CARBON DIOXIDE FLUXES IN A CENTRAL HARDWOODS OAK-HICKORY FOREST ECOSYSTEM

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Abstract—A long-term experiment to measure carbon and water fluxes was initiated in 2004 as part of the Ameriflux network in a second-growth oak-hickory forest in central Missouri. Ecosystem-scale (~ 1 km^2) canopy gas exchange (measured by eddy-covariance methods), vertical CO_2 profile sampling and soil respiration along with meteorological parameters were monitored continuously. Early results from this forest located on the western margin of the Eastern Deciduous Forest indicated high peak rates of canopy CO_2 uptake (35-40 μmol/m^2/second) during the growing season in the relatively wet year of 2004. Late growing-season CO_2 uptake rates declined despite the absence of drought, suggesting declining leaf photosynthetic capacity that preceded leaf fall or removal of leaf area by herbivory. Canopy CO_2 profile measurements in summer indicated substantial accumulation of CO_2 (~ 500 ppm) near the surface in still air at night, venting of this buildup in the morning hours under radiation-induced turbulent air flow, and small vertical gradients of CO_2 during most of the subsequent light period with minimum CO_2 concentrations in the canopy. Flux of CO_2 from the soil ranged from 2 to 8 μmol/m^2/second during the growing season and increased with temperature. Flux of forest floor CO_2 fell below 1 μmol/m^2/second during mid-winter periods. Data from this site and others in the network will also allow characterization of regional spatial variation in carbon fluxes as well as inter-annual differences attributable to climatic events such as droughts.

INTRODUCTION

Traditionally, foresters have assessed the economic value of forests based on quantity and quality of stem wood production. While this assessment remains an important perspective on resource use, there are other approaches that have both economic and ecological utility. The eddy-covariance (EC) technique to monitor exchanges of CO_2, water vapor, and heat at the interface between vegetation and the atmosphere allows a more complete accounting of carbon balance in forest ecosystems (Baldocchi and others 1988, Baldocchi 2003). As carbon uptake or loss is the primary determinant of productivity of forest ecosystems, EC measurements can provide a valuable tool for foresters, forest ecologists and those interested in assessing the capacity of forests to sequester carbon. The latter may be of increasing economic importance as greenhouse gas emissions force climate change.

In the Central Hardwoods Region there are now at least three EC sites operating in forest ecosystems (Walker Branch, TN; Morgan Monroe State Forest, IN; Missouri Ozarks, MO). The Missouri site is the most recent addition and a primary objective of the project is long-term quantification of carbon fluxes of a Central Hardwoods forest in this forest-prairie transition region expected to be limited by water availability. The site has been operating since June of 2004 and data are now available to illustrate the potential value of such research to the forestry community.

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STUDY AREA

The Missouri Ozark Ameriflux site (MOFLUX) site (38°40' N, 92°12' W) is located in the Ozark Border physiographic region at the Baskett Research and Education Area (BREA, owned and managed by the University of Missouri) 30 km SE of Columbia, Missouri, USA. The vegetation at the site, assessed both by long term permanent plot measurements distributed across the BREA (Pallardy and others 1988, Pallardy and Coonley 2005) and from plots placed on spoke-like transects within the footprint of the tower (unpublished), is an oak-hickory forest dominated by white oak (*Quercus alba* L.) and with contributions of several other oak species (black oak, *Q. velutina* Lam.; northern red oak, *Q. rubra* L.; Shumard oak, *Q. shumardii* Buckl.; chinkapin oak, *Q. muehlenbergii* Engelm.; and post oak, *Q. stellata* Wangenh.) and hickories (primarily shagbark hickory, *Carya ovata* [Mill.] K. Koch). A dense understory of sugar maple (*Acer saccharum* Marsh.) is found beneath the canopy, along with eastern redcedar (*Juniperus virginiana* L.) (the latter in localized disturbed areas). Vegetation sampling in the footprint of the eddy flux tower at the site indicated tree density of 583 trees/ha (≥ 9 cm dbh) and tree basal area of 24.2 m^2/ha. Canopy height ranges from 17 to 20 m and leaf area index, measured by leaf litter collection, is about 4.2. Dominant soils are a broadly distributed type classified as Weller silt loam and another type "Steep Stony Land" localized to limestone outcrop areas (Krusekopf and Scrivner 1962). Ridges alternate with relatively gentle side slopes leading to ephemeral streams in shallow valleys with a total local elevation range of 175-245 m across the area. The climate of the area is warm, humid and continental. The monthly mean temperature (1971-2000) is –2.3 °C in January and 25.2 °C in July (http://www.ncdc. noaa.gov/oa/climate/online/ccd/nrmavg.txt). Annual precipitation averages 1023 mm from 1971 to 2000 (http://www.ncdc.noaa.gov/ oa/climate/online/ccd/nrmocp.txt). The study site is centered on a SW facing ridge with gently sloping SE- and NW-facing sides surrounded by a basin about 1 km in diameter. The eddy flux tower is located at the top of this elongated ridge roughly in the center of the basin.

MEASUREMENTS

An EC system is installed at a height of 30.48 m at the top of a walkup tower. It consists of a R. M. Young 81000 three-dimensional sonic anemometer (R. M. Young Company, Traverse City, MI, USA) and a LI-7500 open path gas analyzer (LI-COR Inc., Lincoln, NE, USA). Data are recorded at 10 Hz by a personal computer sheltered at the base of the tower. Vertical fluxes of CO_2, water vapor, temperature and momentum are computed every 30 minutes after two-dimensional coordinate rotation to eliminate errors in fluxes attributable to sonic anemometer tilt relative to the terrain surface, despiking to remove spurious extreme values occasionally produced by the sonic anemometer and CO_2 analyzer, and Webb correction of CO_2 concentrations to adjust for the effects of temperature and water vapor fluxes on CO_2 density (Webb and others 1980).

Also in operation is a CO_2/water vapor profile sampling system. Atmospheric CO_2 concentration and water vapor content are measured by a LI-7000 gas analyzer (LI-COR Inc., Lincoln, NE, USA) at heights of 0.15, 0.30, 0.61, 0.91, 1.52, 3.05, 6.1, 9.14, 12.19, 16.76, 22.86 and 30.48 m. Samples are drawn through Teflon tubing progressively from top to bottom in a continuously recurring cycle. These measurements allow continuous monitoring of the dynamic vertical CO_2 gradient within the ecosystem for estimation of CO_2 storage and correction of eddy-covariance flux data to provide Net Ecosystem Exchange (NEE) of CO_2.

Soil respiration is monitored continuously with an automated system that samples eight tip-down chambers of the design by Edwards and Riggs (2003) that are distributed 30-40 m from the tower along the SE slope.

RESULTS AND DISCUSSION

Eddy-covariance measurement of CO_2 flux is based on very fast (10-20 Hz) measurements of both vertical air movement and CO_2 concentration at the tower top (Aubinet and others 2000, Baldocchi and others 1988, Baldocchi 2003). For example, upward air movement away from the canopy combined with a concurrent fall in CO_2 concentration, or downward air movement into the canopy combined with an increase of CO_2 concentration, indicates depletion of CO_2 of the air below and therefore net CO_2 uptake in photosynthesis. Raw data are usually processed to provide half-hourly values of CO_2 and H_2O flux.

The daily march of EC CO_2 flux data (fig. 1) often shows a distinct pattern. Still air at night results in buildup of CO_2 near the surface by plant and heterotrophic respiration. This dynamic pattern is captured by the profile sampling system which draws air samples from the tower top to the forest floor (fig. 2). Nighttime buildups of CO_2, which can reach 500 µmol/mol or more, are subsequently vented upward (indicated by negative flux values) early the next morning as increasing solar radiation induces increased turbulence and higher daytime wind velocities (fig. 1). Venting is followed by photosynthetic uptake of CO_2 that under well-watered, sunny conditions roughly follows the sinusoidal pattern of solar illumination of the forest canopy. Daytime minimum CO_2 concentrations in the profile are located within the canopy between 5 and 18 m (fig. 2).

Nighttime accumulation of CO_2 near the surface reflects intense respiration from the soil, especially during the growing season (fig. 3A). Soil respiration ultimately depends on the fixed carbon inputs provided by plant litter and carbohydrate translocation to the root system in living trees. However, environmental controls on the process are also quite important. In winter (fig. 3B) low temperatures limit daily mean soil respiration to less than 1 µmol/m^2/second, whereas in summer, when soil temperatures may exceed 25 C in the upper soil (fig. 3A), the daily rate may reach 8 µmol/m^2/second or more. Soil water content may reduce soil respiration independent of temperature (Hanson and others 2003), but during the wet year of 2004 there was little evidence of such limitation at the Missouri site (fig. 3). Interestingly, heavy rain (in the present study >37 mm over the course of a day) may temporarily restrict loss of CO_2 from the soil surface by the formation of a diffusion cap that presumably arises from filling of the soil pore space with water (see arrows in fig. 3A).

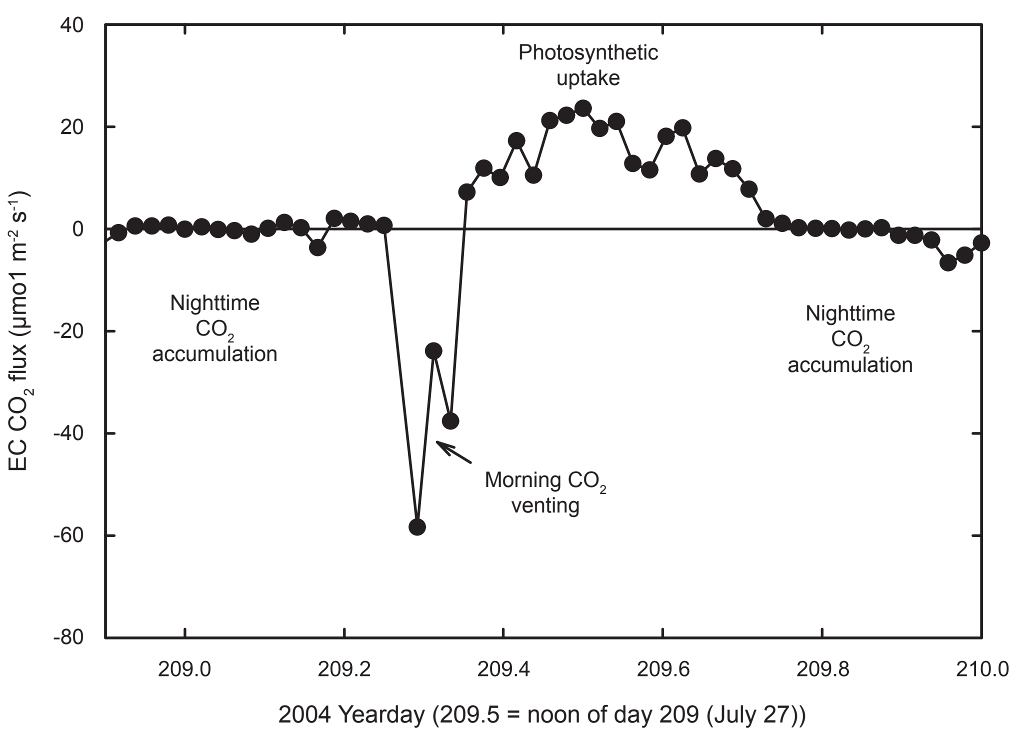

Figure 1—Typical diurnal pattern of CO_2 flux derived from eddy-covariance (EC) measurements at the tower top (30.48 m) at the Missouri Ozark Ameriflux site.

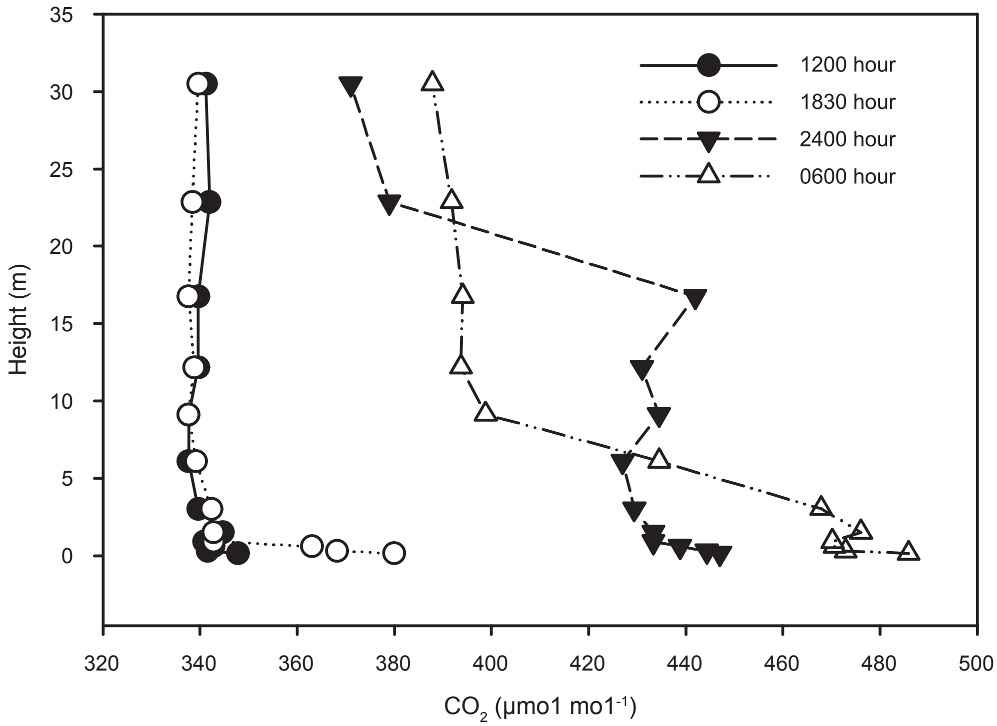

Figure 2—Vertical profiles of CO_2 concentration measured with the Missouri Ozark Ameriflux site CO_2 profile sampling system at four representative times during the diurnal cycle of CO_2 exchange on day 175 (June 23, 2004).

Peak EC CO_2 fluxes at the Missouri site reached 35-40 µmol CO_2/m^2/second during the 2004 growing season (fig. 4), values that are surprisingly high considering its location in the relatively xeric western reaches of the Central Hardwoods region. These flux values are comparable with flux data for CO_2 from deciduous forest EC sites elsewhere (Baldocchi and others 2001, Curtis and others 2002, Ehman and others 2002, Schmid and others 2000, Wilson and Baldocchi 2001). The data in figure 4 also reinforce the recurring nature of the diurnal pattern described in figure 1.

When EC-based flux rates are adjusted for CO_2 storage in the vertical air column, an estimate of NEE of CO_2 can be derived. Mean daily NEE data for CO_2 from the initiation of measurement in mid-June 2004 through the end of the year are shown (fig. 5). The seasonal pattern of NEE is clearly observable through the leaf-on season which ends by mid-October (Day 290). Interestingly, late growing season NEE was reduced despite a lack of limitation by soil water availability or temperature (e.g., Days 200-250). Modeling of NEE based on photosynthetic process models (Gu and others 1999) did not explain all of this reduction and it is possible that the deviation may be attributable to senescence-related metabolic changes although it precedes any visible signs of autumn coloration, or because of leaf area removal by herbivory. Seasonal variations in foliar photosynthetic capacity consistent with this pattern have been observed in eastern Tennessee by Wilson and others (2000). In early winter, NEE values hover around zero, likely reflecting a balance between some residual CO_2 uptake by the evergreen *Juniperus virginiana* on the site and wintertime soil respiration (fig. 3B).

The data provided by the suite of instrumentation on this site enable a comprehensive understanding of short-term dynamics and mid-to-long term drivers of forest productivity. Straightforward integration of NEE on an annual basis provides an independent estimate of ecosystem productivity to compare with conventional biometric (e.g., dendrometer band estimates of growth and whole-tree biomass accounting based on destructive sampling) and the status of a particular forest as a source or sink for CO_2. Once

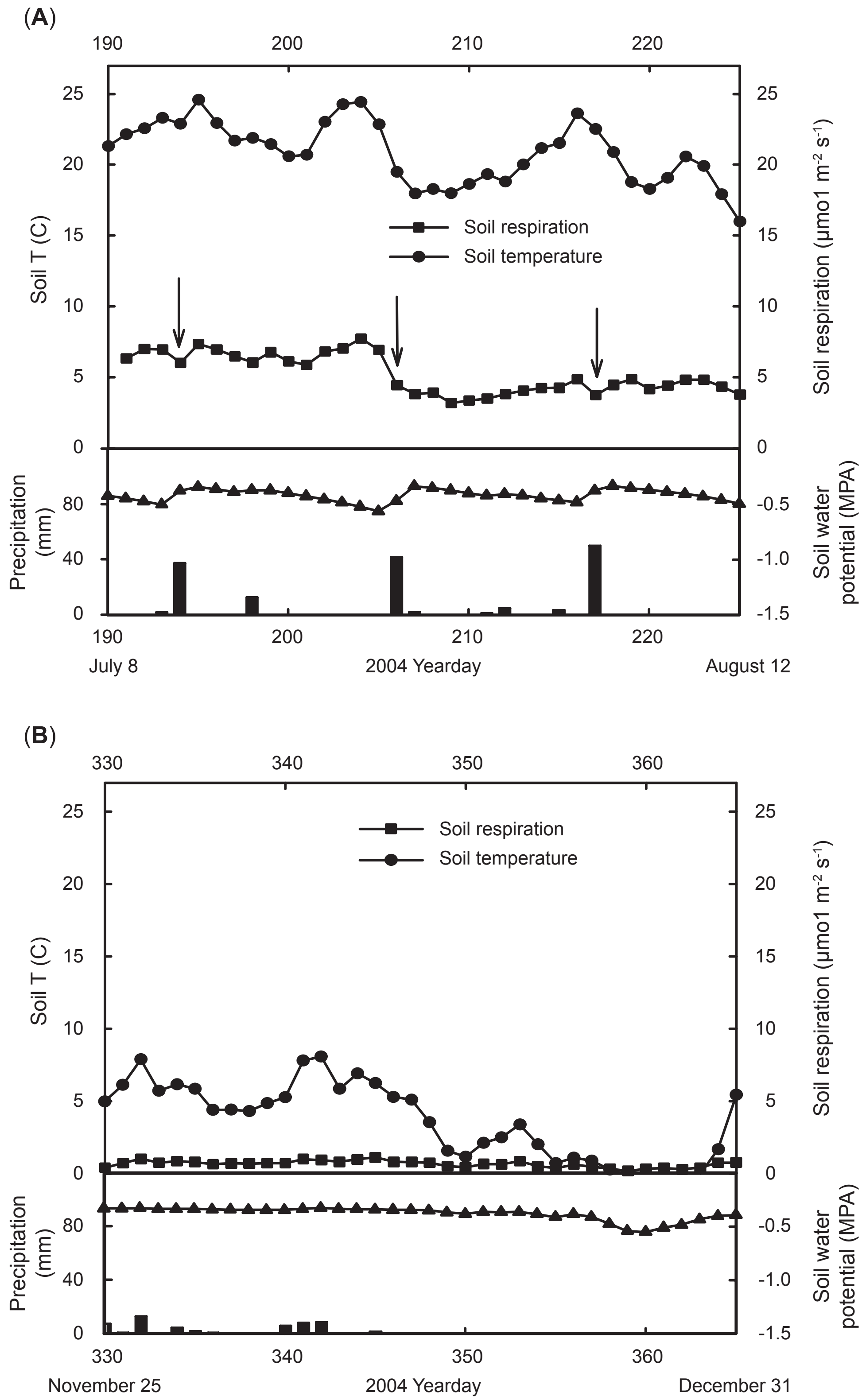

Figure 3—Thirty-five-day traces of soil respiration, soil temperature at 5 cm depth, soil water potential in the upper 30 cm, and precipitation events for the growing season (A) and the dormant season (B) of 2004 at the Missouri Ozark Ameriflux site [arrows in (A) indicate rain events that were associated with dips in soil respiration].

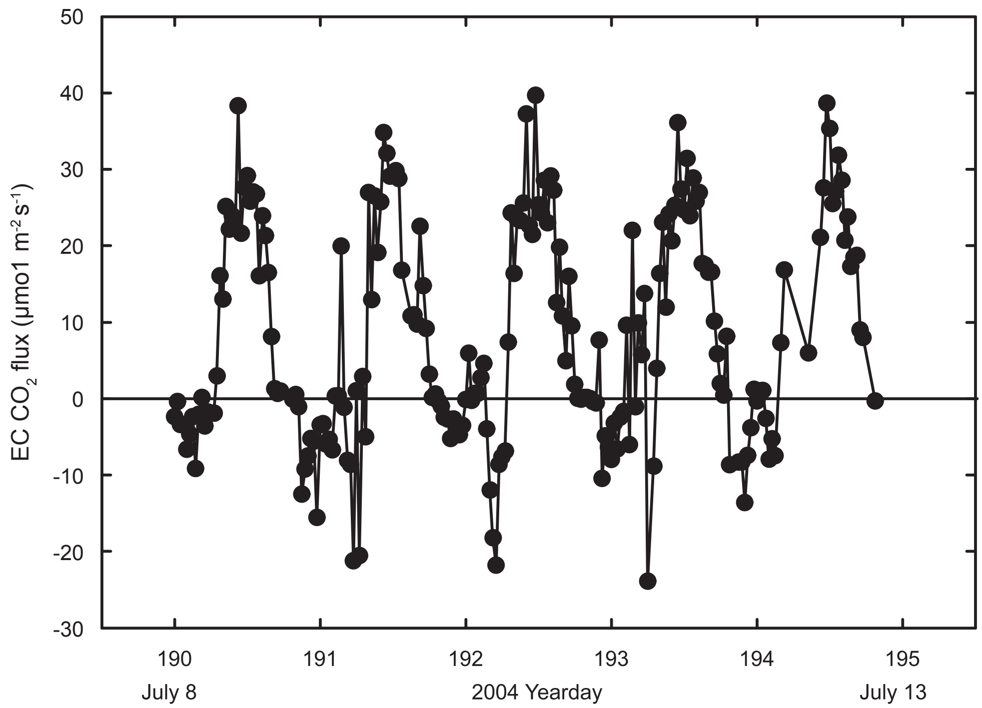

Figure 4—Eddy-covariance (EC) CO_2 fluxes for 5 days in midsummer 2004 at the Missouri Ozark Ameriflux site (compare with figure 1).

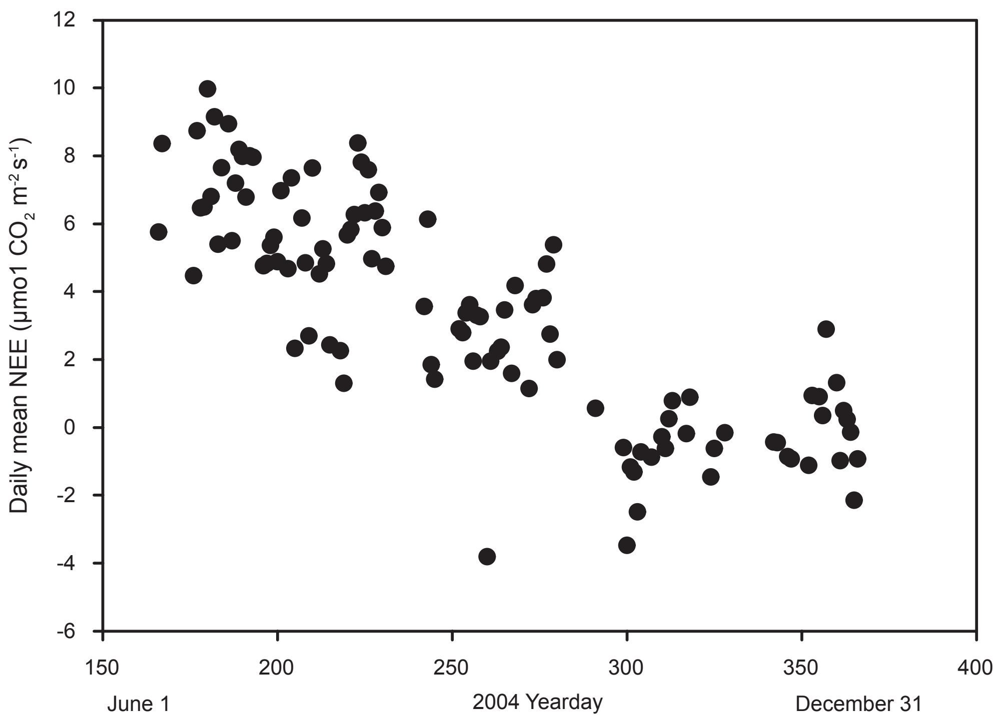

Figure 5—Mean daily net ecosystem exchange (NEE) of CO_2 at the Missouri Ozark Ameriflux site based on eddy-covariance CO_2 flux data corrected for CO_2 storage as estimated with the CO_2 profile system.

an adequate data set is in hand, models can be developed that accurately predict CO_2 exchange based on conventional meteorological variables as drivers (Gu and others 1999, Hanson and others 2004). In this way, CO_2 exchange at a regional scale can be estimated for forest ecosystems with similar species composition. We are also in the process of building biometric data sets against which to contrast annual NEE data as an independent test of the eddy-covariance method to resolve net carbon exchange in this forest.

Although this approach to ecosystem–level carbon exchange has much promise, some issues remain to be worked out. For example, if the topography of the site is dissected and prone to night drainage air (so-called "complex terrain") then some CO_2 produced at night in still air will "leak" away unmeasured. Practical and theoretical methods are being developed to deal with these issues (Gu and others 2005).

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