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Comparing independent estimates of carbon dioxide exchange over 5 years at a deciduous forest in the southeastern United States

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Abstract. At a deciduous forest in the southeast United States (Walker Branch Watershed, Oak Ridge, Tennessee), as at other sites with tall vegetation and/or complex terrain, it is difficult to temporally integrate eddy covariance data to obtain long-term estimates of net ecosystem exchange of carbon dioxide (NEE), primarily because of suspected systematic nocturnal errors. Therefore, although eddy covariance data can be invaluable, additional tools such as empirical gap-filling methods, independent measurements of CO_2 flux using chambers, and simulations using canopy process models are often necessary to obtain reliable annual carbon uptake estimates. Two independent approaches for estimating annual NEE using these tools at the Walker Branch site are discussed. One approach is to cumulatively sum the full set of eddy covariance measurements over time. The second approach is to sum the output of NEE from a biophysical canopy exchange model (CANOAK). CANOAK incorporates independent chamber measurements on leaves, soil, and stems and is driven using the observed canopy architecture, meteorology, soil water content, and soil temperatures to predict NEE. Both methods estimate similar trends and magnitudes of daytime (daylight hours) soil respiration and NEE over 5 years. Both methods also suggest similar differences among years (interannual variability). These two estimates of NEE are used to address possible measurement bias errors at this site and to provide plausible estimates of annual NEE. The estimated mean annual NEE at this site is -574 g C m^{-2} yr^{-1} between 1995 and 1999, ranging from -470 g C m^{-2} y^{-1} (1995) to -629 g C m^{-2} yr^{-1} (1999) (negative NEE indicates uptake by forest).

1. Introduction

To meet the scientific objective of understanding the "terrestrial carbon sink" [*Houghton et al.*, 1998] and the global carbon cycle, over the past decade, there has been a considerable expansion of sites measuring long-term carbon dioxide fluxes using the eddy covariance approach, as demonstrated by the international FLUXNET project [*Running et al.*, 1999; *Baldocchi et al.*, 2001a] and the regional AmeriFlux and EUROFLUX [*Valentini et al.*, 2000] projects. These flux networks have the priorities of (1) understanding the processes controlling net ecosystem exchange of carbon (NEE) and (2) obtaining quantitative estimates of long-term (annual) carbon uptake. These two goals are not completely independent, but this study focuses primarily on the second goal, which is an analysis of methods for quantitatively estimating longer-term carbon uptake rates and interannual variability at a deciduous forest site. The method for calculating annual NEE needs to be critically analyzed before the processes controlling interannual variability can be properly investigated.

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Temporally integrating eddy covariance data to calculate NEE is not possible at most sites. Temporal integration is difficult because of (1) gaps in data coverage [*Falge et al.*, 2001] or (2) suspected systematic errors [*Goulden et al.*, 1996; *Moncrieff et al.*, 1996; *Baldocchi et al.*, 2000]. The first type of problem, data gaps, encompasses ~37% of the total time across 19 FLUXNET sites and is associated with periods of either missing (resulting from instrument malfunction and power outages) or rejected (i.e., resulting from precipitation or the failure of turbulent statistics to fall within expected norms) data [*Falge et al.*, 2001]. Assuming that systematic errors are not present in the accepted data set and that the duration of individual gaps is not too large, the filling of gaps can often be handled statistically from the remainder of the accepted data set using empirical relationships [*Goulden et al.*, 1996; *Falge et al.*, 2001].

Systematic errors, on the other hand, are potential sources of considerable uncertainty when integrated over time [*Moncrieff et al.*, 1996]. Furthermore, it is difficult to confirm the presence of systematic errors unless independent data sources are available to identify and/or correct inconsistencies using the eddy covariance method. Examples of independent data sources are chamber measurements [*Goulden et al.*, 1996; *Lavigne et al.*, 1997; *Law et al.*, 1999], below-canopy eddy covariance measurements [*Norman et al.*, 1997; *Law et al.*, 1999], and other micrometeorological measurements that demonstrate mean advection or drainage flows [*Sun et al*., 1998; *Lee*, 1998; *Baldocchi et al*., 2000; *Lee and Hu*, 2001; *Wilson and Meyers*, 2001]. At the annual time scale, biomass measurements also provide independent constraints [*Valentini et al*., 1996; *Curtis et al*., 2001]. If the spatial representativeness of the measurements is not understood, systematic errors can also occur when temporally integrating NEE. As a result, an understanding of the temporally dependent "flux footprint" characteristics and the biophysical properties within this footprint may be necessary [*Schmid and Lloyd*, 1999]. Therefore eddy covariance should not be interpreted as an isolated measurement technique that directly provides unequivocal estimates of long-term fluxes. Instead, it is becoming more widely understood that eddy covariance measurements are best described as independent semicontinuous measurements that can be the centerpiece of an array of measurement, simulation, and statistical tools that supplement each other and constrain long-term fluxes [*Anthoni et al*., 1999; *Curtis et al*., 2001; *Falge et al*., 2001].

Walker Branch Watershed in Oak Ridge, Tennessee, serves as one of the particularly challenging sites for estimating long-term NEE using eddy covariance techniques. Aspects challenging to the eddy covariance method at the site include hilly terrain (ridge-valley height separation of ~40 m), tall vegetation (26 m), and relatively low mean annual wind speeds (2–2.5 m s^{-1} at 10 m above the canopy). Multiple sites [*Black et al*., 1996; *Goulden et al*., 1996; *Jarvis et al*., 1997; *Lavigne et al*., 1997; *Lee*, 1998; *Anthoni et al*., 1999], including Walker Branch [*Baldocchi et al*., 2000], have shown that nocturnal eddy covariance CO_2 measurements are often systematically biased when compared to chamber respiration measurements. One likely cause of this discrepancy is the presence of mean vertical advection or drainage flows that occur even in terrain with very weak slopes [*Mahrt and Larsen*, 1990; *Lee*, 1998; *Mahrt et al*., 2000]. A majority of the forested FLUXNET sites and many of the forests throughout the world are located on terrain that is conducive to these flows.

Because of data gaps and systematic nocturnal errors, some combination of independent measurements, statistical methods, and/or model simulations is often necessary to obtain integrated flux estimates, especially in tall vegetation [*Goulden et al*., 1996; *Anthoni et al*., 1999]. In this respect, the Walker Branch site is well suited because it has years of on-site independent chamber and eddy covariance estimates of soil respiration [*Hanson et al*., 1993; *Wilson and Meyers*, 2001], chamber measurements of stem respiration [*Edwards and Hanson*, 1996], biomass inventory and canopy structure studies [*Edwards et al*., 1989; *Hutchison and Baldocchi*, 1989; *Hanson et al*., 2001], leaf physiological measurements [*Wilson et al*., 2000a, 2000b] and biophysical model simulations [*Harley and Baldocchi*, 1995; *Baldocchi and Harley*, 1995; *Baldocchi*, 1997; *Wilson et al*., 2001a].

In this paper, annual NEE and the magnitude of its interannual variability are estimated over 5 years at Walker Branch using eddy covariance measurements and supporting measurement and simulation tools. This study stresses the need for independent data sources and model simulations to evaluate and address uncertainty in NEE estimates, either by corroborating or contradicting eddy covariance data. The purpose of the analysis is not to definitively validate simulations or measurement techniques, but to examine agreement between independent methods and suggest approaches that can best estimate annual fluxes at this site. On the basis of analysis of independent methods, annual estimates of NEE and soil respiration are provided over the 5 years of study.

2. Materials and Methods

2.1. Site

Measurements were made in a mixed temperate deciduous forest in Oak Ridge, Tennessee, (35°57′30″N, 84°17′15″W, 365 m above sea level) continuously from 1995 through 1999. The site is located in the southern section of the temperate deciduous forest biome in the eastern United States. The dominant trees in the forest range from 60 to 120 years old and are ~26 m tall. Important dominant species include oak (*Quercus*), maple (*Acer*), and tulip poplar (*Liridodendron tulipifera*). The site is in hilly terrain [*Baldocchi et al*., 2000], and the upwind fetch of forest extends several kilometers in all directions. A more detailed description of the canopy architecture, species composition, climate, soil properties, and other characteristics is provided by *Luxmoore et al*. [1981], *Hutchison and Baldocchi*, [1989], *Johnson and van Hook* [1989], and *Wilson and Baldocchi* [2000].

2.2. Eddy Covariance and Environmental Measurements

Beginning in autumn 1994 one set of eddy covariance instruments has been operating on a scaffold tower 36.9 m above the surface, which is ~10 m above the canopy [*Wilson and Baldocchi*, 2000]. In 1999 a second eddy covariance system was beneath the canopy, 2 m above the forest floor [*Wilson et al*., 2001b; *Wilson and Meyers*, 2001]. This second system was below virtually all vegetation, providing estimates of soil respiration. Wind velocity and virtual temperature fluctuations were measured in both systems with a three-dimensional sonic anemometer (model SWS-211/3K, Applied Technology, Boulder, Colorado). Fluctuations in CO_2 were measured with an open path, infrared absorption gas analyzer [*Auble and Meyers*, 1992], which was calibrated monthly using gas standards traceable to the National Oceanic and Atmospheric Amdinistration's (NOAA's) Climate Monitoring and Diagnostic Laboratory. Calibration factors typically changed by <5% over a month, and the direction of the change in the factor was random and did not introduce large bias errors in the annual sums.

Vertical flux densities were evaluated each half hour by computing the mean covariance of CO_2 fluctuations with the fluctuating vertical velocity [*Baldocchi et al*., 1988]. Scalar fluctuations were determined using the difference between the instantaneous values and the running mean of scalar quantities. The running mean was determined using a digital recursive filter with a 400-s time constant. Coordinate axes were rotated so that the mean vertical velocity was zero [*McMillen*, 1988]. Water vapor and CO_2 fluxes were corrected for the effect of density fluctuations [*Webb et al*., 1980; *Paw et al*., 2000]. CO_2 concentrations were measured sequentially at four heights (0.75, 9.1, 21.7, and 36.9 m) using a LI-6262 (Li-Cor Inc., Lincoln, Nebraska) analyzer to compute the storage contribution to NEE [*Greco and Baldocchi*, 1996]. The LI 6262 system received a zero and span calibration at least once a day.

Environmental and meteorological variables were measured at 1-s intervals, averaged each half hour, and logged on digital data loggers (model 21x, Campbell Scientific, Inc., Logan, Utah). Temperature and relative humidity were measured at 36.9 m with a temperature/humidity probe (HMP-35 A, Vaisala, Helsinki, Finland). Photosynthetically active radiation (PAR) was measured above and below the canopy with a

Table 1. Regression Coefficients Between Gap-Filled and Measured NEE During the Daytime

	Half-Hourly Regression[a]				Daily Regression[b]			
Year	Intercept[c]	Slope	SE[c]	R^2	Intercept[d]	Slope	SE[d]	R^2
1995	−1.33	0.77	2.80	0.77	−0.23	0.94	0.61	0.93
1996	−0.89	0.83	2.57	0.83	−0.16	0.95	0.62	0.96
1997	−1.22	0.78	2.68	0.78	−0.17	0.97	0.62	0.95
1998	−1.14	0.80	2.72	0.80	−0.22	0.93	0.74	0.92
1999	−1.17	0.78	2.64	0.78	−0.22	0.94	0.70	0.94

[a]Coefficients using daytime half-hourly fluxes of CO_2.
[b]Coefficients using daily daytime values of the carbon flux.
[c]Units of intercept and residual standard error (SE) are μmol m^{-2} s^{-1}.
[d]Units of intercept and residual standard error (SE) are g C m^{-2} day^{-1}.

quantum sensor (model LI-190S, Li-cor Inc., Lincoln, Nebraska). The sensor below the canopy was placed on a moving tram to average PAR over a horizontal transect of 20 m. Soil temperature was measured at 5 levels (2, 4, 8, 16, and 32 cm) using two multilevel thermocouple probes. Soil water content was measured at depths from 0 to 30 cm, 30 to 60 cm, and 60 to 90 cm using gravimetric measurements, time domain reflectometers (TDR) (Soil Moisture Equipment Corp., Santa Barbara, California), and water content reflectometers (Model CS615, Campbell Scientific, Inc., Logan, Utah) [*Wilson and Baldocchi*, 2000; *Wilson et al*., 2000a; *Hanson et al*., 2001].

2.3. Statistical Gap-Filling Method

Eddy covariance data were missing or rejected when instrumentation failed, sensor response was off-scale, or turbulence velocity statistics were highly abnormal. Cumulatively summing half-hourly eddy covariance estimates of NEE to longer timescales necessarily requires techniques for "filling in" periods of missing or rejected data [*Falge et al*., 2001]. The gap-filling technique used in this study was "look-up" tables based on empirical relationships between CO_2 fluxes and climate forcing. For each 15-day period during each of the 5 years, data were grouped into eight PAR categories. Within each PAR group, data were further subdivided by air temperature (T_a) into 5° increments. Mean NEE was obtained for each PAR and temperature group [i.e., NEE (PAR, T_a)]. Periods of missing or rejected data were subsequently filled with these empirical means, using the appropriate PAR and temperature at the time of missing data. Tests indicated that segregating the data into these PAR and T_a groups over 15-day periods generally provided sufficient resolution to capture the response of NEE to environmental forcing while minimizing the statistical uncertainty that would be associated with a large number of groups containing limited data. A similar approach has been used in other studies at Walker Branch [*Baldocchi et al*., 2001b; *Falge et al*., 2001] and has been found to be more satisfactory than regression or other approaches.

A similar gap-filling procedure was performed for the eddy covariance system beneath the canopy, but using soil temperature at 16-cm depth as the independent predictor of soil respiration. Missing soil respiration was filled using mean values segregated into 2.5°C categories over 15-day periods. Above-canopy measurements during nocturnal periods were filled in the same manner using soil temperature.

The reliability of the statistical gap-filling procedure was analyzed by comparing the observed CO_2 flux to the empirically gap-filled value had the data been missing. Because we will later demonstrate that the nocturnal eddy covariance data are probably biased and are not used in the final analysis, we focus on the ability of the gap-filling method to estimate the daytime (defined as nonzero solar radiation) NEE. Linear regression statistics are shown in Table 1, showing that the residual standard error between the measured value and gap-filled value was typically ~2.7 μmol m^{-2} s^{-1}.

The performance of the gap-filling procedure on the daily timescale was evaluated by comparing the measured daily carbon flux with the gap-filled daily flux on days when no data were missing (Figure 1 and Table 1). The relationship between measured and gap-filled daily estimates of the CO_2 flux was similar for all years (Table 1). Because the gap-filled data were derived from means, they necessarily average out the highest and lowest flux estimates, which is one reason why the slope is less than unity and the intercept is negative. Tests were per-

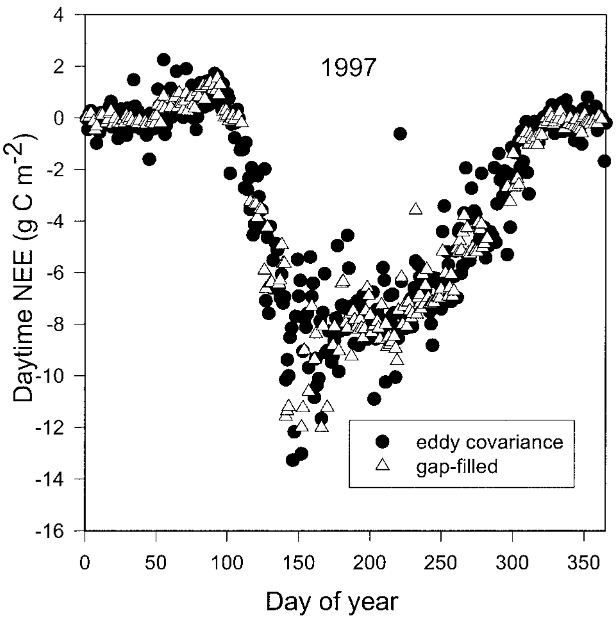

Figure 1. Daily daytime carbon flux measured by eddy covariance above the canopy in 1997 (circles). Also shown, on days when no data were missing, are daily estimates of NEE assuming all data were missing and subsequently gap filled (triangles). Negative values indicate carbon uptake by the forest.

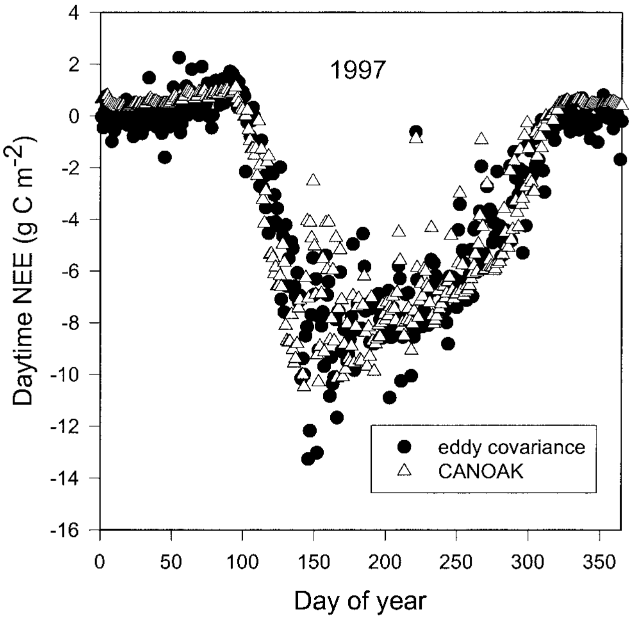

Figure 2. Daily daytime NEE measured using the above-canopy eddy covariance system (circles) and simulated with the biophysical canopy exchange model (CANOAK) (triangles) in 1997.

formed that indicated that there was not a large bias in gap filling by time of day. Generally, there was not a systematic bias between the measured and gap-filled quantities over any period of the year. One exception is a cloudy period around day 150 in 1997 (Figure 2). The gap-filling procedure does not account for the proportions of diffuse and direct radiation, which may bias the procedure during periods when the fraction of diffuse and direct radiation vary. The annually integrated gap-filled and measured estimates of daytime NEE were within 0.5% for each of the 5 years (Table 2), which is expected because mean values were used to provide the gap-filled estimates. Gap-filling procedures at night also resulted in a similar magnitude of error. Missing or rejected data encompassed 22% of the half-hour daytime periods over the 5-year period (Table 2). Similar to the above canopy measurements, the statistical gap-filling method reproduced much of the seasonal variation in the below-canopy eddy covariance data set (not shown). Missing or rejected data encompassed 19% of the half-hour time periods for the system below the canopy. In the remainder of the paper, eddy covariance estimates of CO_2 flux are measured values, but with gap-filling methods used on ~20% of the half-hour periods to provide cumulative sums.

2.4. Biophysical Canopy Exchange Model (CANOAK)

CANOAK is a one-dimensional, multilayer biosphere-atmosphere gas exchange model that computes water vapor, CO_2, and sensible heat flux densities. The model has been described and compared with data during growing seasons [*Baldocchi and Harley*, 1995; *Baldocchi*, 1997; *Wilson et al.*, 2001a] and in a longer-term study [*Baldocchi and Wilson*, 2001].

Micrometeorological and ecophysiological modules are coupled in CANOAK. The micrometeorological modules compute leaf (sunlit and shaded) and soil energy exchange, turbulent (Lagrangian) diffusion, scalar concentration profiles, and radiative transfer at 40 levels in the canopy using observed meteorological conditions above the canopy. The physiological modules are driven by physiological parameters that are obtained directly from extensive on-site chamber measurements. The predicted micrometeorology drives leaf photosynthesis, stomatal conductance, transpiration, and leaf, bole, and soil/root respiration. CANOAK was run with an hourly time step.

Of particular interest in this application are the CANOAK modules that require physiological parameterizations for each of the source/sink strengths for CO_2. These include estimates of the *Farquhar et al.* [1980] photosynthesis parameters, leaf area, and the Q_{10} and baseline respiration values for soil, bole, and leaves. Leaf respiration and the response of photosynthetic parameters to leaf age and soil water potential were derived from extensive leaf gas exchange measurements over the 1997 and 1998 growing seasons [*Wilson et al.*, 2000a, 2000b]. Both leaf age and low soil water potential reduced photosynthetic capacity from a late spring maximum. Parameterizations obtained from the leaf gas exchange data are discussed more fully by *Wilson et al.* [2001a].

Soil respiration was parameterized in CANOAK from chamber data collected with a closed gas exchange system across Walker Branch Watershed [*Hanson et al.*, 1993]. Respiration was estimated using a Q_{10} relationship with soil temperature (Q_{10} value is 2.47) and a factor to account for soil water potential [*Hanson et al.*, 1993; *Wilson et al.*, 2001a]. Bole and stem respiration parameterizations were also based on Q_{10} relationships, which were obtained from measurements on 56 trees in the watershed [*Edwards and Hanson*, 1996].

CANOAK requires that the seasonal trends in leaf area index (LAI) be specified. LAI was inferred from the relative transmission of solar radiation [*Wilson and Baldocchi*, 2000], a method that has been calibrated at this site [*Hutchison and Baldocchi*, 1989]. Two assumptions were made to simplify the analysis of LAI and its incorporation into seasonal CANOAK simulations. Small day-to-day fluctuations in the transmission

Table 2. Annual Daytime NEE[a]

Year	NEE (EC)	NEE (CANOAK)	NEE (Gap)	Percent Missing	R_{soil} (EC)[b]	R_{soil} (CANOAK)[b]
1995	−1027	−1091	−1011	30.4	——	383
1996	−1141	−1092	−1147	15.3	——	387
1997	−1200	−1152	−1204	19.1	——	386
1998	−1164	−1162	−1159	30.9	——	384
1999	−1219	−1248	−1219	13.3	420	392

[a]Measured in g C m^{-2} yr^{-1} using the above-canopy eddy covariance system (EC) with gap filling, simulated using CANOAK (CANOAK) or estimated using only the gap-filled values (Gap). Also shown is the percentage of missing data that required gap filling. Negative values indicate carbon uptake by the forest.

[b]Annual daytime soil respiration (R_{soil}) (g C m^{-2} yr^{-1}), estimated using the eddy covariance system at the forest floor (EC), or simulated in CANOAK (CANOAK).

Table 3. Summary of the Four Methods for Estimating NEE[a]

	Growing Season		Dormant Season	
Method	Day	Night	Day	Night
1	EC	EC	EC	EC
2	CAN	CAN	CAN	CAN
3	EC	CAN	EC	CAN
4	EC	CAN	CAN	CAN

[a]Indicating whether eddy covariance (EC) or CANOAK (CAN) estimates of NEE are used to cumulatively sum NEE during given period. Periods using eddy covariance data also included statistically gap-filled data.

of radiation, and estimated leaf area, resulted from changes in the solar angle and in the relative proportion of diffuse radiation. However, it was assumed that leaf area was constant between the two transition periods of leaf expansion and senescence, which is usually a good assumption in this forest.

The second assumption concerning LAI in CANOAK was that its maximum was 5.5 and was identical for each of the 5 years. Small interannual variations in maximum leaf area detected with litter baskets were within measurement errors. The sensitivity of NEE to maximum leaf area is expected to be small for closed canopies [*Baldocchi*, 1997; *Baldocchi and Meyers*, 1998], and sensitivity tests with CANOAK indicated that differences in a maximum leaf area of 1 resulted in only 2% changes in annual NEE. Alternatively, the dates of bud burst and senescence can be important, and the most notable difference between years was the late budbreak in 1996 [*Wilson and Baldocchi*, 2000].

With two exceptions, the simulations in CANOAK are independent of eddy covariance data and the annual sums derived from that data. The first exception is the parameterization of the velocity turbulence statistics (but not the scalar fluxes) that drives diffusion in the Lagrangian model algorithms, which were derived from historical eddy covariance measurements at the site [*Baldocchi and Meyers*, 1988]. Sensitivity tests have indicated that the simulated carbon flux is insensitive to the nature of this parameterization [*Baldocchi and Wilson*, 2001]. Because gap-filling methods and CANOAK both use meteorological data to estimate fluxes, annual sums estimated from the eddy covariance and CANOAK data require some of the same input data. However, the gap-filling methods are empirical, based exclusively on statistics using eddy covariance data. CANOAK simulates the biophysical processes that control fluxes, based on independent chamber data and published relationships describing canopy structure and function. Although not valid in the most strict sense, the term "independent" is used to describe these estimates because the use of similar data between the model and data is not believed to compromise the comparison.

2.5. Methods for Computing NEE

NEE was computed for each of the 5 years using four methods, summarized in Table 3. The only difference between methods was the relative fraction of eddy covariance data versus CANOAK output used in obtaining cumulative sums. Method 1 summed only eddy covariance data to compute annual NEE. Method 2 summed only CANOAK output and is independent of method 1. Method 3 estimated NEE using eddy covariance data during the daytime and CANOAK output during nocturnal periods. Method 4 is identical to method 3, except that NEE during the dormant season is estimated from CANOAK instead of from eddy covariance. Details of why these methods were chosen will be discussed in section 4.

3. Results

3.1. Eddy Covariance and CANOAK Estimates: Methods 1 and 2

When calculated by cumulatively summing all eddy covariance data (method 1), filling in data gaps statistically, annual NEE over the 5 years was -914 g C m^{-2}, ranging from -819 g C m^{-2} in 1995 to -991 g C m^{-2} in 1999 (Table 4). Annual soil respiration, estimated by summing the eddy covariance system beneath the canopy in 1999 (the only full year with eddy covariance data at the forest floor), was 575 g C m^{-2}.

The simulated NEE by CANOAK (method 2) over the 5-year period averaged -647 g C m^{-2}, or 267 g C m^{-2} (29%) less uptake than eddy covariance estimates (compare methods 1 and 2 in Table 4). Simulated soil respiration was 754 g C m^{-2}, 179 g C m^{-2} (31%) greater than eddy covariance estimates. Although the eddy covariance and CANOAK methods disagree in magnitude, the general ranking between years shows some similarity (compare methods 1 and 2 in Figure 3 and Table 4). In the following analysis, more detail is provided on how well these two independent estimates compare by evaluating NEE estimates after segregating the data into daytime and nocturnal periods.

3.1.1. Daytime comparison. To provide a direct comparison with CANOAK output, half-hourly eddy covariance data were averaged to get mean hourly values. Regression coefficients between eddy covariance (method 1) and CANOAK (method 2) estimates of canopy CO_2 exchange during the daytime are shown in Table 5 at both the hourly and daily timescales. The relationship between eddy covariance and CANOAK estimates was similar for all years, except with a greater slope for the daily values in 1995 (Table 5). Figure 2 shows daily daytime NEE during an entire year (1997), measured by eddy covariance and simulated using CANOAK.

Table 4. Annual NEE for each of the 5 Years Using the Four Different Methods for Integrating to Annual Sums[a]

Year	Method 1: Eddy Covariance	Method 2: CANOAK	Method 3	Method 4	Comments
1995	−819	−592	−528	−470	drought, humidity deficit
1996	−879	−597	−646	−576	late bud break
1997	−933	−652	−700	−618	cloudy June
1998	−946	−656	−658	−592	drought, high temperature
1999	−991	−739	−710	−629	large summer PAR, drought

[a]In g C m^{-2} yr^{-1}. See section 3 for description of methods.

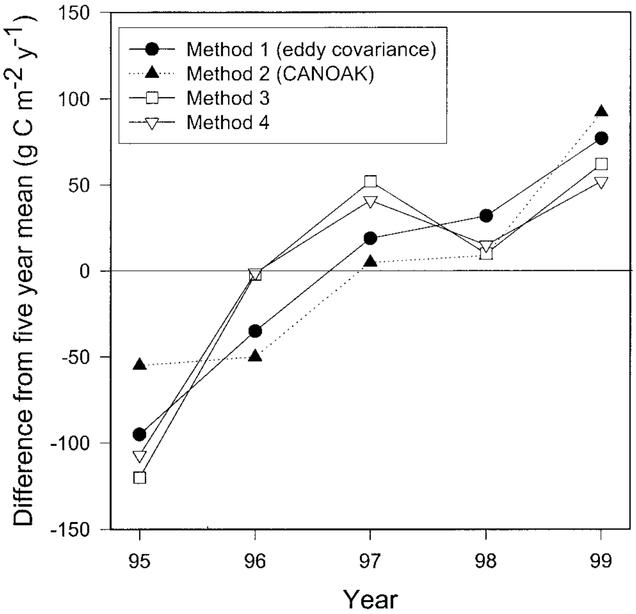

Figure 3. Difference in annual NEE from the 5-year mean using the four different methods described in text. Method 1 (circles) is directly from eddy covariance. Method 2 (solid triangles) is directly from CANOAK simulations. Methods 3 (squares) and 4 (open triangles) incorporate both measurements and CANOAK simulations (see text and Table 3).

There is good agreement on the general seasonal patterns from these fully independent methods for estimating NEE, although winter respiration is lower in the eddy covariance data. The bias near day 150 was during an extended cloudy period, which may indicate that CANOAK was not accurately simulating periods when the proportion of diffuse radiation was especially high. For each of the 5 years, annual estimates of daytime NEE are within 10% for these two methods and, with the exception of 1995, measured and simulated NEE agree to within 50 g C m^{-2} yr^{-1} (4%) (Table 2 and Figure 4).

There was also good agreement between below-canopy eddy covariance estimates of soil respiration and that simulated in CANOAK during the daytime (Figure 5), and both approaches also show a decrease in soil respiration during a period of lower soil water content near day 250. Excluding the period of low soil water content, the eddy covariance data beneath the canopy in 1999 were fit to a Q_{10} relationship:

$$R_s = R_0 Q^{T_s/10},$$

where R_s is the measured soil respiration, R_0 is the respiration at 0°C, Q is the Q_{10} value, and T_s is the soil temperature at 16 cm (°C). Although there was substantial scatter (Figure 6), the best fit value of Q was 1.97, within the range of typical values [*Raich and Schlesinger*, 1992; *Law et al.*, 1999] but less than the value obtained from chamber data at the site (2.47) [*Hanson et al.*, 1993]. R_0 was 0.68 μmol m^{-2} s^{-1}, slightly greater than the chamber data (0.50 μmol m^{-2} s^{-1}) [*Hanson et al.*, 1993]. Therefore chamber and eddy covariance-derived temperature responses were not identical, but the regression estimates were similar over the observed soil temperature range (Figure 6). The total daytime soil respiration in 1999 estimated by eddy covariance was 420 g m^{-2} yr^{-1}, and the simulated estimate was 392 g C m^{-1} yr^{-1}, or 28 g C m^{-2} yr^{-1} (6.7%) lower (Table 2).

3.1.2. Nocturnal comparison. The agreement between eddy covariance (method 1) and CANOAK (method 2) estimates of NEE was much weaker during nocturnal periods than it was during the daytime. Although there is some qualitative agreement on the seasonal patterns between eddy covariance and CANOAK, eddy covariance estimates of nocturnal ecosystem respiration are systematically lower than the simulated values throughout the year (Figure 7 and Table 6). The mean annual difference between measured and simulated estimates of nocturnal ecosystem respiration averaged 265 g C m^{-2} yr^{-1} (Table 6). Nocturnal soil respiration measured by the eddy covariance system at the forest floor is also systematically lower than that simulated by CANOAK (Table 6), although the two methods generally agreed during the day (Figure 5).

Micrometeorological measurements have suggested that vertical advection of CO_2 is frequent at this site, likely due to the downslope drainage of cold air, a process that would result in eddy covariance estimates of nocturnal respiration that are biased low [*Lee*, 1998; *Baldocchi et al.*, 2000; *Wilson and Meyers*, 2001]. CO_2 concentrations near the surface have also been observed to be much higher (50 (μmol mol^{-1}) in lower terrain during nocturnal periods (K. Wilson, unpublished data, 2001), suggesting that CO_2 is advected very near the surface to low terrain and is not detected by the eddy covariance instrumentation.

Table 5. Regression Coefficients between CANOAK and Eddy Covariance Estimates of Carbon Fluxes During Daytime

	Hourly Regression[a]				Daily Regression[b]			
Year	Intercept[c]	Slope	SE[c]	R^2	Intercept[d]	Slope	SE[d]	R^2
1995	−1.04	0.90	3.44	0.69	0.01	1.09	1.01	0.91
1996	−0.48	0.86	3.22	0.80	0.04	0.97	0.95	0.91
1997	−0.70	0.84	3.18	0.75	0.00	0.96	0.96	0.88
1998	−0.55	0.82	3.33	0.73	−0.08	0.96	0.99	0.87
1999	−0.78	0.90	3.17	0.76	0.00	1.02	0.92	0.88

[a]Coefficients using daytime hourly fluxes of CO_2.
[b]Coefficients using daily daytime values of the carbon flux.
[c]Units of intercept and residual standard error (SE) in μmol m^{-2} s^{-1}.
[d]Units of intercept and residual standard error (EC) are g C m^{-2} day^{-1}.

3.2. Methods 3 and 4 for Estimating NEE

Because micrometeorological measurements indicate drainage flows, which violates an assumption implicit in the eddy covariance technique [*Lee*, 1998; *Mahrt et al.*, 2000], and because there is bias in eddy covariance estimates of nocturnal respiration relative to chamber measurements, one approach for estimating annual NEE at Walker Branch is to accept daytime eddy covariance measurements but replace nocturnal estimates with output from CANOAK (i.e., this describes method 3 introduced in section 2.5). Table 7 summarizes the percentage of total hours used in calculating annual sums from eddy covariance measurements, statistically gap-filled data (section 2.3), and CANOAK using each of the four methods outlined in section 2.5. The percentage of hours directly incorporating measured eddy covariance data into annual NEE estimates decreased from 77% (method 1) to 39% (method 3) when nocturnal eddy covariance measurements were rejected.

The mean annual NEE estimated over the entire 5 years is

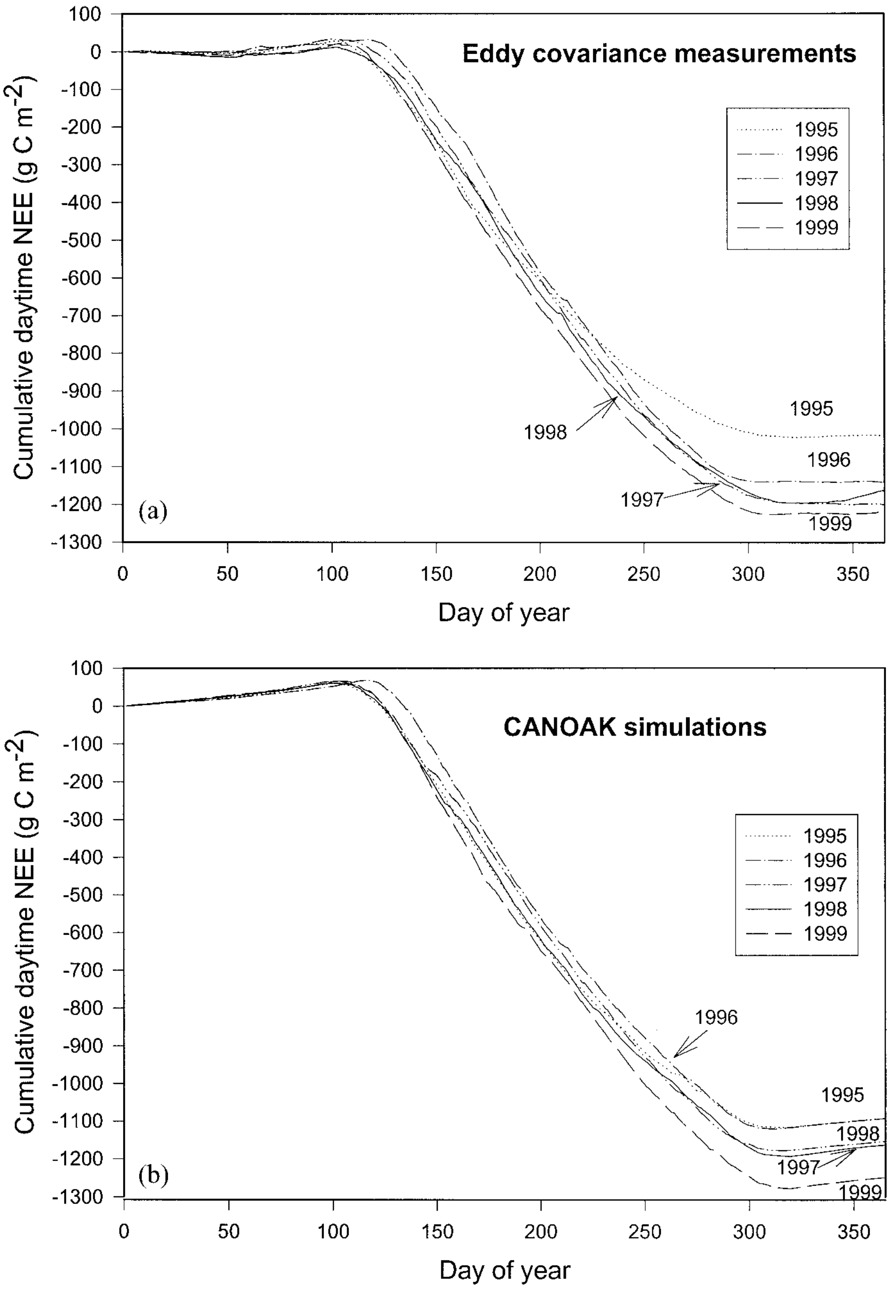

Figure 4. Cumulative daytime NEE for each of the 5 years (a) measured using the above-canopy eddy covariance system and (b) simulated with the biophysical model CANOAK.

almost identical between method 2 (CANOAK simulations, -647 g C m^{-2} yr^{-1}) and method 3 (eddy covariance data during day but CANOAK during nocturnal periods, -646 g C m^{-2} yr^{-1}) (Table 4). The difference between the two methods ranged from $+64$ to -49 g C m^{-2} yr^{-1}.

Method 4 addresses the differences in daytime winter respiration between eddy covariance and CANOAK (Figure 4) by replacing all dormant season (days 1–100 and days 315–365 each year) NEE estimates with those from CANOAK (Table 3). The percentage of time directly using eddy covariance estimates decreased to 25% using method 4 (Table 7). Annual carbon uptake averaged 71 g C m^{-2} yr^{-1} (11%) less than the estimates obtained from method 3, which included dormant season daytime eddy covariance estimates of NEE. Despite differences in magnitude between all the methods (especially between method 1 and the other three methods), there was some general agreement between methods on the relative differences between years (Figure 3 and Table 4).

4. Discussion

4.1. Empirical Gap-Filling Method

The statistical method for filling data gaps during periods of missing data does not appear to introduce unacceptably large errors into daily and annual NEE estimates at this site, especially relative to systematic errors. The look-up table method used in this study does not require an assumed response to environmental forcing, as would a regression fit. Estimating 22% of the daytime data at Walker Branch using gap-filling techniques inevitably results in some level of uncertainty. How-

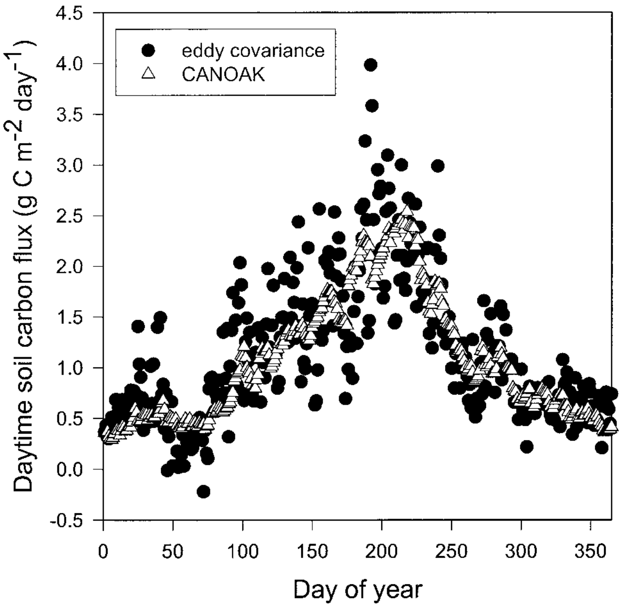

Figure 5. Daily daytime estimates of carbon flux from the soil (loss from soil indicated by positive numbers) measured by eddy covariance (circles) and simulated using chamber data (triangles).

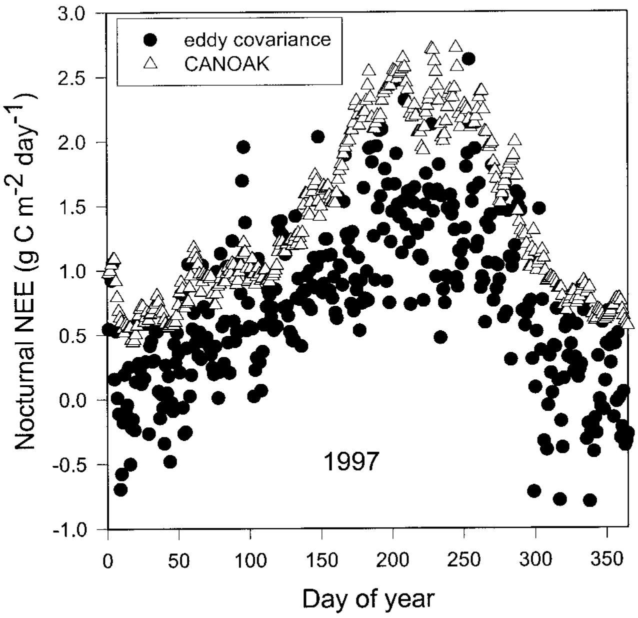

Figure 7. Daily nocturnal carbon flux measured using the above-canopy eddy covariance system (circles) and simulated with the biophysical model CANOAK (triangles) in 1997.

ever, this uncertainty is likely much less than that associated with systematic nocturnal errors or the methods used to correct systematic errors.

4.2. Eddy Covariance and CANOAK Estimates of NEE

4.2.1. Estimates of daytime NEE. Agreement between eddy covariance and CANOAK estimates of daytime NEE (methods 1 and 2) and soil respiration provides some level of confidence in the ability of both approaches to estimate NEE and its components during the day. Agreement between eddy covariance and independent catchment water budget estimates of evapotranspiration over the 5 years provides additional confidence in the daytime turbulent scalar flux estimates [*Wilson et al.*, 2001b]. Energy balance closure is not complete at this site [*Wilson and Baldocchi*, 2000], which is a general problem within FLUXNET and other eddy covariance sites [*Wilson et al.*, 2001c]. The implications of the ~20% lack of closure on the carbon balance estimates at a majority of these sites [*Aubinet et al.*, 2000; *Wilson et al.*, 2001c] is still uncertain, but there are some indications that the magnitude of the CO_2 flux is underestimated when there is an imbalance [*Twine et al.*, 2000; *Wilson et al.*, 2001c]. However, although eddy covariance measurements at night are biased at many forested sites, daytime measurements in complex terrain are often similar to those in more flat terrain [*Lee and Hu*, 2001].

The level of agreement between CANOAK and eddy covariance NEE during the daytime does not necessarily validate the complex mechanisms of each of the carbon source/sink components in CANOAK. However, estimates of one isolated carbon source (soil respiration) were directly available from the eddy covariance system beneath the canopy, and CANOAK estimates of soil respiration compared well with those from eddy covariance during the daytime. In general, CANOAK is capable of using independent input variables (meteorology data set, leaf area, and physiological parameterizations) to replicate the general magnitude and some of the interannual variability present in the observed carbon fluxes below and above the canopy, which provides circumstantial evidence that CANOAK is representing many of the important processes. The data/model comparison of carbon fluxes both above and below the canopy (methods 1 and 2) also gives support to the hypothesis that CANOAK can be used to simulate useful approximations of soil respiration and NEE during periods when

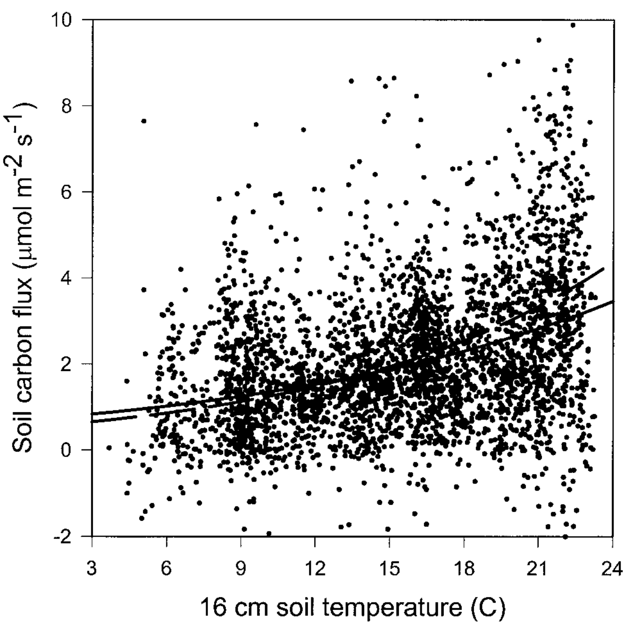

Figure 6. Relationship between half-hourly estimates of soil respiration from the forest floor eddy covariance system and the 16-cm soil temperature. Also shown is the best-fit Q_{10} relationship (solid line) and the Q_{10} relationship obtained from chamber data (dashed line).

Table 6. Annual Nocturnal NEE[a]

Year	NEE (EC)	NEE (CANOAK)	R_{soil} (EC)	R_{soil} (CANOAK)	Leaf (CANOAK)	Bole (CANOAK)
1995	208	499	——	355	52	92
1996	262	495	——	356	51	88
1997	267	500	——	361	51	88
1998	218	506	——	358	54	94
1999	228	509	183	362	54	93

[a]Estimated in g C m^{-2} yr^{-1} in using the above-canopy eddy covariance system (EC) and simulated using CANOAK (CANOAK). Also shown are estimates of nocturnal soil respiration estimated using eddy covariance ($R_{soil\ EC}$) and the annual simulated components of NEE using CANOAK (all in g C m^{-2} yr^{-1}), soil respiration (R_{soil} CANOAK), leaf respiration (Leaf CANOAK), and bole respiration (Bole CANOAK). Positive numbers denote a loss of carbon to the atmosphere.

eddy covariance estimates are known to be unreliable (i.e., methods 3 and 4 for estimating NEE).

The largest divergence between CANOAK and eddy covariance estimates of daytime NEE was during midwinter and during much of 1995. The discrepancy in 1995 may be related to low soil water content during that year [*Wilson and Baldocchi*, 2000]. Although low soil water content also occurred in 1998 and 1999, growth was also inhibited more in 1995 relative to the other drought years 1998 and 1999 [*Hanson et al*., 2001].

The source of the discrepancy between eddy covariance and CANOAK during midwinter appears to be magnified during periods when low inversion heights and little convective mixing are suspected [*Baldocchi et al*., 2000]. Because the forest floor eddy covariance system often estimated more positive daytime CO_2 flux (greater respiration) than the above-canopy measurements during this period, it is also possible that the conifers (~10–15% of biomass) within the flux footprint were assimilating carbon. However, this discrepancy occurred even on the coldest winter days (<0°C) when carbon assimilation is not expected, hinting that the source of discrepancy is not biological but is associated with meteorological processes. The mean systematic difference between winter daytime ecosystem respiration estimated by above-canopy eddy covariance and CANOAK is small (~0.5 μmol m^{-2} s^{-1}), but accumulated over the year it accounts for ~70 g C m^{-2} y^{-1} (difference between methods 3 and 4). Alternatively, daytime soil respiration estimated by the below-canopy eddy covariance system during this time period is similar to that predicted by CANOAK. Because the above-canopy eddy covariance estimates of daytime respiration in winter are usually less than that independently measured by the forest floor eddy covariance system or independently predicted by CANOAK, a bias is suspected in the above-canopy measurements, although the mechanisms are not fully understood. Therefore, method 4, which uses simulated estimates of carbon exchange during winter, is suggested as a better estimate of annual NEE than method 3.

4.2.2. Nocturnal NEE. Although there appears to be an especially large systematic nocturnal bias in eddy covariance estimates of respiration at Walker Branch, other sites have also reported uncertainty and systematic errors during nocturnal periods [e.g., *Goulden et al*., 1996; *Anthoni et al*., 1999; *Aubinet et al*., 2000; *Schmid et al*., 2000]. The handling of suspected systematic errors in all cases depends on the availability of independent measurements, knowledge of micrometeorological processes at the site, and the preference of individual researchers. However, the pervasiveness of this problem indicates that it is highly desirable for all sites to independently test the null hypothesis that their measurements are not subject to systematic errors.

The methods for detecting systematic errors and the handling of the associated uncertainty are often different at each site, but any approach will necessarily introduce a level of uncertainty. At a number of sites, researchers only accept nocturnal NEE data when turbulence (often manifested by u^*, the friction velocity) is considered to surpass some threshold, usually different for each site [*Goulden et al*., 1996; *Jarvis et al*., 1997; *Hollinger et al*., 1999; *Aubinet et al*., 2000; *Falge et al*., 2001; *Schmid et al*., 2000]. A clear dependence of NEE on u^* has not been observed at Walker Branch. The value of u^* chosen as a threshold also varies at different sites, and the choice of this threshold is always subject to some level of subjectivity [*Aubinet et al*., 2000; *Falge et al*., 2001]. Carefully testing this method with other micrometeorological data and independent chamber data [*Goulden et al*., 1996] is a good way to increase confidence in this approach, but this has not been done in a widespread manner.

Without an improved quantitative understanding of the mi-

Table 7. Relative Percentage Contributions of Eddy Covariance Data, Gap-Filled Data, and CANOAK Output Used in Estimating Annual NEE Shown in Table 4

	Method 1			Method 2			Method 3			Method 4		
Year	Percent Data[a]	Percent Gap[b]	Percent CNK[c]	Percent Data[a]	Percent Gap[b]	Percent CNK[c]	Percent Data[a]	Percent Gap[b]	Percent CNK[c]	Percent Data[a]	Percent Gap[b]	Percent CNK[c]
1995	67.9	32.1	0.0	0.0	0.0	100	34.9	15.3	49.8	22.0	10.4	67.6
1996	83.1	16.9	0.0	0.0	0.0	100	42.5	7.7	49.8	27.4	5.0	67.6
1997	79.4	20.6	0.0	0.0	0.0	100	40.6	9.6	49.8	24.6	7.8	67.6
1998	69.9	31.1	0.0	0.0	0.0	100	34.7	15.5	49.8	20.6	11.8	67.6
1999	85.7	14.3	0.0	0.0	0.0	100	43.5	6.7	49.8	30.4	2.0	67.6

[a]Eddy covariance data.
[b]Gap-Filled data.
[c]CANOAK output.

crometeorological processes during nocturnal periods, currently, our best estimates of nocturnal NEE at Walker Branch are from CANOAK, which is based on chamber data and has demonstrated some agreement with eddy covariance measurements above and below the canopy during daytime periods. This approach, used in methods 2, 3, and 4 in this study and by *Anthoni et al*. [1999] for estimating annual NEE, also introduces a set of uncertainties that are dificult to quantify. First, chamber measurements can have problems with sampling and representativeness. Chambers can also present artificial environments involving pressure and concentration gradients [*Lund et al*., 1999]. Because CANOAK appears capable of estimating the seasonal trends in soil respiration and NEE during the day, we have justified the use of CANOAK during nocturnal periods on the premise that respiration can be predicted from estimates of biomass, leaf area, temperature, and soil water content independent of time of day or other factors. The error in this assumption is uncertain, especially since CANOAK does not simulate all the daily variability in soil respiration at the site and soil respiration is believed to be important in the interannual variation of NEE in two New England forests [*Savage and Davidson*, 2001]. The CANOAK parameterization also assumes that Q_{10} is constant with temperature, which may not be correct [*Lloyd and Taylor*, 1994; *Tjoelker et al*., 2001].

4.3. Obtaining an Estimate of Annual NEE

Calculating long-term NEE at the Walker Branch site must necessarily combine eddy covariance data and CANOAK output. Method 4, which uses CANOAK data to estimate nocturnal fluxes and all fluxes during the dormant season, is suggested as currently the best method for estimating the magnitude of the annual carbon flux. It may appear contradictory that our best method of obtaining annual NEE deliberately reduces the amount of eddy covariance data (25% in method 4) and increases the amount of CANOAK output (67.6%, with 7.4% being gap filled). Our justification for this approach is based on two lines of circumstantial evidence but does not suggest blind faith in model estimates or the lack of a necessity for eddy covariance measurements. First, method 4 justifiably eliminates all above-canopy eddy covariance data when micrometeorological evidence suggests violations of assumptions implicit in the eddy covariance method (i.e., nocturnal drainage flows) or when above-canopy NEE estimates are inconsistent with two other independent estimates, those from below-canopy eddy covariance data and those from CANOAK (i.e., midwinter). Second, CANOAK and eddy covariance data often show useful agreement in both NEE and soil respiration during periods when assumptions associated with the eddy covariance technique are least likely to be violated. These periods are primarily in the warm season when sufficient turbulent mixing and deep boundary layers exist and some skill is shown in closing the water [*Wilson et al*., 2001b] and energy budgets [*Wilson and Baldocchi*, 2000]. The increased confidence in CANOAK provided by these comparisons when the data are most trustworthy provides support for using CANOAK during periods when micrometeorological conditions are less optimal. Although the amount of eddy covariance data used in annual flux estimates is reduced when CANOAK output is used, without the increased confidence in CANOAK provided by this data the uncertainty associated with CANOAK would be virtually unknown and its results of much more limited value. This analysis supports the use of multiple measurement and simulation tools in providing independent carbon flux estimates, especially at sites that are likely to violate assumptions implicit in the eddy covariance method (i.e., tall vegetation, sloping terrain, advection, or weak turbulence).

The mean annual estimate of NEE at Walker Branch is -574 g C m^{-2} (method 4). This is close to that in an earlier analysis (-525 g C m^{-2}) before quality control criterion were better understood and nocturnal data were summarily rejected if the CO_2 flux was negative [*Greco and Baldocchi*, 1996]. These estimates of NEE are on the order of two times greater than estimates from biomass inventories at the site [*Edwards et al*., 1989; *Greco and Baldocchi*, 1996; *Curtis et al*., 2001]. The reasons for the difference with biometric estimates are important but still unknown. Significant uncertainties are also present in biomass-based estimates, especially because belowground processes are essentially ignored.

The eddy covariance and CANOAK estimates (methods 1 and 2) are nearly independent but still show some agreement on the interannual variability, increasing confidence that there is some skill in distinguishing differences between years. All methods suggest a maximum variability between the 5 years of between ~150 and almost 200 g C m^{-2} yr^{-1}, or up to ~35% of the 5-year mean. Drought and differences in growing season length are two important contributors to the interannual variability observed at this site [*Wilson and Baldocchi*, 2000].

The uncertainties assigned to these NEE estimates are difficult to quantify. *Goulden et al*. [1996] and *Moncrieff et al*. [1996] discuss the role of random errors, systematic errors, and gap filling in estimating long-term fluxes. If eddy covariance data are accepted for all time periods (method 1), the systematic error associated with nocturnal bias is probably on the order of 270 g C m^{-2} yr^{-1} (difference between methods 1 and 3). Using CANOAK simulations during nocturnal periods in methods 2, 3, and 4 reduces this systematic error but introduces additional unknown, albeit likely smaller, errors. One possible source of bias is measurement errors in the environmental driving variables used in CANOAK, such as temperature, humidity, radiation, and soil water content. Although calibrations and intercomparisons between instruments are performed to reduce these problems, small bias errors in these variables probably occurred over time to some extent, which may introduce unrealistic trends. Such errors can be a significant source of model bias over long time periods if instrumentation is not calibrated regularly. Additional model biases can occur during particular meteorological or environmental conditions, which may explain the apparent underestimate of simulated fluxes during a cloudy period near day 150 in 1997.

Conclusions

1. Estimating long-term NEE using the eddy covariance technique requires independent micrometeorological and ecological measurements for detecting and correcting systematic errors, especially in tall vegetation and/or in terrain that is not flat. It is important to distinguish between uncertainty associated with occasional data gaps, which can often be reduced to a statistical problem, and that involving systematic errors.

2. The daytime estimates of NEE and soil respiration from eddy covariance were usually similar to independent simulations. During nocturnal periods, drainage flows have been observed at the site, which violates assumptions associated with the eddy covariance technique. As a result, systematic mea-

surement errors are likely, and the agreement between simulations and eddy covariance data was substantially less.

3. Although differing in magnitude, interannual variability in NEE showed some similarity between eddy covariance and the simulations, providing some confidence that interannual variability can be characterized at this site.

4. To obtain useful estimates of annual NEE, eddy covariance estimates of NEE were rejected when violations of important assumptions implicit in the eddy covariance technique were suspected or when NEE estimates were consistently different from two other independent methods (eddy covariance estimates below the canopy and scaled chamber data). These periods were replaced with CANOAK output. The estimated annual NEE at this site is -574 g C m^{-2} yr^{-1} with a standard deviation of 63 g C m^{-2} yr^{-1}.

5. Unresolved issues concerning annual estimates of NEE remain. The importance of the lack of energy balance closure at FLUXNET sites, including Walker Branch, on CO_2 fluxes and the discrepancies with biometric estimates at Walker Branch are sources of uncertainty and require further investigation.

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