

EDDY FLUXES OF CO₂, WATER VAPOR, AND SENSIBLE HEAT OVER A DECIDUOUS FOREST*

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Abstract. Fluxes of CO₂, latent heat and sensible heat were measured above a fully-leaved deciduous forest in eastern Tennessee with the eddy correlation technique. These are among the first reported observations over such a surface. The influences of solar radiation, vapor pressure deficit and the aerodynamic and canopy resistances on these mass and energy exchanges are examined. Following a concept introduced by McNaughton and Jarvis (1983), examination of our data suggest that the water vapor exchange of a deciduous forest is not as strongly coupled with net radiation as is that of agricultural crops. The degree of decoupling is smaller than in the case of a coniferous forest. This difference may be attributable in part to the greater aerodynamic resistance to water vapor transfer in a deciduous forest. It appears that the concept of decoupling may be extended to the CO₂ exchange of a deciduous forest as well.

1. Introduction

Many micrometeorological investigations of CO₂ and water vapor exchange have been conducted over the past twenty years. Most studies have been performed over agricultural crops such as barley, corn, wheat, alfalfa and soybeans (e.g., Biscoe *et al.*, 1975; Denmead, 1976; Uchijima, 1976; Baldocchi *et al.*, 1981a, b; Anderson *et al.*, 1984). There have been fewer studies over forest canopies. Prior forest micrometeorological work has concentrated primarily on coniferous species (e.g., Baumgartner, 1969; Denmead, 1969; Jarvis *et al.*, 1976), eucalyptus (Leuning and Attiwill, 1978) and tropical rain forests (Allen and Lemon, 1976). Mid-latitude broadleaf temperate and mixed wood forests constitute over 3% of the earth's land area (Olson *et al.*, 1978). Yet to our knowledge only Droppo and Hamilton (1973) and Rauner (1976) have reported water vapor flux measurements over such a community. No measurements of canopy CO₂ exchange for fully-leaved temperate deciduous forests are reported in the literature.

Measurements of CO₂ and water vapor exchange over temperate deciduous forests are needed to provide information for studies of global-climate and carbon-balance modelling, hydrology, dry deposition of atmospheric pollutants, and ecophysiology. In view of this need, a cooperative experiment was undertaken by the University of Nebraska's Center for Agricultural Meteorology and Climatology and the National Oceanic and Atmospheric Administration's Atmospheric Turbulence and Diffusion Division in Oak Ridge, Tennessee. Rapid response measurements of velocity, tempera-

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ture, humidity, and CO_2 density were made over a fully-leaved deciduous forest canopy. Mass and energy fluxes were computed using the eddy correlation technique. CO_2 density measurements were made with a fast-response sensor developed and built at the Lawrence Livermore National Laboratory (Bingham *et al.*, 1978). The results of this study are presented below. Mass and energy exchange characteristics of forests and agricultural crops are also contrasted.

2. Materials and Methods

2.1. EXPERIMENTAL DETAILS

Data were collected during July–August, 1984 at the Atmospheric Turbulence and Diffusion Division's Forest Meteorology research site, located on the U.S. Department of Energy's Reservation near Oak Ridge, Tennessee (lat. $35^\circ 57' 30''$ N; long. $84^\circ 17' 15''$ W; 365 m above m.s.l.). The experimental site is on a ridge in moderately complex terrain (Figure 1). Predominant winds during the observation period were from the southwest.

The site is forested by an uneven-aged stand of oak and hickory (*Quercus* and *Carya* sp.) extending for several kilometers in all directions, with only small inclusions of

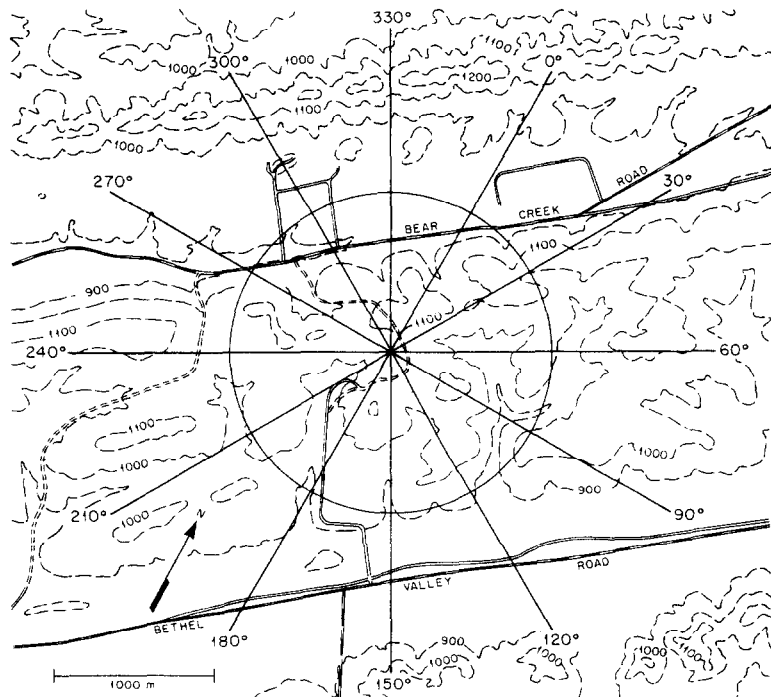


Fig. 1. Topographic map of the NOAA-ATDD Forest Meteorology research site and surrounding area. Compass directions radiate from the instrument tower location.

loblolly pine. The average height of the canopy is 22 m but because of the uneven age structure and mixed species composition of the stand, crown heights range between 17 and 26 m. The leaf area index (LAI) and silhouette woody biomass index (WBI) are about 4.9 and 0.6, respectively. Further details on the architectural characteristics of this canopy are presented in Hutchison *et al.* (1985). During the experimental period, the stand was not short of water since precipitation prior to and during the experimental period was appreciable.

Flux measurements were made with eddy correlation instruments mounted at a height of 28 m above the ground. The instrument array included a three-dimensional sonic anemometer (Applied Technology, Boulder, CO)*, a one-dimensional sonic anemometer and a fine-wire thermocouple (Campbell Scientific, Logan, Utah), a Lyman-alpha hygrometer (Buck, 1976; Redford *et al.*, 1980) with a 5.4 mm path length and a rapid-response CO₂ sensor with a 0.2 m path length (Bingham *et al.*, 1978; Anderson *et al.*, 1984). The instrumentation was oriented toward the SSE (165 deg). Using the one-dimensional (W) sonic anemometer (located at 28 m height) as a reference, the distances to the thermocouple, the hygrometer, and the CO₂ sensor were 0.1, 0.5, and 0.8 m, respectively. The three-dimensional sonic anemometer was located about 1.5 m above the one-dimensional sonic anemometer and was used primarily for computation of momentum transfer. A data acquisition system consisting of an IBM PC-XT, amplifiers and an analog-to-digital converter was used to record turbulence signals. Turbulence signals were low-pass filtered with 8-pole Butterworth active filters (12.5 Hz cutoff frequency) and recorded at 25 Hz. The eddy fluxes were averaged over 45-min periods.

The one-dimensional sonic anemometer was calibrated in a pusher-type wind tunnel. Theoretical calibrations were assumed for the three-dimensional sonic anemometer. The manufacturer's calibration was used for the fine-wire thermocouple. The Lyman-alpha hygrometer was calibrated in a thermally-static chamber consisting of a humidity generator system, a dew point hygrometer and a thermocouple. The CO₂ sensor was calibrated in the field two or three times every day. A hood was placed over the sensor's open cell and purged with a dry gas mixture of known CO₂ concentration. The CO₂ standard gases were calibrated by the Air Resources Laboratory (Geophysical Monitoring for Climatic Change) of NOAA in Boulder, Colorado. Pressure and temperature within the hood were also recorded during calibration to determine CO₂ density. During the entire study period, the slope and intercept of the calibration generally stayed within 5%, indicating a high degree of stability.

During most of the experiment, two sonic anemometers were available to measure vertical velocity. Values of the covariance between fluctuations in vertical velocity (w') and CO₂ density (c') from the two vertical velocity sensors are presented in Figure 2(a). Except for a few outliers, the values generally agreed within about 5%.

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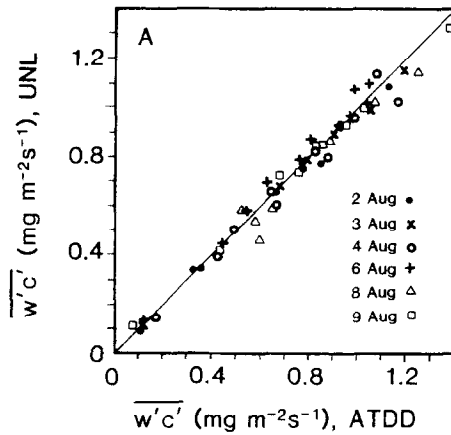


Fig. 2(a). A comparison of $\overline{w'c'}$ values. CO₂ density was measured with the UNL CO₂ sensor. Vertical velocity was measured with two sonic anemometers (UNL one-dimensional anemometer and ATDD three-dimensional anemometer). The ATDD anemometer was located about 1.5 m above the UNL anemometer. The CO₂ sensor (UNL) was located 0.8 and 1.5 m from the UNL and ATDD anemometers, respectively. Deciduous forest, Oak Ridge, TN.

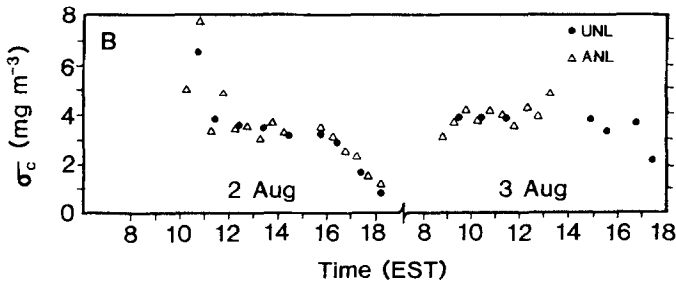


Fig. 2(b). Comparison of standard deviations of CO₂ fluctuations (σ_c) measured by the UNL and ANL sensors. Deciduous forest, Oak Ridge, TN.

During a brief period, another rapid response CO₂ sensor (also built by the Lawrence Livermore National Laboratory for Argonne National Laboratory)* was available. The ANL CO₂ sensor was located about 1.0 m above the UNL CO₂ sensor. Values** of standard deviations of CO₂ fluctuations measured by the two sensors are compared in Figure 2(b). The agreement is good, generally within 10%.

Global shortwave (R_g), diffuse shortwave (R_d), and net (R_n) radiation were measured above the canopy with a system described by Baldocchi *et al.* (1984). Air temperature and humidity were measured at several levels above and within the canopy with

* On loan from Dr M. L. Wesely of Argonne National Laboratory.

** Signals from the two CO₂ sensors were recorded on different data acquisition systems (UNL and ATDD). The averaging time on the UNL data system was 45 min and that on the ATDD data system was 30 min.

thermistors and lithium–chloride dew cells, respectively. These data were sampled and recorded three times per minute with a Campbell Scientific CR-7 data logger and were averaged over 30 min periods.

2.2. THEORETICAL CONSIDERATIONS

Covariances and variances were computed in real-time using a running-mean removal technique. The time constant of this digital filter was about 400 s (for further details on such computations, see Dyer *et al.*, 1967; Kanemasu *et al.*, 1979; and McMillen, 1983).

Webb *et al.* (1980) have shown that variations in air density as a result of simultaneous transfer of latent and sensible heat can appreciably affect flux measurements of atmospheric constituents in low absolute concentration such as CO₂. Thus, CO₂ fluxes were corrected by reference to the concurrent fluxes of water vapor and sensible heat, following a method described in Webb *et al.* (1980).

Soil heat flux (S) was assumed to equal the flux density of net radiation at the forest floor. This was estimated using the relationship reported by Baldocchi *et al.* (1984):

$$S = 0.036R_n. \quad (1)$$

The canopy heat storage term (G) can be expressed as (Jarvis *et al.*, 1976):

$$G = \int_0^z \left(\rho C_p \frac{\partial T_a}{\partial t} \right) dz + \int_0^z \left(m C_w \frac{\partial T}{\partial t} \right) dz + \int_0^z \left(L \frac{\partial \rho_v}{\partial t} \right) dz, \quad (2a)$$

where $\partial T/\partial t$, $\partial T_a/\partial t$, and $\partial \rho_v/\partial t$ are the time rates of change in canopy temperature, air temperature and absolute humidity; ρ is the air density, C_p is the specific heat of air at constant pressure, m is mass of wood per unit canopy volume, C_w is the specific heat of wood, and L is the latent heat of vaporization of water. The first two terms in Equation (2a) represent the temporal changes in sensible heat in the air and in the trees, respectively. The third term represents the temporal change in latent heat in the air. Using appropriate values for air and biomass densities and thermal properties and integrating the right-hand terms between 0 and 28 m, Equation (2a) reduces to:

$$G = 19.2 \frac{\partial T_a}{\partial t} + 86.6 \frac{\partial T}{\partial t} + 17.6 \frac{\partial \rho_v}{\partial t}. \quad (2b)$$

Air temperature measured at 28 m was used for T_a . Absolute humidity measured at 14 m was used for ρ_v . The term $\partial T/\partial t$ was assumed to be equal to the time rate of change of air temperature within canopy, measured at 14 m (below crown closure). A similar assumption was made in the earlier work of Thom (1975).

Aerodynamic resistance (r_{av}) to water vapor transfer was computed using the following equation (see e.g., Stewart and Thom, 1973):

$$r_{av} = \left(\frac{\phi_v}{\phi_m} \right) \left(\frac{\bar{U}}{u_*^2} \right) + r_{bv}, \quad (3)$$

where \bar{U} is the mean wind speed and u_* is the friction velocity. The factor (ϕ_v/ϕ_m) allows for the non-similarity of the diabatic influence on vertical fluxes of water vapor and momentum and was approximated by the relationships* developed by Dyer and Hicks (1970) and Webb (1970). The 'excess resistance' term, r_{bv} , arises from the consideration that the transfer of water vapor from a rough vegetated surface encounters greater aerodynamic resistance than does the transfer of momentum (see Owen and Thomson, 1963; Chamberlain, 1966; Thom, 1972, for further details). This term was approximated by:

$$r_{bv} = \frac{B^{-1}}{u_*} = \left(\frac{2}{ku_*} \right) \left(\frac{\kappa}{D_v} \right)^{2/3} \quad (4)$$

where B^{-1} is a dimensionless surface transfer function, k is von Karman's constant, κ is the thermal diffusivity, and D_v is the molecular diffusivity of water vapor. Following Garratt and Hicks (1973), Wesely and Hicks (1977), and Wesely *et al.* (1978), kB^{-1} was assumed to be equal to $2(\kappa/D_v)^{2/3}$. The factor $(\kappa/D_v)^{2/3}$ was incorporated to account for the differences in molecular diffusivities of water vapor and heat.

Canopy resistance (r_c) was computed by employing the computed values of r_{av} and measured values of R_n , latent heat flux (LE), air temperature and vapor pressure deficit in the Penman-Monteith equation (Monteith, 1965).

3. Results and Discussion

3.1. ENERGY FLUXES

3.1.1. Energy Budget Closure Considerations

The energy balance over a forest can be approximated by:

$$R_n = LE + H + S + G. \quad (5)$$

Ideally* the sum of sensible and latent heat fluxes, $(H + LE)$, should be balanced by $(R_n - S - G)$. The data plotted in Figure 3 exhibit considerable scatter, on the order of $\pm 30\%$ around the 1 : 1 line. Errors in the measurement of LE , H , R_n , and S can account for variability of about $\pm 20\%$. Variability exceeding this value is probably due to the following two factors. First, estimating the canopy storage term, G , with the method described above is subject to large errors and uncertainties. In a forest canopy, G is strongly dependent on the temporal change in canopy biomass temperature. Temporal

* We realize that the applicability of such stability corrections over forests has been questioned in some recent studies (e.g., Thom *et al.*, 1975; Raupach and Legg, 1984). The effect on our computed canopy resistance values, however, should be rather small.

* As shown in the next section, the energy used in photosynthesis was around 1.5 to 3.5% of the net radiation during most of the day and consequently was ignored here.

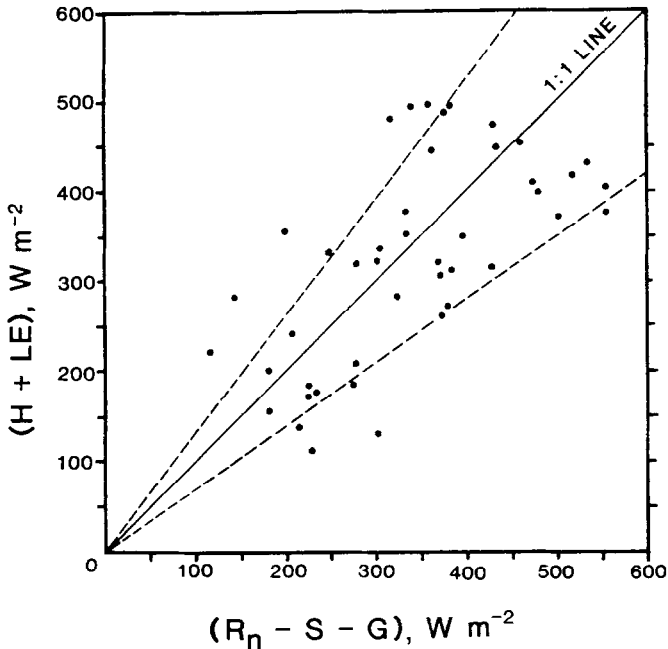


Fig. 3. Balance of energy budget terms. LE and H were measured by eddy correlation. R_n was measured with a net radiometer. S and G were estimated by Equations (1) and (2). Dashed lines represent $\pm 30\%$ around the 1 : 1 line. Deciduous forest, Oak Ridge, TN.

changes in canopy air temperature may not always reflect the temporal change in canopy biomass temperature because of differences in thermal inertia. McCaughey (1985a), for example, shows that in a dry, mixed-forest, the temporal change in biomass temperature underestimates the temporal change in air temperature within the canopy by about 1 to 2 °C in the morning and overestimates it by about 1 °C in the late afternoon and evening. Agreement between these two variables is reasonable several hours after noon. The second factor affecting energy balance closure is the influence of complex terrain on the upwind net radiation regime. Different slopes and aspects receive and partition different amounts of solar radiation (see Nunez, 1980). Consequently, the net radiation balance measured on the horizontal may differ from that incident on the upwind slopes. A discussion of the influence of wind direction and upwind fetch on energy balance closure at this site is also presented in Baldocchi *et al.* (1985a).

3.1.2. Diurnal Patterns of Energy Fluxes

Diurnal patterns of the fluxes of sensible heat (H), latent heat (LE), and net radiation (R_n) measured on six days in early August are shown in Figure 4. Information on pertinent conditions is provided in Figure 5.

Maximal values of H ranged from about 150 to 200 $W m^{-2}$. The peak values of LE were about 300 to 350 $W m^{-2}$. On several days the greatest evapotranspiration rates occurred between the period 14 : 00–15 : 00 EST. Values of LE are plotted as a function

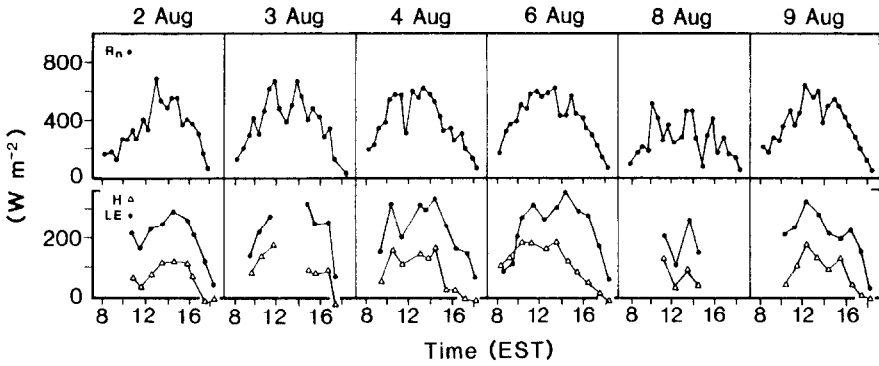


Fig. 4. Diurnal patterns of R_n , H , and LE over a deciduous forest, Oak Ridge, TN.

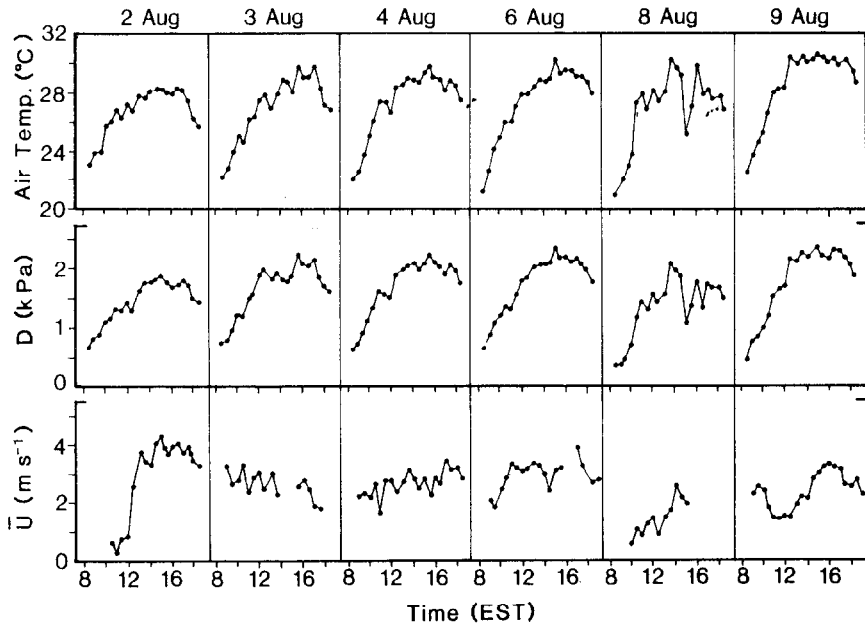


Fig. 5. Air temperature, vapor pressure deficit and mean horizontal wind speed measured at 29 m above the floor of a deciduous forest, Oak Ridge, TN.

of R_n and vapor pressure deficit (D) in Figure 6(a). This figure seems to indicate some dependence of LE on both R_n and D . The ratio LE/R_n increases from about 0.25 to 0.9 as D increases from near zero to 2.0 kPa (Figure 6(b)). These values fall within the range of values reported by McNaughton and Jarvis (1983) for forest canopies and Rauner (1976) for a linden-oak forest in the Soviet Union.

The coupling between LE and R_n for a deciduous forest is very different from that often observed over agricultural crops. Latent heat exchange in agricultural crops is

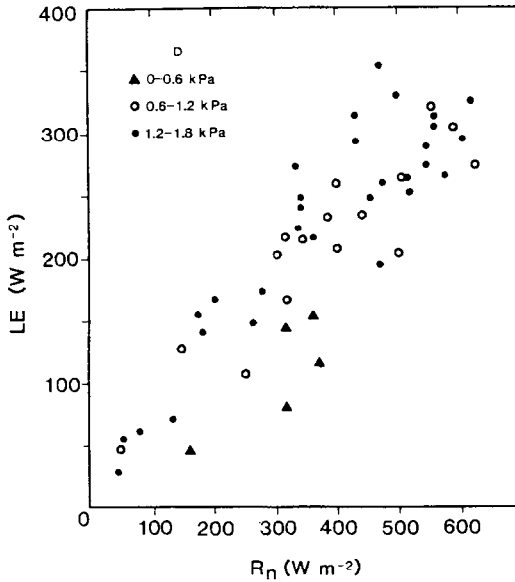


Fig. 6(a). Latent heat flux (LE) in relation to net radiation (R_n) and vapor pressure deficit (D). Deciduous forest, Oak Ridge, TN.

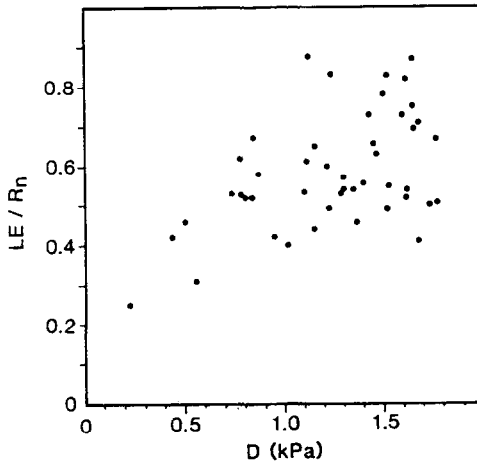


Fig. 6(b). LE/R_n as a function of vapor pressure deficit (D). Deciduous forest, Oak Ridge, TN.

highly correlated with R_n . For well-watered soybeans, sugar beets, rice, and corn crops, the ratio LE/R_n has been found to range between 0.8 and 1.2 (Brown, 1976; Uchijima, 1976; Baldocchi *et al.*, 1985b). Jarvis (1985), however, points out the limitations of such a correlative approach since D is often significantly correlated with the net radiation and suggests examination of the 'Omega factor' instead (see below).

3.1.3. Aerodynamic and Canopy Resistances, the Omega Factor

Values of the aerodynamic resistance (r_{av}) to water vapor transfer are shown in Figure 7(a). Relatively high values, ranging from 50 to 60 s m^{-1} , were observed during early morning and late afternoon periods, when wind speeds were low. On most days the value of r_{av} tended to be fairly constant, from 15 to 22 s m^{-1} between 10:00 to 16:00 EST. Higher values were observed on two days (August 8 and 9) when the wind speed was quite low. Over a Douglas fir forest canopy, McNaughton and Black (1973) reported daytime values of the aerodynamic resistance to momentum transfer ranging between 5 and 8 s m^{-1} . Shuttleworth *et al.* (1984) observed aerodynamic resistance to momentum transfer over an Amazonian forest to range from 10 to 20 s m^{-1} when wind speed (measured at 45 m, canopy height ≈ 35 m) exceeded 1.5 m s^{-1} . Murphy *et al.* (1981) measured r_{av} over a loblolly pine plantation in the Southeastern United States and reported values between about 5 and 40 s m^{-1} .

Our values of r_{av} are higher than many values reported over coniferous forests for several reasons. First, prevailing wind speeds were light to moderate (2 to 3 m s^{-1}).

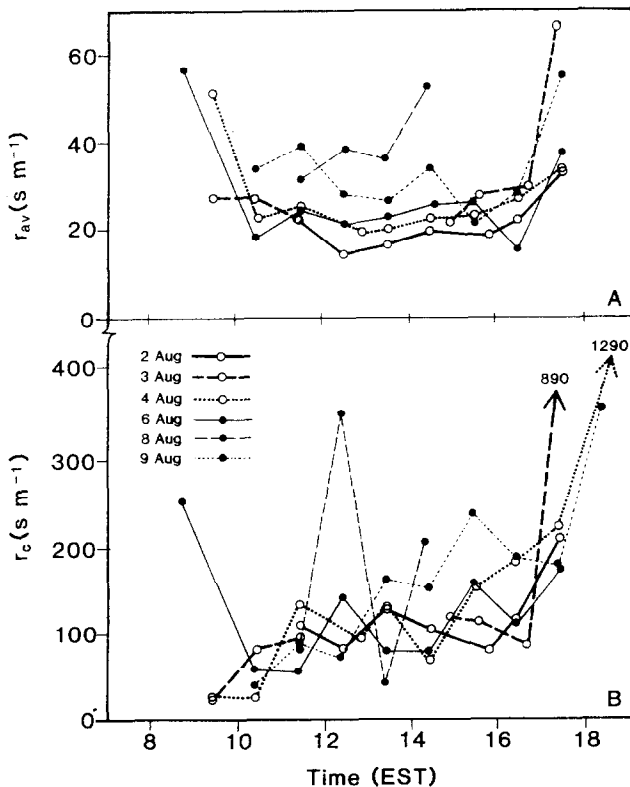


Fig. 7(a). Diurnal patterns of aerodynamic resistance to water vapor transfer, r_{av} . Deciduous forest, Oak Ridge, TN.

Fig. 7(b). Diurnal patterns of canopy resistance, r_c . Deciduous forest, Oak Ridge, TN.

Second, a deciduous forest is not as aerodynamically rough as a coniferous forest (the drag coefficient, $C_d = u_*^2/\bar{U}^2$ of this canopy is about 0.016 as compared to 0.04 to 0.16 reported by Jarvis *et al.* (1976) for coniferous canopies). Third, we include the 'excess resistance' term which is of the order of 5 to 15 s m⁻¹ during midday periods in our computation of r_{av} .

Canopy resistance (r_c) values are plotted in Figure 7(b). During early evening hours (17 : 00–18 : 00 hr), the canopy resistance was high in association with the low quantum flux densities, which result in stomatal closure. Very low values (less than 50 s m⁻¹) were observed during several mornings (August 3, 4, and 9). These low resistances are due to the canopy being wet because of heavy dewfall or rain during the previous night. Except on August 8, which was dominated by intermittent cloudiness, the midday values of canopy resistance ranged between 75 and 160 s m⁻¹. After mid-morning, r_c generally tended to increase with the time of day, reaching very high values during late afternoon. Canopy resistance of this forest increases in the afternoon, primarily in response to increasing D which has a 'feedback influence' on stomatal closure (see Jarvis, 1981; Murphy *et al.*, 1981; McNaughton and Jarvis, 1983) and to temporary water deficit (Hinckley *et al.*, 1978). The diurnal pattern and magnitudes of r_c , reported here, are similar to those observed over Douglas fir (McNaughton and Black, 1973), loblolly pine (Murphy *et al.*, 1981), and over an Amazonian forest (Shuttleworth *et al.*, 1984).

McNaughton and Jarvis (1983) and Jarvis (1985) introduced the concept of coupling between the canopy and the atmosphere in terms of the Omega factor, given by:

$$\Omega_c = (s/\gamma + 1)/(s/\gamma + 1 + r_c/r_{av}), \quad (6)$$

where s is the slope of the temperature-dependent saturation vapor pressure curve and γ is the psychrometric constant. The term Ω_c is a dimensionless factor with values between zero and one. McNaughton and Jarvis (1983) and Jarvis (1985) suggest Omega values of about 0.1 and 0.2 for forests and about 0.8 for grasslands. Based on their analysis, transpiration from trees (small Omega) is expected to follow closely the vapor pressure deficit of the ambient air-stream and to be controlled sensitively by canopy resistance. Transpiration from grasslands and agricultural crops, on the other hand (Omega close to one), is expected to follow net radiation closely and to be relatively insensitive to small changes in canopy resistance.

Midday values of Ω_c , over the deciduous forest studied here, were generally around 0.35 to 0.65. These values are somewhat higher than those suggested by McNaughton and Jarvis (1983) and Jarvis (1985). This difference is due, at least in part, to the higher aerodynamic resistances observed in this study. If the aerodynamic resistances to momentum and water vapor transfer are assumed identical (i.e., bluff body effects are neglected), midday Omega values of about 0.2 to 0.35 would result from our data.

3.1.4. The Bowen Ratio

Partitioning of the available energy is generally represented in terms of the Bowen ratio ($\beta = H/LE$). Values of β from this study are plotted in Figure 8. On one day (August 6), relatively high values of the Bowen ratio (about 1.1 to 1.2) were observed during the early

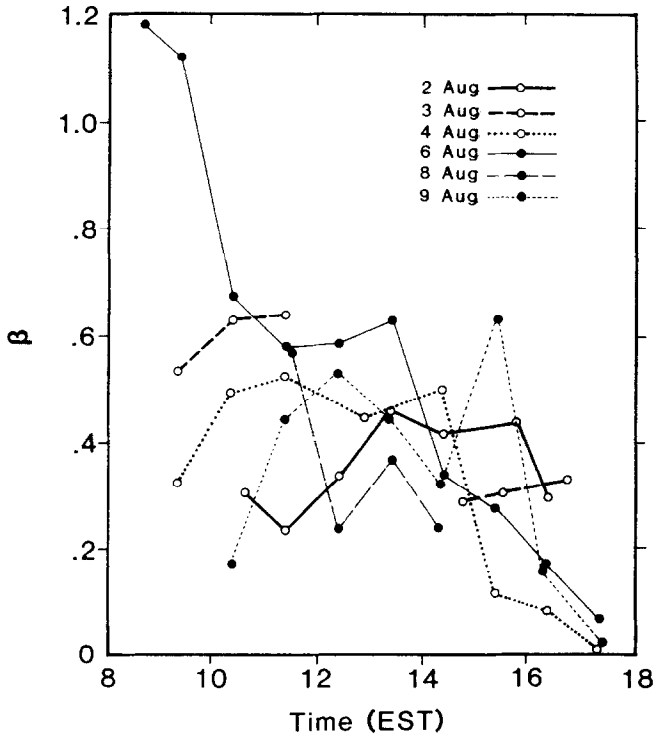


Fig. 8. Diurnal patterns of the Bowen ratio (β). Deciduous forest, Oak Ridge, TN.

morning (08 : 00–09 : 00 hr). On August 3, 4 and 9, the Bowen ratio was low in the early morning and increased as the day approached noon. This response reflects the drying of a wet canopy from the previous night's dew or rainfall and is consistent with other results in the literature (see e.g., McNaughton and Jarvis, 1983). During the period 11 : 00–15 : 00 hr on most days, values of the Bowen ratio generally ranged from about 0.25 to 0.65. Later in the day, β became much smaller and changed sign when the sensible heat flux was directed toward the surface.

Day-to-day variation in midday values of β can also be seen in Figure 8. For example, during the 12 : 00–13 : 00 hr period, β was between 0.58 to 0.62 on August 6 and was relatively lower (between 0.23 and 0.36) on August 8. Intermediate values ($\beta \approx 0.33$ to 0.45) were observed on August 2. These differences in β can be explained in terms of concurrently measured meteorological variables. Examination on Figures 4, 5, and 8 shows that greater values of β were associated with greater R_n and D .

Similar midday values of β have been observed over a forest at Marmot Creek in Alberta, Canada (Storr *et al.*, 1970), over a Southeastern loblolly pine plantation (Murphy *et al.*, 1981) and over an Amazonian forest (Shuttleworth *et al.*, 1984). Black and McNaughton (1971) and McCaughey (1985b) report somewhat higher midday values of β (~ 0.8 to 1.2) over a Douglas fir forest in British Columbia and a mixed forest

in Ontario, respectively. Substantially higher values of β (1 to 4) have been observed at Thetford over *Pinus sylvestris* (Stewart and Thom, 1973) and at Fetteresso over *Picea sitchensis* in the U.K. (Jarvis *et al.*, 1976). Jarvis *et al.* (1976) and Jarvis (1981) explain these large Bowen ratios in terms of a 'climatological resistance' (r_i). The climatological resistance (introduced by Monteith, 1965; and Stewart and Thom, 1973) is defined as:

$$r_i = \frac{\rho C_p (D)}{\gamma A}, \quad (7)$$

where ρ is the air density, C_p is the specific heat of air at constant pressure, and A is the available energy ($A = R_n - S - G$). Employing r_i in the Penman-Monteith model for evaporation, they expressed the Bowen ratio as:

$$\beta = \frac{1 + r_c/r_{av} - r_i/r_{av}}{s/\gamma + r_i/r_{av}}. \quad (8)$$

Equation (8) clearly indicates that the partitioning of A depends not only on the aerodynamic and canopy resistances, but also on the general nature of the climate and weather as parameterized by r_i . Based on such an analysis, Jarvis *et al.* (1976) suggested that the very large values of β in the late afternoon at Thetford resulted from stomatal closure, whereas generally high values at Fetteresso were the result of small vapor pressure deficits due to the oceanic climate of the site.

As an example, let us consider midday conditions ($r_i \approx 50 \text{ s m}^{-1}$, $r_c \approx 100 \text{ s m}^{-1}$ and $r_{av} \approx 20 \text{ s m}^{-1}$) on a day like August 6 from this study. These values of r_i , r_c , and r_{av} , when incorporated in the model represented by Equation (3), would yield a value of $\beta \approx 0.6$. As indicated in the analysis of Jarvis *et al.* (1976), Bowen ratios less than one are expected over forests in continental climates, such as the site studied here.

3.2. CARBON DIOXIDE FLUX

3.2.1. Diurnal Patterns of CO₂ fluxes

CO₂ flux* (F_c) and solar radiation (R_g) measured on six days in early August are shown in Figure 9. On most days, F_c was about 0.4 to 0.5 mg m⁻² s⁻¹ by midmorning. The peak CO₂ flux ranged from about 0.7 to 0.9 mg m⁻² s⁻¹, and generally occurred between 12 : 00 to 14 : 00 EST. Later in the afternoon, F_c diminished rapidly in response to decreasing solar radiation, approaching about 0.1 mg m⁻² s⁻¹ around 18 : 00 EST.

No CO₂ flux measurements over other fully leafed temperate deciduous forests are available in the literature to provide a direct basis against which our measurements can be compared. Dougherty *et al.* (1979), however, report that, under optimal conditions, the maximum leaf photosynthetic rate of *Quercus alba* is of the order of 0.4 mg s⁻¹ per m² of leaf area. Based on their data, our CO₂ flux measurements seem reasonable since canopy photosynthesis (expressed on a per ground area basis) in forest species can,

* CO₂ fluxes are reported on a per ground area basis.

theoretically, be on the order of two to three times the leaf photosynthesis (expressed on a per leaf area basis) (Horn, 1971).

There does exist a body of literature on CO_2 fluxes for coniferous forest canopies. These values are on the order of 0.5 to $1.3 \text{ mg m}^{-2} \text{ s}^{-1}$ (see Baumgartner, 1969; and Jarvis *et al.*, 1976 for details). Recent observations of Denmead *et al.* (1983) over *Pinus ponderosa* in Ubriarra forest in Australia indicate a range of F_c from 0.4 to $1.2 \text{ mg m}^{-2} \text{ s}^{-1}$, corresponding to net radiation ranging from 400 to 600 W m^{-2} . Alvo *et al.* (1984) reported aircraft measurements of CO_2 exchange over a mixed surface of shrubs, reforested pine and clearings near Ottawa, Canada. Mean values during 14 : 00 to 16 : 35 hr (local time) ranged from 0.22 to $0.39 \text{ mg m}^{-2} \text{ s}^{-1}$.

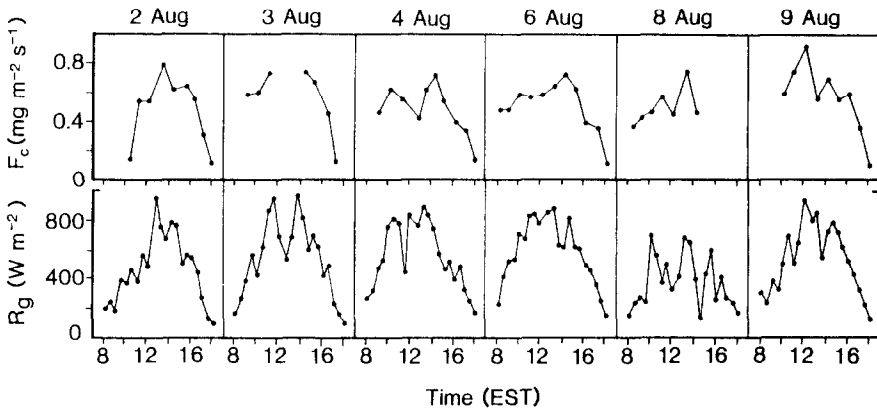


Fig. 9. Diurnal patterns of CO_2 flux (F_c) and solar radiation (R_g) over a deciduous forest, Oak Ridge, TN.

The CO_2 fluxes shown in Figure 9 are smaller than values measured over agricultural crops. Peak CO_2 flux values over crops such as alfalfa, wheat and soybeans, under similar environmental conditions, are of the order of 1.0 to $2.0 \text{ mg m}^{-2} \text{ s}^{-1}$ (Denmead, 1976; Baldocchi *et al.*, 1981a, b; Anderson *et al.*, 1984). Higher canopy resistance values observed over this deciduous forest partially explain the lower CO_2 flux rates (see Jarvis, 1981). The difference in leaf area is not a factor here since the leaf area index of this forest is larger than that of the previously mentioned agricultural crop canopies.

3.2.2. F_c -light Response

CO_2 fluxes from the entire study period are plotted against solar radiation in Figure 10. Data in this figure are distinguished for different ranges of vapor pressure deficit. Although considerable scatter is evident, the CO_2 flux increased with solar radiation in a curvilinear manner. Figure 10 also shows that the deciduous forest canopy did not exhibit canopy light-saturation. Similar observations have been made over alfalfa (Baldocchi *et al.*, 1981a), soybeans (Baldocchi *et al.*, 1981b; Anderson *et al.*, 1984), *Pinus ponderosa* (Denmead *et al.*, 1983) and rice (Ohtaki, 1984). Often in non-planophile

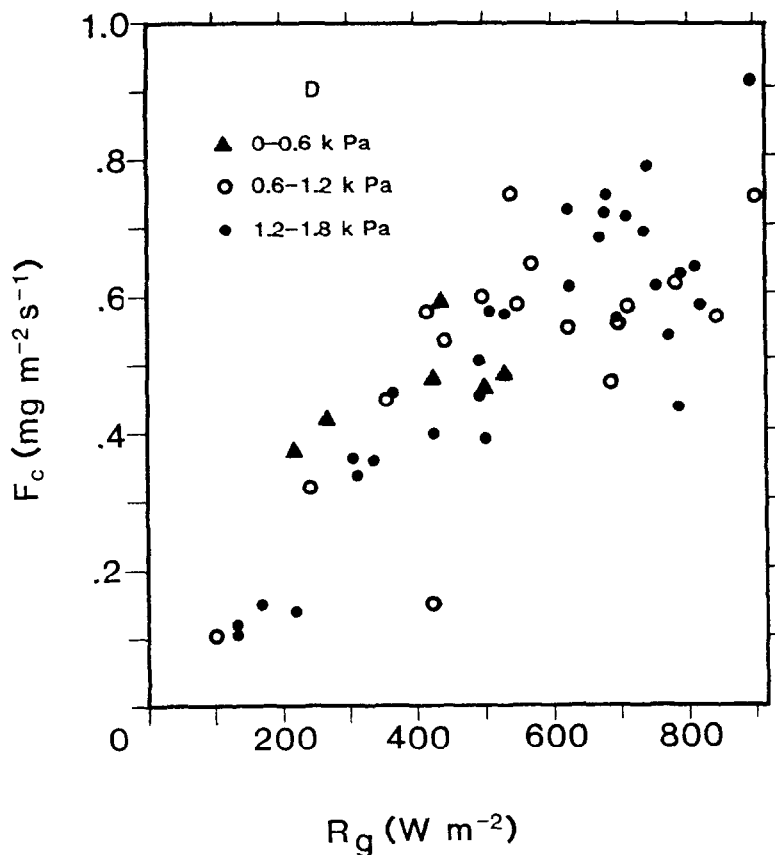


Fig. 10. CO₂ flux (F_c) in relation to solar radiation (R_g) and vapor pressure deficit (D). Deciduous forest, Oak Ridge, TN.

canopies, such as this forest, light saturation does not occur since light penetration increases with solar elevation. Consequently, more light is available to the lower light-unsaturated leaves during periods with high light levels.

Vapor pressure deficit, air temperature, turbulent mixing, and water stress have been reported to influence the F_c -light response curve for vegetated canopies (Baldocchi *et al.*, 1981a; Denmead, 1976; Jarvis *et al.*, 1981, 1985; Ohtaki, 1984). Variations in vapor pressure deficit (D) do not seem to account for the scatter in Figure 10, however. Air temperature and wind speed were generally moderate (see Figure 5) during the study period. The canopy was in a well watered state. Therefore, the scatter observed in Figure 10 cannot be attributed to the individual effects of air temperature, turbulent mixing or vapor pressure deficit. The combined effects of these variables may account for some of the scatter in this figure. Diurnal variations in r_c (Figure 7(b)) could also have contributed.

Jarvis (1985) extrapolates the 'Omega factor' hypothesis to canopy assimilation. He states that, in comparison to agricultural crops, CO₂ exchange in a forest should be

relatively decoupled with solar radiation and strongly coupled to canopy conductance. Agricultural crops, on the other hand, should be strongly coupled to solar radiation. This hypothesis can be tested by comparing the slope ($\partial F_c / \partial R_g$) of the light response curve in Figure 10 against data from well-watered soybeans (Baldocchi *et al.*, 1981b). Figure 10 shows that under light levels exceeding values for stomatal closure (e.g., for $R_g > 100 \text{ W m}^{-2}$), $\partial F_c / \partial R_g$ is about $2.0 \mu\text{g m}^{-2} \text{ s}^{-1} (\text{W m}^{-2})^{-1}$. In comparison, the value of ($\partial F_c / \partial R_g$) for soybeans is about $1.0 \mu\text{g m}^{-2} \text{ s}^{-1} (\text{W m}^{-2})^{-1}$. While CO_2 uptake is a light-driven process, these results suggest a somewhat weaker coupling of this process with solar radiation in this deciduous forest.

3.2.3. Photosynthetic Efficiency

The efficiency of conversion of solar energy in photosynthesis can be expressed in terms either of $\mu F_c / R_n$ or $\mu F_c / R_g$. The term μ is the energy equivalent of photosynthesis. A value of 16.7 kJ g^{-1} cited by Rauner (1976) for forest vegetation has been used here. The efficiencies $\mu F_c / R_n$ and $\mu F_c / R_g$ are plotted in Figure 11. Except for early and late afternoon hours, $\mu F_c / R_n$ was generally around 1.5 to 3.5% on most days. Denmead (1969) found a range* of 2.5 to 5.8% over *Pinus radiata* near Canberra, Australia. When expressed in terms of solar irradiance, the photosynthetic efficiency ($\mu F_c / R_g$) varied from about 1.0 to 2.3% over the midday period (Figure 11). Denmead (1969) found a mean value of $\mu F_c / R_g$ of 2.5% over *Pinus radiata*. Lemon (1967) reported that $\mu F_c / R_g$ approached 5% in C_4 species, such as corn.

In estimating latent heat flux (LE) using the Bowen ratio-energy balance method, it is often assumed that the energy fixed chemically in the process of photosynthesis is a

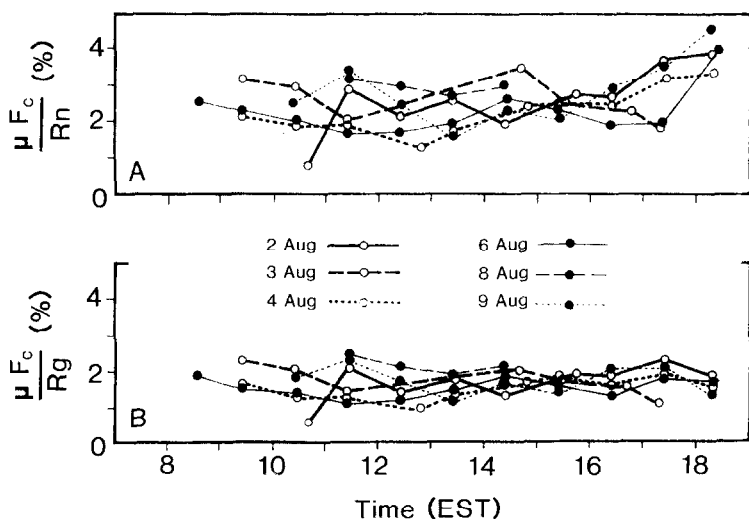


Fig. 11. Diurnal patterns of photosynthetic efficiency: (A) $\mu F_c / R_n$, (B) $\mu F_c / R_g$. Deciduous forest, Oak Ridge, TN.

* Denmead (1969) assumed that the fixation of 1 g of CO_2 in photosynthesis required 2500 calories, which translates to $\mu = 10.47 \text{ kJ g}^{-1}$.

negligible component of the overall energy balance. The results reported here indicate that ignoring the energy fixed in photosynthesis would lead to small errors.

3.2.4. Carbon Dioxide–Water Flux Ratio

The efficiency with which vegetation consumes water while photosynthesizing can be described in terms of water use efficiency, which is defined as photosynthetic fixation of CO₂ per unit of water transpired or, alternatively, by the CO₂–water vapor flux ratio (CWFR) defined as:

$$CWFR = F_c/E, \tag{9}$$

where E is the flux of water vapor ($\text{g m}^{-2} \text{s}^{-1}$). Diurnal patterns of CWFR for the six days studied are presented in Figure 12. Except on days with large variations in solar radiation, CWFR remains fairly steady (about 4 to 7 mg g^{-1}) from midmorning to late afternoon (10–17 hr). For alfalfa, soybeans, and grain sorghum grown in Nebraska under nonadvective conditions, CWFR values from about 7 to 12 mg g^{-1} have been reported (Baldocchi *et al.*, 1981a, b; and Anderson *et al.*, 1984; Anderson and Verma, 1985). These latter studies have also shown that CWFR decreases with increasing R_n under nonadvective conditions. Figure 13, on the other hand, shows that CWFR is relatively independent of R_n in a deciduous forest.

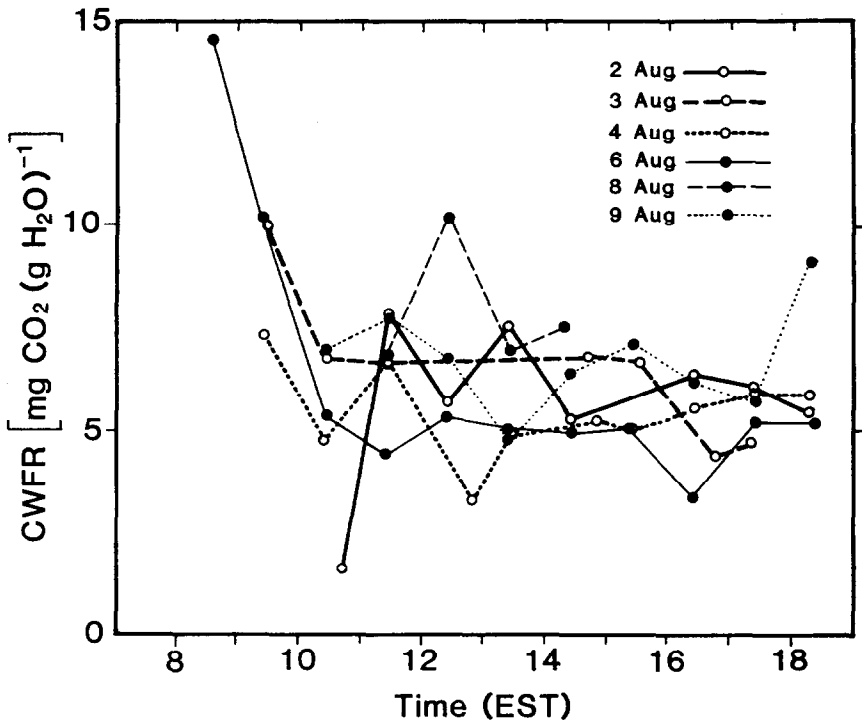


Fig. 12. Diurnal patterns of carbon dioxide-water flux ratio (CWFR) over a deciduous forest, Oak Ridge, TN.

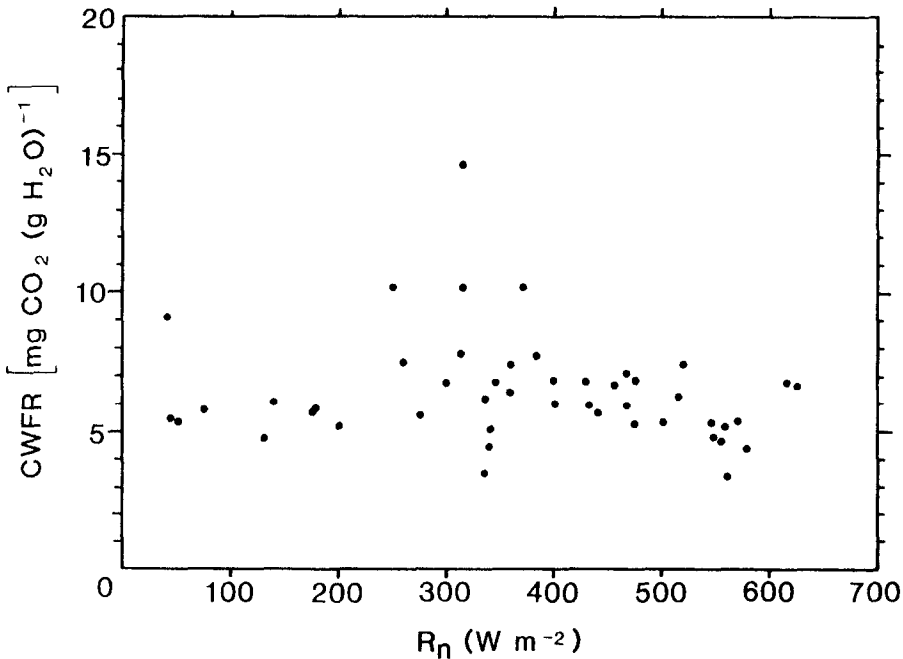


Fig. 13. Carbon dioxide-water flux ratio (CWFR) as a function of net radiation (R_n). Deciduous forest, Oak Ridge, TN.

4. Summary and Conclusions

Eddy correlation measurements were made of CO_2 , latent heat and sensible heat fluxes over a deciduous forest near Oak Ridge, TN. The instrument array included a rapid-response CO_2 sensor developed by the Lawrence Livermore National Laboratory. The forest had received plentiful precipitation prior to the study. Typically the midday magnitude of sensible heat flux was about $150\text{--}200 \text{ W m}^{-2}$, whereas the latent heat flux was about $300\text{--}350 \text{ W m}^{-2}$. The aerodynamic resistance to water vapor transfer was generally between $15\text{--}22 \text{ s m}^{-1}$ during midday. Midday values of canopy resistance ranged from 75 to 160 s m^{-1} .

CO_2 flux rates during midmorning were about 0.4 to $0.5 \text{ mg m}^{-2} \text{ s}^{-1}$. The peak CO_2 flux ranged from about 0.7 to $0.9 \text{ mg m}^{-2} \text{ s}^{-1}$. The midday carbon dioxide-water vapor flux ratio varied from 4 to $8 \text{ mg CO}_2 (\text{g H}_2\text{O})^{-1}$. Photosynthetic efficiency (expressed in terms of net radiation) was generally between 1.5 and 3.5% .

The Omega factor (Ω_c), a term introduced by McNaughton and Jarvis (1983), was evaluated. The value of Ω_c was generally between 0.35 and 0.65 . Results from this study suggest that latent heat and CO_2 exchanges of this deciduous forest are not as strongly coupled with the solar radiation receipts as are those of agricultural crops (e.g., soybeans).

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