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EDDY-CORRELATION MEASUREMENTS OF CARBON DIOXIDE EFFLUX FROM THE FLOOR OF A DECIDUOUS FOREST

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SUMMARY

(1) The eddy-correlation technique was used to measure CO_2 efflux from the floor of a deciduous forest. Midday values of CO_2 efflux typically ranged between 0·30 and 0·45 mg m^{-2} s^{-1}. These values were somewhat larger than those from previous chamber studies, which typically ranged from 0·2 to 0·3 mg m^{-2} s^{-1}.

(2) Daytime CO_2 efflux from the canopy floor was correlated with air temperature. A suppression in CO_2 efflux was observed late in the afternoon and a burst in CO_2 efflux was observed near dusk, which was independent of temperature.

(3) CO_2 efflux from the floor of a deciduous forest was insensitive to changes in wind speed under the conditions studied. This insensitivity was probably due to the soil type and soil litter at the experimental site and the low wind speeds encountered near the forest floor.

(4) The eddy-correlation technique seems to provide a promising means for measuring CO_2 efflux from a forest or orchard floor. More work, however, is needed to examine the role of the dispersive term on subcanopy mass and energy exchange. Further examination into the mechanism causing the late afternoon suppression and early evening burst in CO_2 efflux is also needed. The role of canopy water deficits or pressure fluctuations should be investigated as possible factors contributing to this suppression. Future studies of the early evening respiratory burst should include measurements of photosynthetic translocation to the roots.

INTRODUCTION

The efflux of CO_2 from the soil of the terrestrial biosphere is an important component of the global carbon balance. Reichle *et al.* (1973), for example, report that about 64% of the gross primary production of an East Tennessee deciduous forest is consumed by the respiratory processes at and below the soil surface. The reported range of CO_2 efflux from the soil of temperate deciduous forests is large, ranging between 171 and 1400 g m^{-2} $year^{-1}$ of carbon (Schlesinger 1977). Consequently, more measurements of soil CO_2 efflux are needed to evaluate this component of the carbon budget.

CO_2 efflux from a forest floor originates from microbial decomposition of organic matter and root and soil biota respiration. This efflux is governed by temperature, moisture, pH, available substrates and nutrients (Witkamp 1969; Edwards 1975; Schlesinger 1977; Edwards & McLaughlin 1978) and pressure fluctuations (Kimball & Lemon 1971).

Although CO_2 efflux has been measured from the floor of many crop and forest canopies (e.g. Monteith, Szeicz & Yabuki 1964; Reiners 1968; Witkamp 1969; Edwards & Sollins 1973; Edwards 1975), these past studies may be limited by their dependence on

either dynamic or static chamber techniques. The dynamic technique is based on measuring the change in CO_2 density as a known flow rate of air passes through a chamber. These measurements are affected by whether air is drawn or blown through the chamber. For example, Kanemasu, Powers & Sij (1974) found that measurements of CO_2 efflux were an order of magnitude larger when air was drawn through the chamber than when it was blown through the chamber. The static method is based on the adsorption of CO_2 by KOH or $Ba(OH)_2$. Witkamp (1969) found that the static technique underestimates the dynamic method by 20%. Edwards & Sollins (1973) report that the errors in the static technique are temperature dependent. CO_2 efflux measured with the static technique is 63% of the dynamic technique at 20 °C and 90% at 12 °C. Chamber techniques are also susceptible to errors from disturbance to the micro-environment and dampening of ambient pressure fluctuations, which influence soil–gas exchange (see Kimball & Lemon 1970, 1971; Schlesinger 1977; Kimball 1983).

The eddy-correlation technique (e.g. Kanemasu *et al.* 1979) provides an alternative means of measuring CO_2 efflux. This technique measures the flux directly and imposes minimal influence on the ambient environment. Application of this technique has been limited by the unavailability of appropriate instrumentation. Recent development of fast-response, CO_2 sensors (Bingham, Gillespie & McQuaid 1978) now makes it possible to use the eddy-correlation technique to measure CO_2 efflux.

In 1984 a cooperative study was conducted between scientists at Atmospheric Turbulence and Diffusion Division's Laboratory and the University of Nebraska's Center for Agricultural Meteorology and Climatology to measure CO_3 exchange above and below a fully-leafed, East Tennessee, deciduous forest. Here we report on our measurements of CO_2 efflux made near the floor of the forest. Results from the measurements of CO_2 flux above the canopy are presented in Verma *et al.* (1986).

MATERIALS AND METHODS

Site

This study was conducted at the United States Department of Energy Reservation, near Oak Ridge, TN (lat. 35°57′30″; long. 84°17′15″; altitude 365 m above mean sea level). The site is on a ridge in moderately complex terrain and is forested with an uneven-aged, oak-hickory stand (sp. *Carya* and *Quercus*), representative of the Appalachian region. The forest stand extends several kilometers in all directions from the measurement site. The soil at the site is Fullerton cherty silt loam (Typic Paleudult) and is covered with a layer of detritus.

The average height of the forest was about 22 m and the leaf area index was about 4·9 (see Hutchison *et al.* 1986 for further details regarding the canopy structure and composition). Appreciable precipitation occurred before and during the experiment and values of volumetric soil moisture content, measured with a neutron probe, are presented in Table 1.

Instrumentation

Wind speed components were measured with a three-dimensional sonic anemometer (Model BH-478B/3, Applied Technology, Boulder, CO). CO_2 density in air was measured with an open-path, fast-response CO_2 sensor (Bingham, Gillespie & McQuaid 1978; Anderson 1983). A Lyman-alpha hygrometer (Electromagnetic Research Corporation, College Park, MD) was used to measure water vapour. Air temperature was measured

TABLE 1. Vertical profile of volumetric soil moisture on 8 August 1984 (day 221). These values are the mean of seven profiles and were measured with a neutron probe

Depth (m)	Volumetric soil moisture (%)	Coefficient variation (%)
0·15	22·3	7·9
0·30	27·0	7·2
0·45	31·5	12·9
0·60	36·3	10·9
0·75	39·8	8·6
0·90	41·5	9·6

with a microbead thermistor. The instrument time constants were less than 0·10 s. These instruments were mounted 1·75 m above the ground; little vegetation existed below this level. The spatial separation between the anemometer and the CO_2 sensor was about 0·70 m and the distance between the anemometer and the hygrometer and thermistor was about 0·30 m. A Hewlett-Packard 1000L minicomputer data acquisition system was used to sample and record the fast-response turbulence data at a rate of about 7 Hz. This sampling rate was sufficient to measure the spectrum of frequencies that contribute to transfer processes within a forest canopy (Allen 1968).

Solar radiation components were measured above the canopy with instruments described in Baldocchi *et al.* (1984). Air temperatures were measured above and within the canopy with thermistors. Net radiation (R_n) at the forest floor was estimated as 0·036 R_n (Baldocchi *et al.* 1984). A micrologger (Model CR-7, Campbell Scientific Instrument Co., Logan, UT) was used to monitor ambient conditions. The sensors were sampled three times per minute. The data presented in this paper are reported as half-hour averages and were acquired between days 217 and 222 (4–9 August) 1984.

Measurement techniques and theoretical considerations

The eddy fluxes were computed as the mean covariance between turbulent fluctuations in the vertical wind velocity (w) and the scalar of interest (x). Turbulent fluctuations were computed as the difference between the instantaneous and mean values. Mean values were computed in real-time using a digital recursive filter (McMillen 1983). The filter computations were performed using a 200 s time constant.

The flux densities of CO_2 and latent heat were corrected for the effects of fluctuations in air density (see Webb *et al.* 1980). These corrections, however, were small due to the low values in latent and sensible heat exchange.

The turbulent fluxes were measured close enough to the surface to minimize flux convergence or divergence, yet far enough from the surface to minimize the loss in flux contributed by eddies with frequencies higher than we could measure. However, the mean vertical velocity ($\bar{w}$) at 1·75 m was generally non-zero (0·1–0·2 m s^{-1}) and directed downward. Using experimental and theoretical arguments, we feel that this phenomenon did not affect our measurements of CO_2 efflux. Experimentally, $\bar{w}$ was not well correlated with CO_2 efflux measured between 09.00 and 16.00 h (r^2 of 0·13, with 53 degrees of freedom). Theoretically, the volume-averaged conservation of mass equation, within a horizontally homogeneous canopy, under steady-state conditions, can be expressed as the balance between the source and sink terms and the partial derivative, with respect to height, z, of the turbulence covariance and dispersive terms (Raupach & Thom 1981). The sink–source terms above the forest floor should be near

zero since there was little vegetation to uptake or respire CO_2. The dispersive term is generally insignificant in a homogeneous canopy and is significant only if spatial variations in $\bar{w}$ are correlated with spatial variations in the mean scalar entity (Raupach & Thom 1981). Furthermore, $\bar{w}$ can be non-zero and not contribute to the exchange processes if the dispersive term is zero. We assume that the dispersive term is insignificant since the wavelengths of the peak eddies associated with subcanopy mass transfer are much greater than any spatial inhomogeneities in the canopy structure (see Allen 1968; Denmead & Bradley 1985) and spatial variations in CO_2 soil efflux (Garrett, Cox & Roberts 1978).

RESULTS AND DISCUSSION

Diurnal variation in CO_2 efflux

Below we discuss a diurnal pattern of CO_2 efflux from a typical summer day (day 219, 1984). Environmental conditions measured above the canopy are presented in Table 2. The diurnal pattern of net radiation (R_n), latent heat (LE) and sensible heat (H) flux measured near the canopy floor are presented in Fig. 1a. Midday values of R_n were estimated to be on the order of 20–30 W m^{-2}. LE was on the order of 15–25 W m^{-2} and H was near zero. The residual energy ($R_n - LE - H$) was consumed via soil heat flux and canopy heat storage. Mean wind speeds and air temperatures inside the canopy are presented in Fig. 1b and 1c, respectively. Wind speeds in the subcanopy were of the order of 0·2–0·5 m s^{-1} and maximal air temperatures were moderate, near 28 °C.

CO_2 efflux from the soil was typically low in the morning (Fig. 2). It then increased to a maximum around mid afternoon. Afterward, it decreased and then exhibited a burst at dusk. The magnitude of CO_2 efflux was of the order of 0·05–0·25 mg m^{-2} s^{-1} in the morning and late afternoon. About mid afternoon, CO_2 efflux was of the order of 0·25–0·45 mg m^{-2} s^{-1}. CO_2 efflux, during the burst at dusk, was greatest, being on the order of 0·6 mg m^{-2} s^{-1}. The evening burst, however, was not always this large. On day 222 the magnitude of the burst was about 0·4 mg m^{-2} s^{-1}.

TABLE 2. Ambient environmental conditions measured above the deciduous forest at the site near Oak Ridge, TN on day 219, 1984. R_g is global shortwave radiation, D is diffuse shortwave radiation, T_a is air temperature, measured at 29 m and u is wind speed, measured at 44 m

Time (hour)	R_g (W m^{-2})	D (W m^{-2})	T_a (°C)	u (m s^{-1})
09.00	415	161	22·6	1·22
09.30	514	125	24·1	1·25
10.00	540	139	24·8	2·25
10.30	725	143	25·8	2·55
11.00	687	135	25·9	2·86
11.30	830	124	26·8	2·59
12.00	845	116	27·7	2·75
12.30	802	165	27·7	3·01
13.00	852	152	28·3	3·04
13.30	875	154	28·7	3·06
14.30	674	—	29·3	2·50
15.30	620	—	29·2	3·20
16.30	498	—	29·2	—
17.30	330	—	28·7	3·20
18.30	130	—	27·5	2·70

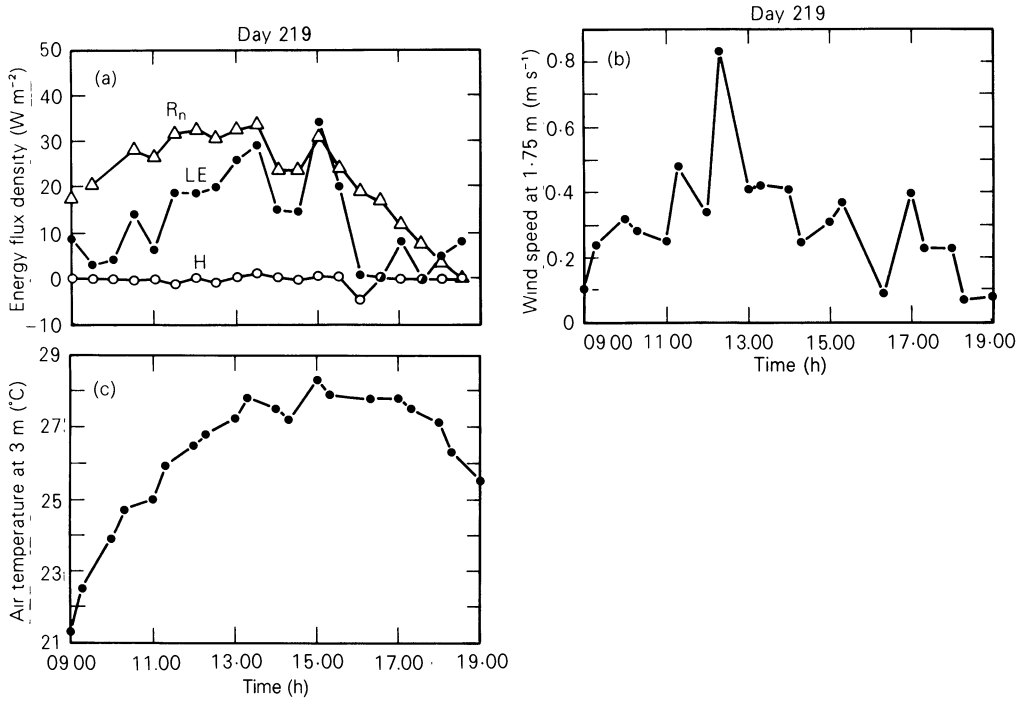

FIG. 1. Diurnal variation of environmental variables measured near the floor of an oak–hickory forest. Data are from day 219. (a) Net radiation (R_n), sensible heat (H) and latent heat (LE) flux. (b) Wind speed. (c) Air temperature at 3 m.

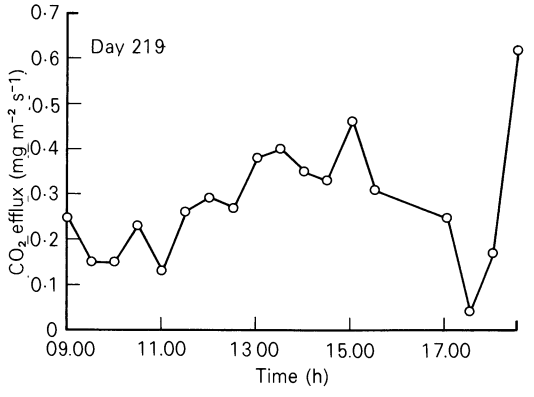

FIG. 2. Typical diurnal variation in CO_2 efflux from the floor of an oak–hickory forest. Data are from day 219.

Reported maximum summertime CO_2 effluxes from the floor of temperate deciduous forests are on the order of 0·2–0·3 mg m^{-2} s^{-1} (Reiners 1968; Witkamp 1969; Edwards & Sollins 1973; Garrett & Cox 1973; Edwards 1975; Garrett, Cox & Roberts 1978). These values are somewhat smaller than our measurements made with the eddy-correlation technique. Smaller values of CO_2 efflux may be observed with chamber techniques either because the chambers can dampen the influence of pressure fluctuations or suppress CO_2 evolution (Kanemasu, Powers & Sij 1974).

The diurnal pattern of CO_2 efflux agrees with the typical diurnal pattern assessed by Schlesinger (1977) in his review of CO_2 efflux from the soil of temperate deciduous forests. Edwards & Sollins (1973), on the other hand, observed that CO_2 efflux increases in the late afternoon. They attribute this response to the effects of convection at the soil surface. Edwards & McLaughlin (1978) report that an early evening respiratory burst occurs as a result of increased catabolism of the roots and boles. This is in response to the high availability of substrates, provided by daytime photosynthesis and translocation and is not correlated with temperature. This hypothesis is reasonable if appreciable substrate translocation can be maintained over long distances of the phloem over the course of a day (see Tyree, Christy & Ferrier 1974). Further study of this process is needed.

The influence of temperature on CO_2 efflux

CO_2 efflux significantly increased with increasing within-canopy air temperature (Fig. 3) and is in agreement with other observations in deciduous forests (Reiners 1968; Witkamp 1969; Edwards & Sollins 1973; Garrett & Cox 1973; Edwards 1975).

In spite of the dependency of CO_2 efflux on temperature, considerable scatter and several outliers are evident. A regression through the data, excluding the indicated outliers, yielded a coefficient of determination (r^2) of only 0·33, a small but significant value. Use of air temperature instead of litter or soil temperature may partly account for this low r^2 because differences in thermal properties of the air, soil and litter cause the diurnal course in the temperatures of these properties to differ in amplitude and phase (Rosenberg, Blad & Verma 1983), thus introducing scatter into the correlation between CO_2 efflux and temperature. Witkamp (1969) and Edwards & Sollins (1973) also hypothesize that temperature-related convection may influence CO_2 efflux. However, our observation of negligible sensible heat flux near the forest floor do not allow us to confidently conclude that convection contributed to the scatter in Fig. 3.

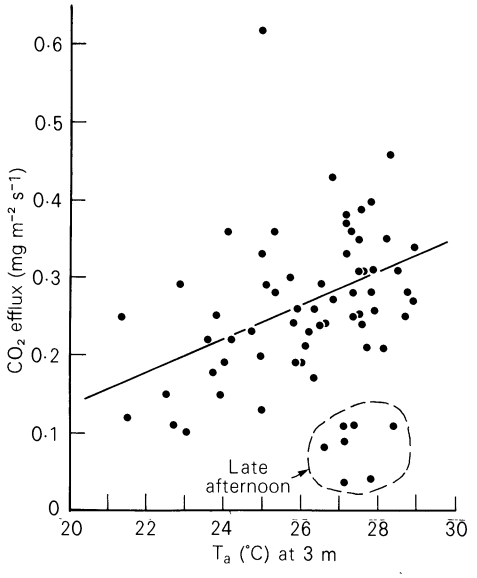

FIG. 3. Influence of air temperature on CO_2 efflux. The regression was computed with data obtained between 09.00 and 16.30 h on days 217, 218, 219, 221 and 222. The coefficient of determination is 0·33.

The indicated outliers in Fig. 3 occurred during late afternoon periods (after 16.30 h). Temporary afternoon water deficits in the roots and mycorrhizae may account for these observations because water deficits may cause a reduction in rates of respiration (Begg & Turner 1976). However, further work is needed before we can conclude with confidence the cause of the late afternoon reduction in CO_2 efflux.

Computations based on the regression in Fig. 3 yield a mean Q_{10} value of about 2·89. This value agrees well with the results of Edwards (1975), who reports that CO_2 efflux below a *Liriodendron tulipifera* canopy increases by a factor of about 2·78 as litter temperature increases from 15 to 25 °C. Edwards & McLaughlin (1978), however, report that nocturnal rates of CO_2 efflux from roots and boles are greater than daytime values, in spite of lower nocturnal temperatures. Consequently, estimates of 24-hour soil CO_2 exchange should not be made on the basis of Q_{10} relationships.

The influence of wind speed on CO_2 efflux

Our data show no direct influence of wind speed (u) on CO_2 efflux (F_c) since r^2 was not significantly different from zero (Fig. 4). The relationship between F_c and u was not confounded by temperature effects. A multiple regression was computed with T_a and u as independent variables. The r^2 value increased from only 0·006 to 0·04, a value still not significantly different from zero. This lack of correlation is partly due to the low range of wind speeds encountered below the forest canopy (Fig. 1b). The relationship between soil-atmosphere gas exchange and wind speed reported by Kimball & Lemon (1971) were based on wind speed data between zero and 4 m s^{-1}. Soil type can also affect the relationship between wind speed and soil–atmosphere gas exchange. Kimball & Lemon (1971) report that gas exchange from coarse soils is highly dependent on wind speed. However, they found no correlation between soil–atmosphere gas exchange and wind speed for soils comprised of small particle size (e.g. loams). The soil at the experimental site is a Fullerton cherty loam, a soil comprised of relatively fine particles, and is covered by litter.

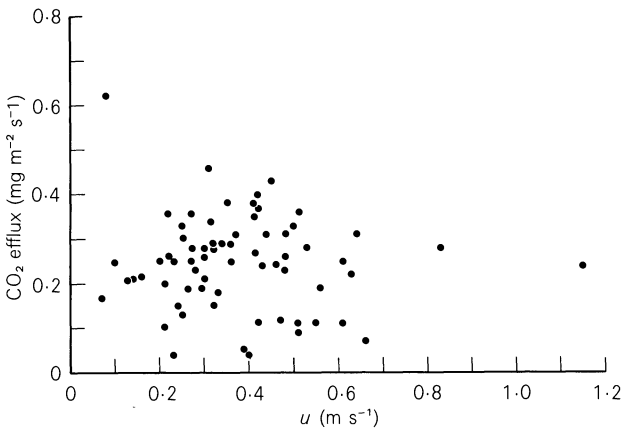

FIG. 4. Influence of wind speed on CO_2 efflux. The coefficient of determination is 0·006. Data are from days 217, 218, 219, 221 and 222.

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