D. Baldocchi, tel. +510 642 2874, fax +510 643 5098, e-mail: Baldocchi@nature.berkeley.edu

Introduction

A prime focus of much research in the biogeosciences is on the net carbon balance of ecosystems (Running *et al*., 1999; Geider *et al*., 2001). Such work requires the assessment of carbon dioxide fluxes on hourly, daily, seasonal and yearly time scales and across the spatial scale of leaves, individual plants and arrays of plants.

Traditional tools used to assess net carbon exchange of ecosystem components include leaf cuvettes (Field *et al*., 1982; Collatz *et al*., 1991) and whole-plant (Denmead *et al*., 1993) and soil (Livingston & Hutchinson, 1995; Goulden & Crill, 1997) chambers. The *forte* of cuvette and chamber systems is their ability to measure diurnal variations of carbon fluxes and to define environmental response functions (Schulze & Koch, 1969; Collatz *et al*., 1991). The physical placement of a cuvette on a leaf or a chamber over a plant or the soil, however, may produce biases and artifacts. For example, the manual dependency of a cuvette limits the number of leaves that can be measured across the domain of a plant canopy within a reasonable time frame, e.g., an hour. Hence, it is difficult to sample, with high statistical confidence, the natural variability that exists in photosynthesis; sources of variation include the acclimation of leaf photosynthesis to sun or shade environments and vertical gradients in photosynthetic capacity (Ellsworth & Reich, 1993). Similarly, the spatial extent that is sampled by a soil chamber, or a set of chambers, is relatively small compared to the spatial variability of the CO_2 efflux from the soil (Livingston & Hutchinson, 1995; Law *et al*., 2001); the coefficient of spatial variation for soil respiration can reach 100% due to spatial gradients in soil texture, moisture, nutrients, temperature and roots.

Experimental artifacts introduced by cuvettes can be small if one is controlling the temperature, light, CO_2 and humidity, as is usually done when one is quantifying environmental response functions (Field *et al*., 1982; Collatz *et al*., 1991). On the other hand, placing a chamber over the soil to measure respiration by the rhizosphere introduces several bias errors. These include perturbations of local pressure, wind and CO_2 concentration fields and an alteration of the heat and water balance of the soil (Livingston & Hutchinson, 1995; Lund *et al*., 1999; Davidson *et al*., 2002). Enshrouding plants or trees in large transparent chambers (as is done when measuring the integrated carbon exchange of the plant-soil system) diffuses light, alters the canopy microclimate (Denmead *et al*., 1993), and suppresses soil respiration (Lund *et al*., 1999). Consequently, the shape of functions defining the response of canopy-scale, CO_2 exchange to environmental perturbations (as generated by whole-plant chambers) differ from those detected with independent micrometeorological measurements (Denmead *et al*., 1993; Ruimy *et al*., 1995).

The traditional means of addressing net ecosystem carbon exchange of an ecosystem over multiple years involves quantifying temporal changes of biomass (Clark *et al*., 2001) and soil carbon (Amundson *et al*., 1998; Lal *et al*., 2001). In principle, inventory studies of biomass change produce estimates of annual net primary productivity. Furthermore, forest biomass inventory studies rely on allometric relations to scale incremental changes in diameter at breast height to net primary production at plot and landscape scales (Barford *et al*., 2001; Clark *et al*., 2001). Bias errors are introduced when allometric relationships ignore trees in small size classes, understory 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). There are also practical limitations with measuring temporal changes in soil carbon inventories. These arise from high degrees of spatial variability (vertical and horizontal) in bulk density and soil carbon (Lal *et al*., 2001). One also needs to quantify soil carbon in slow and fast pools (Amundson *et al*., 1998).

In recent years the eddy covariance technique has emerged as an alternative way to assess ecosystem carbon exchange (Running *et al*., 1999; Canadell *et al*., 2000; Geider *et al*., 2001). Four factors account for this popularity. Most importantly, it is a scale-appropriate method because it provides ecosystem scientists with a method to assesses net CO_2 exchange of a whole ecosystem – one can consider it to be the canopy-scale equivalent to the cuvette, the primary tool for examining CO_2 exchange of leaves. Secondly, the eddy covariance technique produces a direct measure of net carbon dioxide exchange across the canopy–atmosphere interface. This task is accomplished by using micrometeorological theory to interpret measurements of the covariance between vertical wind velocity and scalar concentration fluctuations (Baldocchi *et al*., 1988; Verma, 1990; Desjardins, 1991; Lenschow, 1995). Thirdly, the area sampled with this technique, called the flux footprint, possesses longitudinal dimensions ranging between a hundred meters and several kilometers (Schmid, 1994). And finally, the technique is capable of measuring ecosystem CO_2 exchange across a spectrum of times scales, ranging from hours to years (Wofsy *et al*., 1993; Baldocchi *et al*., 2001a).

The eddy covariance method is particularly adept as studying ecosystem physiology. Specifically, it can be used to quantify how CO_2 exchange rates of whole ecosystems respond to environmental perturbations (Law *et al*., in press), and when paired systems are applied the method can be used to assess management questions such as the effects of disturbance and stand age (Anthoni *et al*., 2002; Chen *et al*., 2002) or plant functional type (Baldocchi & Vogel, 1996; Law *et al*., in press).

Like cuvettes and chambers, the eddy covariance method has limitations, too. This method is most applicable: (1) over flat terrain; (2) when the environmental conditions are steady and (3) when the underlying vegetation extends upwind for an extended distance. Violation of these assumptions can cause systematic errors in the interpretation of the eddy covariance measurements (Baldocchi *et al*., 1988; Foken & Wichura, 1995; Massman & Lee, 2002), which magnify when integrated over time to produce daily and annual sums (Moncrieff *et al*., 1996). In fact controversy has already occurred for this reason. The eddy covariance technique has attracted criticism from members of the ecological community because there have been cases when results produced from eddy covariance technique did not match estimates of net ecosystem productivity produced with established ecological methods (Keller *et al*., 1996; Piovesan & Adams, 2000). The eddy covariance research community is working feverishly to understand and remedy bias errors by carefully re-evaluating theory used to interpret flux measurements (Massman & Lee, 2002) and by conducting comparative studies with models (Wilson & Baldocchi, 2001) or biomass inventories to constrain flux estimates (Barford *et al*., 2001; Curtis *et al*., 2002).

Because so many advances have been made in the last decade and because many ecological questions require use of the eddy covariance method over extended time periods and over non-ideal landscapes there is a need to produce a contemporary review the eddy covariance technique and discuss its merits and limitations. To achieve this goal I: (1) present an overview of the historical development of the technique; (2) discuss its theoretical foundation; (3) assess how it can be applied to construct daily and yearly sums of net carbon dioxide exchange between ecosystems and the atmosphere over ideal and non-ideal surfaces and (4) discuss directions of future research.

Historical development

Use of the eddy covariance technique has accelerated in recent years. A citation search of published papers that index the term 'eddy covariance' produced over 300 records and over 550 papers referred to the analogous and older term 'eddy correlation'. The popular use of this method has not evolved spontaneously. Instead, it is built on a long history of fundamental research in the fields of fluid dynamics and micrometeorology and on technological developments associated with meteorological instruments, computers and data acquisition systems. In this section I give a brief survey of the history of research leading to contemporary application of the eddy covariance method.

Sir Osborne Reynolds is credited with establishing the theoretical framework for the eddy covariance technique (Reynolds, 1895). A lack of instrumentation, however, hindered the application of the eddy covariance method until 1926, when Scrase (1930) conducted a study on momentum transfer, the so-called Reynolds' stress, with simple analog instruments and strip-chart data logging. The next wave of advancement in the eddy covariance technique came after World War II, with the development of fast responding hot-wire anemometry and thermometry and digital computers (Swinbank, 1951). The first postwar eddy covariance studies were conducted over short vegetation at locales with extremely level terrain and windy, sunny climes and they focused on the structure of turbulence in the atmospheric boundary layer and the transfer of heat and momentum, rather than on CO_2 exchange (Swinbank, 1951; Kaimal & Wyngaard, 1990). Nevertheless, these pioneering studies are notable for laying the theoretical and experimental foundation for subsequent work on measuring CO_2 exchange, which occurred during the late 1950s and early 1960s over short and ideal agricultural crops by Japanese, British and American scientists (Inoue, 1958; Lemon, 1960; Monteith & Szeicz, 1960). These first CO_2 exchange measurements, however, relied on the flux-gradient method (an indirect technique that evaluates flux densities of CO_2 as the product of a turbulent diffusivity (K) and the vertical gradient of CO_2 concentration, dc/dz), rather than the eddy covariance technique, due to a lacking of fast responding anemometers and CO_2 sensors.

The first CO_2 flux measurements made over forests (Baumgartner, 1969; Denmead, 1969; Jarvis *et al*., 1976) and native ecosystems, such as tundra, grasslands and wetlands (Coyne & Kelly, 1975; Ripley & Redman, 1976; Houghton & Woodwell, 1980), did not occur until the late 1960s and early 1970s. Application of flux-gradient theory over tall vegetation was found to be problematic at the onset (Raupach, 1979). Over tall forests vertical gradients of CO_2 are small and difficult to resolve because turbulent mixing is efficient. Secondly, evaluation of eddy exchange coefficients (K), using Monin–Obukhov similarity theory (Lenschow, 1995), is invalid above forests because turbulent transport is enhanced by the presences of a roughness sublayer (Raupach, 1979; Simpson *et al*., 1998). At this point in time, additional studies on CO_2 exchange over forests would need to wait for technical developments that would permit use of the eddy covariance technique.

The first eddy covariance measurements of carbon dioxide exchange occurred in the early 1970s (Desjardins & Lemon, 1974; Desjardins, 1974). This set of studies was performed over corn using a propeller anemometer and a modified, closed-path infrared gas analyser, with a capacitance detector; a set of sensors with relatively slow time constants – on the order of 0.5 s. The slow time-response of the sensors used by Desjardins & Lemon (1974) prompted Garratt (1975) to critique those measurements and conclude that the CO_2 fluxes suffered from large errors (~40%) because they were unable to sample the high frequency portion of the flux cospectrum.

The next wave of technological improvements came nearly a decade later and relied on the commercial sonic anemometers and the development of rapid-responding, open path infrared gas analysers (Bingham *et al*., 1978; Jones *et al*., 1978; Brach *et al*., 1981; Ohtaki & Matsui, 1982). Open-path CO_2 sensors, using solid-state, lead-selenium (PbSe) detectors, were a key innovation because they are able to sense CO_2 fluctuations as rapidly as 10 times per second. And the open architecture of the CO_2 sensors enabled them to sample parcels of air with minimal aerodynamic disturbance. The first application of open-path CO_2 sensors was to measure eddy fluxes over crops. Among the first studies to apply this technology were those conducted by Anderson *et al*. (1984) over soybeans, Anderson & Verma (1986) over sorghum, Ohtaki (1984) over rice and Desjardins (1985) over corn. These initial efforts were soon followed by sets of experiments of CO_2 exchange over native vegetation, such as temperate deciduous forests (Wesely *et al*., 1983; Verma *et al*., 1986), a prairie grassland (Verma *et al*., 1989; Kim & Verma, 1990), a tropical forest (Fan *et al*., 1990) and Mediterranean macchia (Valentini *et al*., 1991).

Prior to 1990, limitations in sensor performance and data acquisition systems restricted the duration of the eddy covariance studies to short campaigns during the growing season (e.g. Anderson *et al*., 1984; Verma *et al*., 1986). Subsequent production of commercial infrared spectrometers, that were stable and had short time constants, enabled scientists to conduct eddy covariance measurements 24 h a day, seven days a week, 52 weeks a year. Wofsy *et al*. (1993) are credited with conducting the first yearlong study of CO_2 exchange with the eddy covariance technique; these measurements were made over a deciduous forest, starting in 1990, and continue to this day. By 1993, a handful of additional eddy covariance studies, measuring CO_2 and water vapor exchange, began operating over forests in North America (Black *et al*., 1996; Goulden *et al*., 1996a, b; Greco & Baldocchi, 1996), Japan (Yamamoto *et al*., 1999), and Europe (Valentini *et al*., 1996). And by 1997, regional networks of flux measurement sites were operating in Europe (CarboEuroflux, Aubinet *et al*., 2000; Valentini *et al*., 2000) and North America (AmeriFlux, Running *et al*., 1999; Law *et al*., submitted). Currently, the eddy covariance method is being used at over 180 sites worldwide, as part of the FLUXNET program (Baldocchi *et al*., 2001a) and involves new regional networks in North America (Fluxnet, Canada), Brazil, Asia (AsiaFlux), Australia (OzFlux) and Africa.

Principles and concepts

The atmosphere contains turbulent motions of upward and downward moving air that transport trace gases such as CO_2. The eddy covariance technique samples these turbulent motions to determine the net difference of material moving across the canopy-atmosphere interface. In practice, this task is accomplished by statistical analysis of the instantaneous vertical mass flux density ($F = w\rho_c$, $\mu mol\, m^{-2}\, s^{-1}$), using Reynolds' rules of averaging (Reynolds, 1895), which are described below. The product of this operation is a relationship that expresses the mean flux density of CO_2 averaged over some time span (such as an hour) as the covariance between fluctuations in vertical velocity (w) and the CO_2 mixing ratio ($c = \rho_c/\rho_a$ where ρ_a is air density and ρ_c is CO_2 density):

$$F = \bar{\rho}_a \cdot \overline{w'c'}. \qquad (1)$$

In Eqn 1, 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.

Interpreting eddy covariance measurements

The equation defining the conservation of mass provides theoretical guidance for implementing the eddy covariance technique (Baldocchi *et al*., 1988; Paw *et al*., 2000; Massman & Lee, 2002). Conceptually, the problem being analysed is analogous to the case of maintaining a certain water level in a bathtub by governing the flow of water in and out of the tub; when the water level is steady, we know that the rate of water leaving the tub equals the rate entering so we only need to measure one of the flows. With the case of assessing turbulent transfer of CO_2 in the atmosphere, we use the conservation equation to deduce the exchange of carbon in and out of the plant-soil system on the basis of eddy covariance measurements made in the surface boundary layer several meters above a plant canopy. How this process is accomplished is discussed next.

For the case of CO_2, the conservation of mass states that the sum of the local time rate of change of the CO_2 mixing ratio (term I), c, and advection (term II) is balanced by the sum of the flux divergence of CO_2 in the vertical (z), lateral (y) and longitudinal (x) directions (term III) and the biological source sink-strength (S_B) (term IV):

$$\frac{d\bar{c}}{dt} = \underset{\text{I}}{\frac{\partial \bar{c}}{\partial t}} + \underset{\text{II}}{\bar{u}\frac{\partial \bar{c}}{\partial x} + \bar{v}\frac{\partial \bar{c}}{\partial y} + \bar{w}\frac{\partial \bar{c}}{\partial z}} = -\left(\underset{\text{III}}{\frac{\partial F_z}{\partial z} + \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y}} + \underset{\text{IV}}{S_B(x, y, z)}\right). \tag{2}$$

In Eqn 2, $\overline{u}$, $\overline{v}$ and $\overline{w}$ are the vertical velocities in the x, y and z directions, respectively. Figure 1 is a conceptual diagram of the processes described by Eqn 2. Under ideal conditions, the scalar concentrations and wind velocities in the atmosphere are steady with time (term I equals zero) and the underlying surface is horizontally homogeneous and on flat terrain (there is no advection, term II) so the horizontal flux divergences, $\partial F_x/\partial x$ and $\partial F_y/\partial y$, in term III equal zero. 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, (term IV):

$$\frac{\partial F_z}{\partial z} = -S_B(z). \tag{3}$$

By integrating Eqn 3 with respect to height, one derives an equality between the mean vertical flux density measured at some height above the canopy, $F_z(h)$, and the net flux density of material in and out of the underlying soil, $F_z(0)$, and vegetation:

$$F_z(h) = F_z(0) - \int_0^h S_B(z)\,dz. \tag{4}$$

In practice it is the term $F_z(h)$ that is evaluated with the eddy covariance technique.

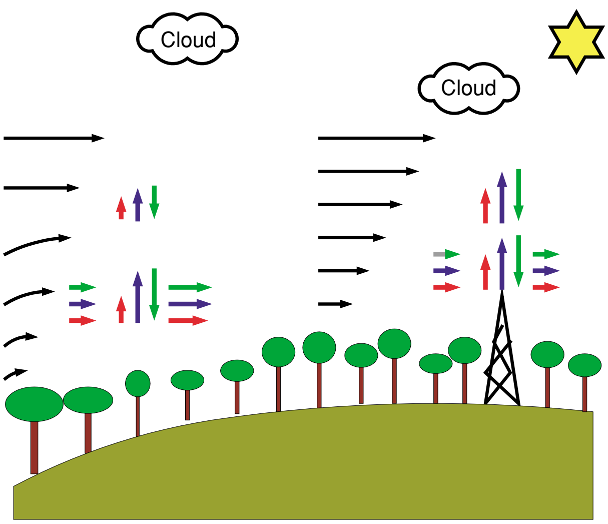

Fig. 1 Conceptual diagram of an eddy flux tower on terrain that experiences a transition from less ideal sloping to ideal flat region. Flux densities of water (blue arrows), heat (red) and CO_2 (green) are generally orthogonal to the wind streamlines (black arrows). On the upwind side of the hill wind accelerates as the hill compresses the wind velocity streamlines. Advection occurs and produces divergence of the fluxes of heat, water vapor and CO_2, causing the vertical exchange to vary with height (denoted by changes in arrow length). Over the flat part of the landscape, a constant flux layer and logarithmic wind profile are re-established. Fluxes of mass and energy are constant with height as denoted by arrows of similar length at two different heights above the canopy.

Evaluating the flux covariance

Assessment of the flux covariance requires that we sample the cospectrum of turbulent motions that exist in the atmosphere (Garratt, 1975):

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

where S_{wc} is cospectral density between w and c (the amount of flux that is associated with a given frequency) and ω is angular frequency (ω is related to natural frequency, n, by a factor of 2π). To sample all significant scales of motion that contribute to turbulent transfer of CO_2, one needs to sample the atmosphere frequently and for a sufficient duration. Sampling rates on the order of 10 times per second generally enable one to sample the high frequency portion of the flux cospectrum (Anderson *et al.*, 1984, 1986; Goulden *et al.*, 1996a). To capture low frequency contribution to the flux covariance, the sampling duration must be long enough to sample motions associated with the convective boundary layer, but the sampling duration should not be too long to be affected by diurnal changes in CO_2 (Lenschow, 1995). It is common practice to sample and average atmospheric turbulence over 30–60 min periods during daylight hours (Anderson *et al.*, 1984, 1986; Aubinet *et al.*, 2000; Massman & Lee, 2002). Longer averaging times may be needed at night when the thermal stratification of the atmosphere is stable and turbulence is intermittent (Lee *et al.*, 1996; Massman & Lee, 2002).

In practice, numerous instrument, sampling and turbulence issues influence how well the cospectrum integral (Eqn 5) is measured. The w-c covariance, that is measured by a set of instruments, is a function of its true cospectral density, $S_{wc}(\omega)$, and a filter function, $H(\omega)$ (Moore, 1986; Leuning & Judd, 1996; Aubinet *et al.*, 2000; Massman, 2000; Berger *et al.*, 2001):

$$\overline{w'c'}_{\text{measured}} = \int_0^\infty H(\omega)\,S_{wc}(\omega)\,d\omega. \tag{6}$$

High pass filtering of the turbulence signals (w or c) (the attenuation of high frequency contributions to the flux) can be caused by a sensor's slow response time, a long sensor path, or a slow sampling rate. High pass filtering will also occur if wind velocity and trace gas sensors are placed too far abreast from one another or too close to the ground (Moore, 1986; Aubinet *et al.*, 2000; Massman, 2000). A third means of filtering high frequency scalar fluctuations involves sampling air through a tube (Suyker & Verma, 1993; Leuning & Judd, 1996; Massman, 2000).

Low pass filtering (the attenuation of low frequency contributions to the flux) is imposed by the averaging method used to compute the flux covariance and the sampling duration (Moore, 1986; Aubinet *et al.*, 2000; Massman, 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.

How one computes means and fluctuations from the mean is an issue that affects the computation of Eqn 1. It is common practice to compute fluctuations by removing the arithmetic mean or one determined with a digital recursive filter (McMillen, 1988) from instantaneous measurements. Some investigators detrend signals (Foken & Wichura, 1995) before computing fluctuations from the mean. This author is not an advocate of detrending turbulent signals because he considers it to be redundant to detrend turbulence signals and to compensate for storage of CO_2 in the canopy air space (see below). Relying on fundamental grounds, Reynolds' averaging rules do not consider detrending when defining flux covariances (Reynolds, 1895; Paw *et al.*, 2000). The reader should recognize that detrending is a historical artifact that needs careful evaluation before applying. When the eddy covariance method was being developed it was necessary to detrend electrical signals because instruments suffered from electronic drift (Shuttleworth, 1988). Sensors are now stable, so this need has been eliminated for the most part.

At present, 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 (Eqn 6) 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 analysers) and the spectral corrections range 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 to correct eddy covariance measurements. 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 artificially '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 across the fixed distance of the anemometer path and it fails when sensible heat flux density is near zero.

The analytical method used to measure CO_2 also has an impact on the computation of the flux covariance. In practice, CO_2 is measured with a non-dispersive, infrared spectrometer. This sensor does not measure mixing ratio, c. Instead it samples molar density, ρ_c (moles per unit volume). In principle, changes in molar density can occur by adding molecules to or removing them from a controlled volume or by changing the size of the controlled 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 re-expressed as:

$$F = \overline{w\rho_c} = \underbrace{\overline{w'\rho_c'}}_{\text{I}} + \underbrace{\overline{w}\ \overline{\rho_c}}_{\text{II}}. \tag{7}$$

The new term, on the right hand side of Eqn 7 (term II), is the product of the mean vertical velocity and CO_2 density. The mean vertical velocity is non-zero and arises from air density fluctuations (Webb *et al.*, 1980; Kramm *et al.*, 1995). In practice, the magnitude of $\overline{w}$ is too small ($<1\,\mathrm{mm\,s^{-1}}$) to be detected by anemometry, so it is usually computed on the basis of temperature (T) and humidity density (ρ_v) fluctuations using the Webb–Pearman–Leuning (1980) algorithm:

$$F_c = \overline{w'\rho_c'} + \frac{m_a}{m_v}\frac{\bar{\rho}_c}{\bar{\rho}_a}\overline{w'\rho_v'} + \left(1 + \frac{\bar{\rho}_v m_a}{\bar{\rho}_a m_v}\right)\frac{\bar{\rho}_c}{\overline{\overline{T}}}\overline{w'T'}, \tag{8}$$

(other variables in Eqn 8 are the molecular weights of air, m_a, and water vapor, m_v). The derivation of Eqn 8 ignores effects of pressure fluctuations, which may be significant under high winds (Massman & Lee, 2002), and covariances between temperature and pressure (Fuehrer & Friehe, 2002). It also ignores advection (Paw *et al.*, 2000), which will be important when it is applied over sloping terrain. Despite the assumptions used in deriving Eqn 8, there is experimental evidence supporting its validity. Leuning *et al.* (1982) measured CO_2 exchange over a flat, bare, dry field and found that photosynthesis was 'detected' when they did not apply the density corrections. In contrast, application of Eqn 8 produced CO_2 flux densities near zero, a value supported with independent chamber measurements.

Significant terms in Eqn 8 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 Eqn 8 (Leuning & Moncrieff, 1990; Leuning & Judd, 1996).

Evaluating the biosphere–atmosphere exchange rates

There are times during the day when the flux density of CO_2 crossing a horizontal plane above the canopy does not equal the net flux density of carbon moving into and out of the plant/soil system. At night, for example, the thermal stratification of the atmosphere is stable CO_2. Under this condition, CO_2 exiting leaves and the soil may not reach a set of instruments at a reference height, h, above the canopy, causing the eddy covariance method to underestimate ecosystem respiration. Another case occurs at sunrise. Then, there is a break-up of the stable nocturnal boundary layer as convective turbulence resumes. This phenomenon vents the canopy of CO_2 stored within the canopy air space over the course of the night. This short-term venting will cause the eddy covariance technique to overestimate the time-local flux density (Grace *et al*., 1996; Moncrieff *et al*., 1996; Yang *et al*., 1999). Under the non-steady conditions identified above, the storage of CO_2 in the underlying airspace, $\bar{\rho}_a \int_0^h (\partial\bar{c}/\partial t)\,\mathrm{d}t$, is non-zero. Storage must be assessed and 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; Goulden *et al*., 1996a; Grace *et al*., 1996; Moncrieff *et al*., 1996; Yang *et al*., 1999; Aubinet *et al*., 2000; Baldocchi *et al*., 2000). 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 so errors in its evaluation are not critical (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; Fig. 1). Classical application of the eddy covariance method involves mathematical rotation of the wind coordinate system to force $\overline{w}$ to zero. This rotation enables one to compute flux covariances that are orthogonal to the mean streamlines flowing over the landscape (Wesely, 1970; Baldocchi *et al*., 1988; Foken & Wichura, 1995). If mesoscale circulations persist, there are wind biases introduced by the eddies shed from the instrument tower or zero-offsets associated with the anemometer, 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 which will depend on wind direction, instrument biases and the slope of the upwind terrain (Paw *et al*., 2000).

Wind flow over non-uniform terrain can also generate advective fluxes (Fig. 1). From a practical standpoint, it is difficult to assess horizontal advection terms over tall forests. Motivated by this problem, Lee (1998) developed simplified version of the conservation of mass equation (Eqn 2) that represents net ecosystem-atmosphere CO_2 exchange (N_e) as a function of a one-dimensional, vertical advection term. General application of the model of Lee (1998) is still subject to debate. Theoretically, Finnigan (1999) argues that topography and spatial changes in surface roughness and CO_2 sources and sinks strengths, produce spatial variations in the scalar concentration and wind velocity fields that may not be accommodated by this one-dimensional advection equation. From a practical standpoint, the introduction of an additional term to the conservation budget introduces new sources of measurement error (Baldocchi *et al*., 2000). Alternative approaches to assessing CO_2 advection include measuring flux divergence profiles over and under plant canopies (Lee *et al*., 1999; Baldocchi *et al*., 2000; Yi *et al*., 2000), measuring horizontal transects across landscapes (Baldocchi & Rao, 1995) or by assessing regional box budgets (Sun *et al*., 1998; Eugster & Siegrist, 2000). As a word of caution, drainage flows may transport CO_2 from the vicinity of the eddy covariance measurement tower and vent it elsewhere (Sun *et al*., 1998), thereby leading to a systematic bias error and an underestimate of ecosystem respiration.

Evaluating daily and annual carbon fluxes

The influence of random and systematic bias errors

Because of 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 technique. In this section, we assess potential errors 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 a set of random and systematic bias errors that are associated with measurements, sampling and theoretical issues relating to the application of the eddy covariance technique to non-ideal conditions. With proper system design and implementation, random measurement errors of are generally small. For example, calibration errors of infrared gas analysers are on the order of 2–3%. and errors associated with time lags between velocity and scalar sensors are less than 2% (Berger *et al*., 2001). In general, the covariance measurement error is less than 7% during the day and less than 12%

at night (Moore, 1986; Soegaard *et al*., 2000; Berger *et al*., 2001).

The natural variability of turbulence is on the order of 10–20% (Wesely & Hart, 1985) and sets a limit on the run-to-run variability of flux measurements under similar conditions. Averaging numerous flux density measurements to construct longer-term averages (e.g. daily, weekly, monthly) reduces random sampling errors to a value within $\pm 5\%$, thereby increasing the precision of CO_2 flux measurements (Goulden *et al*., 1996a; Moncrieff *et al*., 1996).

There is a practical limit with the concept of constructing long-term averages. Gaps in long-term data records will inevitably occur as sensors break down, they are being calibrated or when measurements over range the data acquisition system. Furthermore, data are generally rejected when the wind is blowing through a tower, when wind is coming from an undesirable wind sector, when sensors are wet, or when the measurements fail to meet preset acceptance criteria (Foken & 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); data gaps tend be lower for systems that employ closed path CO_2 sensors because they do not need to reject data because the sensor is wet.

Several methods are being employed to fill data gaps. One approach fills missing flux data on the basis of empirically derived algorithms that are driven by easily measured 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 because seasonal changes in leaf area, soil moisture, and photosynthetic capacity will alter any empirical relation. Another approach involves interpolation between adjacent periods. This method may work well for small data gaps but it 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 several gap filling methods and found that they produced similar results and did not introduce any particular methodological bias. Falge *et al*. (2001) also found that rejecting up to 40% of data produces repeatable annual sums, as there is an adequate sampling of the data population.

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*., 2002); practitioners often find that the sum of latent and sensible heat exchange, measured with the eddy covariance technique do not match the independent measurement of available energy. The other systematic bias error is associated with a perceived underestimate of nocturnal ecosystem efflux during low wind conditions (Black *et al*., 1996; Goulden *et al*., 1996a; Grace *et al*., 1996; Moncrieff *et al*., 1996; Malhi *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*., 2000; Twine *et al*., 2000; Wilson *et al*., 2002). These results raise the possibility that CO_2 fluxes are underestimated, too. For investigators using open-path CO_2 sensors, errors in energy balance closure will translate into an additional source of errors in assessment of the Webb *et al*. (1980) density corrections (Eqn 8), which 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*., 2000; Wilson *et al*., 2002).

Some researchers 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 measurement of 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). In addition, independent tests of evaporative fluxes, based on lysimeters and watershed water balances, agree well with eddy covariance measurements (Barr *et al*., 2000; Wilson *et al*., 2001), which lend 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). At present, it is common practice to apply 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*., 1999). Others correct nocturnal CO_2 flux density measurements with values measured 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; Malhi *et al*., 1998; Hollinger *et al*., 1999; 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_c and friction velocity, u*, tend to be poor; typically, the coefficient of determination (r^2) is less than 0.2 (Aubinet *et al*., 2000). Longer averaging periods reduce the sampling error of individual data points (Suyker & 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 (averaged over long periods) 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; Baldocchi *et al*., 2001a, b; Suyker & Verma, 2001; Falge *et al*., 2002). The zero intercept of the light response curve is a stable estimate of ecosystem respiration because it is determined using daytime flux measurements when mixing is better and the flux measurements are more accurate. And, respiratory fluxes averaged over the whole night tend to capture more eddies that transfer CO_2, as opposed to individually hourly runs that experience much variability.

Comparing nocturnal eddy flux measurements with scaled estimates of ecosystem respiration components using soil, bole and plant chambers, on the other hand, have produced mixed results. Lavigne *et al*. (1997), studying an array of boreal forest stands (10–15 m tall), and Law *et al*. (1999), studying a 34-m ponderosa pine forest, report poor agreement between nocturnal eddy covariance measurements and scaled respiration measurements. The assessment of these studies, however, needs qualification. Lavigne *et al*. (1997), for example, relied on a relatively small sample size of soil respiration measurements and that study was conducted during the early years of long-term eddy covariance measurements (ca. 1994). The independent of assessment of nighttime term eddy fluxes has improved since that time. A more recent comparative study produced good agreement between the nocturnal eddy covariance and chamber-based measurements of nocturnal respiration (Law *et al*., 2001). Ultimately, the validity of nocturnal flux measurements will depend on 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.

Error bounds on annual carbon flux sums

Several groups have produced formal error analyses on annual sum of net ecosystem CO_2 exchange. Goulden *et al*. (1996a) concluded that the sampling error, with 90% certainty, was $\pm 30\,g\,C\,m^{-2}\,yr^{-1}$ at Harvard forest, a site with an net annual uptake of CO_2 that is on the order of $200\,g\,C\,m^{-2}\,yr^{-1}$. Similar error sums have been computed by Lee *et al*. (1999) for a temperate broadleaved forest ($\pm 40\,g\,C\,m^{-2}\,yr^{-1}$), by Yang *et al*. (1999) for a boreal aspen stand ($\pm$ $30\,g\,C\,m^{-2}\,yr^{-1}$) and by Lafleur *et al*. (2001) for a short bog ($\pm 68\,g\,C\,m^{-2}\,yr^{-1}$); 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 hilly and the site is near two power plants. 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 $\pm 130\,g\,C\,m^{-2}\,yr^{-1}$ for a site that takes up about $600\,g\,C\,m^{-2}\,yr^{-1}$ (Baldocchi *et al*., 2000; Wilson & Baldocchi, 2001), and a larger error bound has been reported for a ponderosa pine stand in even rougher terrain (Anthoni *et al*., 1999). This site was positioned along a pronounced ridge and has a bounded error term of its annual net carbon exchange of $\pm 180\,g\,C\,m^{-2}\,yr^{-1}$ on its annual net carbon uptake of about $300\,g\,C\,m^{-2}\,yr^{-1}$.

Comparisons between annual estimates of net ecosystem carbon exchange using eddy covariance measurements and traditional ecological methods are another way to assess bias errors. At this moment, only a few comparisons have been produced and they have generated mixed results (Curtis *et al*., 2002). On the favorable side, eddy covariance measurements by Schmid *et al*. (2000) agree within 5% of values determined using traditional ecological methods. and reports by Barford *et al*. (2001), Ehman *et al*. (2002) and Curtis *et al*. (2002) indicate that annual sums of CO_2 produced by the eddy covariance method agree within 30% of biomass studies. A less successful study was reported by Granier *et al*. (2000), who found a discrepancy of about 100% between net ecosystem productivity (NEP) measured with the eddy covariance method and annual biomass increment of stand (a difference of about $200\,g\,C\,m^{-2}\,yr^{-1}$); their carbon balance however, did not consider respiration of woody debris. The emerging trend being generated by contemporary field studies is a convergence between eddy covariance and biomass inventories when data records are evaluated over multiple years (Barford *et al*., 2001; Chen *et al*., 2002; Ehman *et al*., 2002).

Future prospects

Much progress has been made in applying and interpreting eddy covariance measurements for ecological problems over the past two decades. At present, annual carbon budgets produced by eddy covariance measurements are most trustworthy when they come from micrometeorologically ideal sites, extensive canopies on flat terrain.

Eddy covariance measurements made over non-ideal sites have value, too, even though annual estimates of net CO_2 exchange may be error prone. Flux measurements from complex sites can provide information on the relationship between carbon fluxes and phenology, they can quantify how stand-scale carbon fluxes respond to environmental perturbations and they can quantify the factors causing year-to-year variability in carbon fluxes (e.g. Baldocchi *et al*., 2001b). At non-ideal sites, a better understanding of bias errors due to advection and drainage will be needed to reduce uncertainties in annual carbon fluxes from between 100 and 200 $g\,C\,m^{-2}\,yr^{-1}$ to less than 50 $g\,C\,m^{-2}\,yr^{-1}$. Future studies of CO_2 exchange on complex terrain should employ a combination of approaches (mesoscale modeling, remote sensing, ecophysiological measurements) to constrain fluxes. One example would involve using a network of sapflow measurements of trees on sloping terrain and scale these measurements to photosynthesis using estimates of water use efficiency that is derived from cuvettes or isotope content of leaves. Another example would involve explicit measurements of advection terms, storage and drainage terms.

Another priority for eddy covariance research will involve producing annual sums of carbon exchanges that represent scenes viewed by satellites (Running *et al*., 1999). To evaluate carbon fluxes over mosaics of vegetation we will need to quantify how carbon dioxide fluxes, the underlying vegetation and the flux footprint vary with wind direction (Amiro, 1998; Schmid & Lloyd, 1999; Soegaard *et al*., 2000; Aubinet *et al*., 2001). To accomplish this task, we will need to partition net carbon fluxes into the components, GPP, NPP and ecosystem respiration, so field data generated at eddy covariance study sites can be used to validate products developed by biogeochemical models and remote sensing indices (Running *et al*., 1999). To perform landscape integration of carbon fluxes we also need to understand how they vary with stand age, a problem that will require more chronosequence studies. Ultimately, 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.

Acknowledgements

The author is supported by grants from NASA EOS Validation Program (FLUXNET), US Department of Energy's Terrestrial Carbon Program and the California Agricultural Experiment Station. This review is the fruition of my collaboration and interaction with numerous colleagues over the years (Shashi Verma, Dean Anderson, Bruce Hicks, Tilden Meyers, Riccardo Valentini, Bev Law, Eva Falge and Kell Wilson). In particular I thank, Drs Shashi Verma, Kell Wilson and Kai Morgenstern for their expert internal reviews of this manuscript.

References

Amiro BD (1998) Footprint climatologies for evapotranspiration in a boreal catchment. *Agriculture For Meteorology*, **90**, 195–201.

Amundson R, Stern L, Raisden T *et al.* (1998) The isotopic composition of soil and soil-respired CO_2. *Geodermatology*, **82**, 83–114.

Anderson DE, Verma SB (1986) Carbon dioxide, water vapor and sensible heat exchanges of a grain sorghum canopy. *Boundary Layer Meteorology*, **34**, 317–331.

Anderson DE, Verma SB, Clement RE *et al.* (1986) Turbulence spectra of CO_2, water vapor, temperature and velocity over a deciduous forest. *Agricultural and Forest Meteorology*, **38**, 81–99.

Anderson DE, Verma SB, Rosenberg NJ (1984) Eddy correlation measurements of CO_2, latent heat and sensible heat fluxes over a crop surface. *Boundary Layer Meteorology*, **29**, 167–183.

Anthoni PM, Law BE, Unsworth MH (1999) Carbon and water vapor exchange of an open-canopied ponderosa pine ecosystem. *Agricultural and Forest Meteorology*, **95**, 115–168.

Anthoni PM, Unsworth MH, Law BE *et al.* (2002) Seasonal differences in carbon and water vapor exchange in young and old- growth ponderosa pine ecosystems. *Agricultural and Forest Meteorology*, **111** (3), 203–222.

Aubinet M, Chermanne B, Vandenhaute M *et al.* (2001) Long-term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. *Agricultural and Forest Meteorology*, **108**, 293–315.

Aubinet M, Grelle A, Ibrom A *et al.* (2000) Estimates of the annual net carbon and water exchange of European forests: the EUROFLUX methodology. *Advances in Ecological Research*, **30**, 113–175.

Baldocchi DD, Falge E, Gu L *et al.* (2001a) FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bulletin of the American Meteorological Society*, **82**, 2415–2434.

Baldocchi DD, Falge E, Wilson KW (2001b) A spectral analysis of biosphere-atmosphere trace gas flux densities and meteorological variables across hour to multi-year time scales. *Agricultural and Forest Meteorology*, **107**, 1–27.

Baldocchi DD, Finnigan JJ, Wilson KW *et al.* (2000) On measuring net ecosystem carbon exchange in complex terrain over tall vegetation. *Boundary Layer Meteorology*, **96**, 257–291.

Baldocchi DD, Hicks BB, Meyers TP (1988) Measuring biosphere–atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology*, **69**, 1331–1340.

Baldocchi DD, Rao KS (1995) Intra-field variability of scalar flux densities across a transition between a desert and an irrigated potato field. *Boundary Layer Meteorology*, **76**, 109–136.

Baldocchi DD, Vogel C (1996) A comparative study of water vapor, energy and CO_2 flux densities above and below a temperate broadleaf and a boreal pine forest. *Tree Physiology*, **16**, 5–16.

Barford CC, Wofsy SC, Goulden ML *et al.* (2001) Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. *Science*, **294**, 1688–1691.

Barr AG, van der Kamp G, Schmidt R *et al.* (2000) Monitoring the moisture balance of a boreal aspen forest using a deep groundwater piezometer. *Agriculture For Meteorology*, **102**, 13–24.

Baumgartner A (1969) Meteorological approach to the exchange of CO_2 between atmosphere and vegetation, particularly forests stands. *Photosynthetica*, **3**, 127–149.

Berger BW, Davis KJ, Yi C *et al.* (2001) Long-term carbon dioxide fluxes from a very tall tower in a northern forest: flux measurement methodology. *Journal of Atmosphere and Ocean Technology*, **18**, 529–542.

Bingham GE, Gillespie CH, McQuaid JH (1978) Development of a miniature, rapid response CO_2 sensor. *Lawrence Livermore National Laboratory Report UCRL-52440.*

Black TA, den Hartog G, Neumann H *et al.* (1996) Annual cycles of CO_2 and water vapor fluxes above and within a Boreal aspen stand. *Global Change Biology*, **2**, 219–230.

Brach EJ, Desjardins RL, St Amour GT (1981) Open path CO_2 analyser. *Journal of Physics and Earth Science Instrumentation*, **14**, 1415–1419.

Canadell J, Mooney H, Baldocchi D *et al.* (2000) Carbon metabolism of the terrestrial biosphere. *Ecosystems*, **3**, 115–130.

Carey EV, Sala A, Keane R *et al.* (2001) Are old forests underestimated as global carbon sinks? *Global Change Biology*, **7**, 339–344.

Chen J, Falk M, Euskirchen E *et al.* (2002) Biophysical controls of carbon flows in three successional Douglas-fir stands based on eddy-covariance measurements. *Tree Physiology*, **22**, 169–177.

Clark DA, Brown S, Kicklighter DW *et al.* (2001) Measuring net primary production in forests: concepts and field measurements. *Ecological Applications*, **11**, 356–370.

Collatz GJ, Ball JT, Grivet C *et al.* (1991) Regulation of stomatal conductance and transpiration: a physiological model of canopy processes. *Agricultural and Forest Meteorology*, **54**, 107–136.

Coyne PI, Kelly JJ (1975) CO_2 exchange over the Alaskan arctic tundra: meteorological assessment by an aerodynamic method. *Journal of Applied Ecology*, **12**, 587–611.

Curtis PS, Hanson PJ, Bolstad P *et al.* (2002) Biometric and eddy covariance based estimates of annual carbon storage in five eastern North American deciduous forests. *Agricultural and Forest Meteorology*, **113**, 3–19.

Davidson EA, Savage K, Verchot LV *et al.* (2002) Minimizing artifacts and biases in chamber-based measurements of soil respiration. *Agricultural and Forest Meteorology*, **113**, 21–37.

Denmead OT (1969) Comparative micrometeorology of a wheat field and a forest of *Pinus radiata*. *Agricultural Meteorology*, **6**, 357–371.

Denmead OT, Dunin FX, Wong SC *et al.* (1993) Measuring water use efficiency of Eucalpyt trees with chambers and micrometeorological techniques. *Journal of Hydrology*, **150**, 649–664.

Desjardins RL (1974) A technique to measure CO_2 exchange under field conditions. *International Journal of Biometeorology*, **18**, 76–83.

Desjardins RL (1985) Carbon dioxide budget of maize. *Agricultural and Forest Meteorology*, **36**, 29–41.

Desjardins RL (1991) Review of techniques to measure CO_2 flux densities from surface and airborne sensors. In: *Advances in Bioclimatology*, pp. 2–23. Springer, Berlin.

Desjardins RL, Lemon ER (1974) Limitations of an eddy covariance technique for the determination of the carbon dioxide and sensible heat fluxes. *Boundary Layer Meteorology*, **5**, 475–488.

Ehman JL, Schmid HP, Grimmond CSB *et al.* (2002) An initial intercomparison of micrometeorological and ecological inventory estimates of carbon exchange in a mid-latitude deciduous forest. *Global Change Biology*, **8**, 575–589.

Ellsworth DS, Reich PB (1993) Canopy structure and vertical patterns of photosynthesis and related leaf traits in a deciduous forest. *Oecologia*, **96**, 169–178.

Eugster W, Siegrist F (2000) The influence of nocturnal CO_2 advection on CO_2 flux measurements. *Basic and Applied Ecology*, **1**, 177–188.

Falge E, Baldocchi DD, Olson R *et al.* (2001) Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology*, **107**, 43–69.

Falge E, Baldocchi D, Tenhunen J *et al.* (2002) Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. *Agricultural and Forest Meteorology*, **113**, 53–74.

Fan SM, Wofsy SC, Bakwin PS *et al.* (1990) Atmosphere–biosphere exchange of CO_2 and O_3 in the central Amazon forest. *Journal of Geophysical Research*, **95**, 16851–16864.

Field CB, Berry JA, Mooney HA (1982) A portable system for measuring carbon dioxide and water vapor exchanges of leaves. *Plant, Cell and Environment*, **5**, 179–186.

Finnigan JJ (1999) A comment on the paper by Lee (1998): On micrometeorological observations of surface-air exchange over tall vegetation. *Agricultural and Forest Meteorology*, **97**, 55–64.

Foken Th, Wichura B (1995) Tools for quality assessment of surface-based flux measurements. *Agricultural and Forest Meteorology*, **78**, 83–105.

Fuehrer PL, Friehe C (2002) Flux corrections revisited. *Boundary Layer Meteorology*, **102**, 415–457.

Garratt JR (1975) Limitations of the eddy correlation technique for determination of turbulent fluxes near the surface. *Boundary Layer Meteorology*, **8**, 255–259.

Geider RJ, Delucia EH, Falkowski PG *et al.* (2001) Primary productivity of planet earth: biological determinants and physical constraints in terrestrial and aquatic habitats. *Global Change Biology*, **7**, 849–882.

Goulden ML, Crill PM (1997) Automated measurements of CO_2 exchange at the moss surface of a black spruce forest. *Tree Physiology*, **17**, 537–542.

Goulden ML, Munger JW, Fan SM *et al.* (1996a) Measurement of carbon storage by long-term eddy correlation: methods and a critical assessment of accuracy. *Global Change Biology*, **2**, 169–182.

Goulden ML, Munger JW, Fan SM *et al.* (1996b) Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. *Science*, **271**, 1576–1578.

Grace J, Malhi Y, Lloyd J *et al.* (1996) The use of eddy covariance to infer the net carbon dioxide uptake of Brazilian rain forest. *Global Change Biology*, **2**, 209–217.

Granier A, Ceschia E, Damesin C *et al.* (2000) The carbon balance of a young beech forest. *Functional Ecology*, **14**, 312–325.

Greco S, Baldocchi DD (1996) Seasonal variations of CO_2 and water vapor exchange rates over a temperate deciduous forest. *Global Change Biology*, **2**, 183–198.

Hollinger DY, Goltz SM, Davidson EA *et al.* (1999) Seasonal patterns and environmental control of carbon dioxide and water vapor exchange in an ecotonal boreal forest. *Global Change Biology*, **5**, 891–902.

Houghton RA, Woodwell G (1980) The flax pond ecosystem study: exchanges of CO_2 between a salt marsh and the atmosphere. *Ecology*, **61**, 1434–1445.

Inoue I (1958) An aerodynamic measurement of photosynthesis over a paddy field. In: *Proceedings of the 7th Japan National Congress of Applied Mechanics*, pp. 211–214.

Jarvis PG, James GB, Landsberg JJ (1976) Coniferous forest. In: *Vegetation and the Atmosphere*, Vol. 2 (ed. Monteith JJ), pp. 171–240. Academic Press, London.

Jarvis PG, Massheder J, Hale S *et al.* (1997) Seasonal variation of carbon dioxide, water vapor and energy exchanges of a boreal black spruce forest. *Journal of Geophysical Research*, **102**, 28953–28967.

Jones EP, Zwick H, Ward TV (1978) A fast response atmospheric CO_2 sensor for eddy correlation flux measurement. *Atmospheric Environment*, **12**, 845–851.

Kaimal JC, Wyngaard JC (1990) The Kansas and Minnesota experiments. *Boundary Layer Meteorology*, **50**, 31–47.

Keller M, Clark DA, Clark DB *et al.* (1996) If a tree falls in the forest. *Science*, **273**, 201.

Kim J, Verma SB (1990) Carbon dioxide exchange in a temperate grassland ecosystem. *Boundary Layer Meteorology*, **52**, 135–149.

Kramm G, Dlugi R, Lenschow DH (1995) A re-evaluation of the Webb correction using density-weighted averages. *Journal of Hydrology*, **166**, 283–292.

Lafleur PM, Roulet NT, Admiral SW (2001) Annual cycle of CO_2 exchange at a bog peatland. *Journal of Geophysical Research*, **106**, 3071–3081.

Lal R, Kimble JM, Follett RF *et al.* (2001) *Assessment Methods for Soil Carbon. Advances in Soil Science*, pp. 676. Lewis Press, Boca Raton, FL.

Lavigne MB, Ryan MG, Anderson DE *et al.* (1997) Comparing nocturnal eddy covariance measurements to estimates of ecosystem respiration made by scaling chamber measurements. *Journal of Geophysical Research*, **102**, 28977–28986.

Law BE, Bakwin PS, Baldocchi DD *et al.* (in press) The AmeriFlux network paradigm for measuring and understanding the role of the terrestrial biosphere in global climate change. *Bioscience*.

Law BE, Kelliher FM, Baldocchi DD *et al.* (2001) Spatial and temporal variation in respiration in a young Ponderosa pine forest during a summer drought. *Agricultural and Forest Meteorology*, **110**, 27–43.

Law BE, Ryan MG, Anthoni PM (1999) Seasonal and annual respiration of a ponderosa pine ecosystem. *Global Change Biology*, **5**, 169–182.

Lee X (1998) On micrometeorological observations of surface-air exchange over tall vegetation. *Agricultural and Forest Meteorology*, **91**, 39–50.

Lee X, Black TA, denHartog G *et al.* (1996) Carbon dioxide exchange and nocturnal processes over a mixed deciduous forest. *Agricultural and Forest Meteorology*, **81**, 13–29.

Lee X, Fuentes JD, Staebler RM *et al.* (1999) Long-term observation of the atmospheric exchange of CO_2 with a temperate deciduous forest in southern Ontario, Canada. *Journal of Geophysical Research*, **104**, 15975–15984.

Lemon ER (1960) Photosynthesis under field conditions. II. An aerodynamic method for determining the turbulent carbon dioxide exchange between the atmosphere and a corn field. *Agronomy Journal*, **52**, 697–703.

Lenschow DH (1995) Micrometeorological techniques for measuring biosphere–atmosphere trace gas exchange. In: *Biogenic Trace Gases: Measuring Emissions from Soil and Water* (eds Matson PA & Harriss RC), pp. 126–163. Blackwell, London.

Leuning R, Denmead OT, Lang ARG *et al.* (1982) Effects of heat and water vapor transport on eddy covariance measurements of CO_2 fluxes. *Boundary Layer Meteorology*, **23**, 209–222.

Leuning R, Judd MJ (1996) The relative merits of open and closed path analysers for measurement of eddy fluxes. *Global Change Biology*, **2**, 241–253.

Leuning R, Moncrieff J (1990) Eddy covariance CO_2 flux measurements using open- and closed-path CO_2 analysers: corrections for analyzer water vapour sensitivity and damping of fluctuations in air sampling tubes. *Boundary Layer Meteorology*, **53**, 63–76.

Lindroth A, Grelle A, Moren AS (1998) Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity. *Global Change Biology*, **4**, 443–450.

Livingston GP, Hutchinson GL (1995) Enclosure-based measurements of trace gas exchange: applications and sources of error. In: *Biogenic Trace Gases: Measuring Emissions from Soil and Water* (eds Matson PA, Harriss RC), pp. 14–51. Blackwell Science, London.

Lund CP, Riley WJ, Pierce LL *et al.* (1999) The effects of chamber pressurization on soil-surface CO_2 flux and the implications for NEE measurements under elevated CO_2. *Global Change Biology*, **5**, 269.

Malhi Y, Nobre AD, Grace J *et al.* (1998) Carbon dioxide transfer over a central Amazonian rain forest. *Journal of Geophysical Research*, **103**, 31593–31612.

Massman WJ (2000) A simple method for estimating frequency response corrections for eddy covariance systems. *Agricultural and Forest Meteorology*, **104**, 185–198.

Massman WJ, Lee X (2002) Eddy covariance flux corrections and uncertainties in long term studies of carbon and energy exchanges. *Agricultural and Forest Meteorology*, **113**, 121–144.

McMillen RT (1988) An eddy correlation technique with extended applicability to non-simple terrain. *Boundary Layer Meteorology*, **43**, 231–245.

Moncrieff JB, Mahli Y, Leuning R (1996) The propagation of errors in long term measurements of land atmosphere fluxes of carbon and water. *Global Change Biology*, **2**, 231–240.

Monteith JL, Szeicz G (1960) The CO_2 flux over a field of sugar beets. *Quarterly Journal of the Royal Meteorological Society*, **86**, 205–214.

Moore CJ (1986) Frequency response corrections for eddy covariance systems. *Boundary Layer Meteorology*, **37**, 17–35.

Ohtaki E (1984) Application of an infrared carbon dioxide and humidity instrument to studies of turbulent transport. *Boundary Layer Meteorology*, **29**, 85–107.

Ohtaki E, Matsui T (1982) Infrared device for simultaneous measurements of fluctuations of atmospheric CO_2 and water vapor. *Boundary Layer Meteorology*, **24**, 109–119.

Paw UK, Baldocchi DD, Meyers TP *et al.* (2000) Correction of eddy covariance measurements incorporating both advective effects and density fluxes. *Boundary Layer Meteorology*, **97**, 487–511.

Piovesan G, Adams JM (2000) Carbon balance in European forests: interpreting Euroflux. *Journal of Vegetable Science*, **11**, 923–926.

Raupach MR (1979) Anomalies in flux-gradient relationships over forests. *Boundary Layer Meteorology*, **16**, 467–486.

Reynolds O (1895) On the dynamical theory of incompressible viscous fluids and the determination of criterion. *Philosophical Transactions of Royal Society of London*, **A174**, 935–982.

Ripley EA, Redman RE (1976) Grasslands. In: *Vegetation and the Atmosphere,* Vol. 2 (eds Monteith JL*)*, pp. 349–398. Academic Press, London.

Ruimy A, Jarvis PG, Baldocchi DD *et al.* (1995) CO_2 fluxes over plant canopies: a literature review. *Advances in Ecological Research*, **26**, 1–68.

Running SW, Baldocchi DD, Turner D *et al.* (1999) A global terrestrial monitoring network, scaling tower fluxes with ecosystem modeling and EOS satellite data. *Remote Sensing Environment*, **70**, 108–127.

Schmid HP (1994) Source areas for scalars and scalar fluxes. *Boundary Layer Meteorology*, **67**, 293–318.

Schmid HP, Grimmond CS, Cropley F *et al.* (2000) Measurements of CO_2 and energy fluxes over a mixed hardwood forest in the mid-western United States. *Agricultural and Forest Meteorology*, **103**, 357–374.

Schmid HP, Lloyd CR (1999) Spatial representativeness and the location bias of flux footprints over inhomogeneous areas. *Agricultural and Forest Meteorology*, **93**, 195–209.

Schulze E-D, Koch W (1969) Measurement of primary productivity with cuvettes. In: *Productivity of Forest Ecosystems, Proceedings of the Brussels Symposium*. UNESCO, pp. 141–157.

Scrase FJ (1930) *Some Characteristics of Eddy Motion in the Atmosphere, Geophysical Memoirs*, #52, pp. 56. Meteorological Office, London.

Shuttleworth WJ (1988) Corrections for the effect of background concentration change and sensor drift in real-time eddy covariance systems. *Boundary Layer Meteorology*, **42**, 167–180.

Simpson IJ, Thurtell GW, Neumann HH *et al.* (1998) The validity of similarity theory in the roughness sublayer above forests. *Boundary Layer Meteorology*, **87**, 69–99.

Soegaard H, Nordstroem C, Friborg T *et al.* (2000) Trace gas exchange in a high-arctic valley, 3. Integrating and scaling CO_2 fluxes from canopy to landscape using flux data, footprint modeling and remote sensing. *Global Biogeochemical Cycles*, **14**, 725–744.

Sun J, Desjardins R, Mahrt L *et al.* (1998) Transport of carbon dioxide, water vapor and ozone by turbulence and local circulations. *Journal of Geophysical Research*, **103**, 25873–25885.

Suyker AE, Verma SB (1993) Eddy correlation measurements of CO_2 flux using a closed path sensor: theory and field test against an open path sensor. *Boundary Layer Meteorology*, **64**, 391–407.

Suyker AE, Verma SB (2001) Year-round observations of the net ecosystem exchange of carbon dioxide in a native tall grass prairie. *Global Change Biology*, **7**, 279–290.

Swinbank WC (1951) Measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere. *Journal of Meteorology*, **8**, 135–145.

Twine TE, Kustas WP, Norman JM *et al.* (2000) Correcting eddy-covariance flux underestimates over a grassland. *Agricultural and Forest Meteorology*, **103**, 279–300.

Valentini RP, de Angelis G, Matteucci R *et al.* (1996) Seasonal net carbon dioxide exchange of a beech forest with the atmosphere. *Global Change Biology*, **2**, 199–208.

Valentini R, Matteucci G, Dolman AJ *et al.* (2000) Respiration as the main determinant of carbon balance in European forests. *Nature*, **404**, 861–864.

Valentini R, Scarascia Mugnozza GE, deAngelis P *et al.* (1991) An experimental test of the eddy correlation technique over a Mediterranean macchia canopy. *Plant, Cell and Environment*, **14**, 987–994.

Verma SB (1990) Micrometeorological methods for measuring surface fluxes of mass and energy. *Remote Sensing Reviews*, **5**, 99–115.

Verma SB, Baldocchi DD, Anderson DE *et al.* (1986) Eddy fluxes of CO_2, water vapor, and sensible heat over a deciduous forest. *Boundary Layer Meteorology*, **36**, 71–91.

Verma SB, Kim J, Clement RJ (1989) Carbon dioxide, water vapor and sensible heat fluxes over a tall grass prairie. *Boundary Layer Meteorology*, **46**, 53–67.

Webb EK, Pearman G, Leuning R (1980) Correction of flux measurements for density effects due to heat and water vapor transfer. *Quarterly Journal of Royal Meteorological Society*, **106**, 85–100.

Wesely ML (1970) Eddy correlation measurements in the atmospheric surface layer over agricultural crops. PhD Dissertation. University of Wisconsin.

Wesely ML, Cook DR, Hart RL (1983) Fluxes of gases and particles above a deciduous forest in wintertime. *Boundary Layer Meteorology*, **27**, 237–255.

Wesely ML, Hart RL (1985) Variability of short term eddy correlation estimates of mass exchange. In: *Forest–Atmosphere Interaction* (eds Hutchison BA, Hicks BB), pp. 591–612. Reidel Publications, Dordrecht, Netherlands.

Wilson KB, Baldocchi DD (2001) Comparing independent estimates of carbon dioxide exchange over five years at a deciduous forest in the southern United States. *Journal of Geophysical Research*, **106**, 34167–34178.

Wilson KB, Goldstein AH, Falge E *et al.* (2002) Energy balance closure at FLUXNET sites. *Agricultural and Forest Meteorology*, **113**, 223–243.

Wilson KB, Hanson PJ, Mulholland P *et al.* (2001) A comparison of methods for determining forest evapotranspiration and its components: sap flow, soil water budget, eddy covariance and catchment water balance. *Agricultural and Forest Meteorology*, **106**, 153–168.

Wofsy SC, Goulden ML, Munger JW *et al.* (1993) Net exchange of CO_2 in a mid-latitude forest. *Science*, **260**, 1314–1317.
Yamamoto S, Murayama S, Saigusa N *et al.* (1999) Seasonal and interannual variation of CO_2 flux between a temperate forest and the atmosphere in Japan. *Tellus*, **51B**, 402–413.
Yang PC, Black TA, Neumann HH *et al.* (1999) Spatial and temporal variability of CO_2 concentration and flux in a boreal aspen forest. *Journal of Geophysical Research*, **104**, 27653–27661.
Yi C, Davis KJ, Bakwin PS *et al.* (2000) Influence of advection on measurements of the net ecosystem-atmosphere exchange of CO_2 from a very tall tower. *Journal of Geophysical Research*, **105**, 9991–9999.