CARBON DIOXIDE, WATER VAPOR AND SENSIBLE HEAT FLUXES OVER A TALLGRASS PRAIRIE*

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Abstract. Fluxes of CO_2, water vapor and sensible heat were measured in a grassland ecosystem near Manhattan, Kansas, employing the eddy correlation technique. The vegetation at this site is dominated by big bluestem (*Andropogon gerardii*), switchgrass (*Panicum virgatum*), and indiangrass (*Sorghastrum nutans*). Diurnal patterns of the energy budget components and CO_2 fluxes are evaluated on a few selected days. Influence of high atmospheric evaporative demand and low availability of soil water are examined on (a) energy partitioning, and (b) the magnitudes and patterns of atmospheric carbon dioxide exchange.

1. Introduction

Grasslands constitute almost 24% of the global plant cover and are responsible for 3.9 to 6.1 Gg of net primary productivity annually (e.g., Harlan, 1956; Risser *et al.*, 1981). The tallgrass prairie in the eastern portion of the North American Great Plains is dominated by big bluestem (*Andropogon gerardii*), little bluestem (*Schizachyrium scoparium*), indiangrass (*Sorghastrum nutans*), and switchgrass (*Panicum virgatum*) (Risser *et al.*, 1981). The prairie has been subjected to grazing, burning, and extreme climatic conditions. A considerable amount of research has been conducted on the morphological and physiological adaptations of individual grass species (Risser, 1985). Very little information, however, is available on the carbon dioxide and energy exchange in grasslands. Few estimates have been made as to the role of grasslands as a source or sink for atmospheric carbon (Brown and Lugo, 1981). Measurements of CO_2 and energy exchange in this important ecosystem are needed to provide information for studies of global-climate, carbon-balance modeling, hydrology and ecophysiology.

Accordingly, an organized program of observations was initiated at a tallgrass prairie site in northeastern Kansas. Here we present results from a pilot study on carbon dioxide and energy exchanges between the atmosphere and the prairie. The eddy correlation technique (see e.g., Kaimal, 1975; Kanemasu *et al.*, 1979; Anderson and Verma, 1986; Verma *et al.*, 1986) was employed to measure these fluxes.

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2. Materials and Methods

Measurements were made during late July and early August, 1986 over a tallgrass prairie near Manhattan, Kansas (39° 03′ N, 96° 32′ W, 445 m above m.s.l.). Soil at the experimental site is mainly Dwight silty clay loam (Typic Natrustolls). The experimental area was burned in early spring to improve the mix of grasses and forbs. The area had been lightly grazed for several years, but was not grazed during the experimental period. The vegetation at the site is dominated by warm season C_4 grasses* such as big bluestem (*Andropogon gerardii*), switchgrass (*Panicum virgatum*) and indiangrass (*Sorghastrum nutans*). Numerous other grasses, sedges, forbs and woody plants constitute the remainder of the plant community. Canopy height ranged from 0.6 to 1.2 m for the three dominant species, and from 0.4 to 0.6 m for the other grasses. The vegetation was in the heading stage. The leaf area index† (LAI) was about 2.0.

Fluxes of CO_2, water vapor and sensible heat were measured using the eddy correlation technique. The eddy correlation sensor array included a one-dimensional (vertical) sonic anemometer (Campbell and Unsworth, 1979), a fine wire (0.025 mm) thermocouple (Campbell Scientific, Logan, Utah, Model CA27-T), a Lyman-alpha hygrometer (Buck, 1976; Redford *et al.*, 1980) with a 5.4-mm path length, and a rapid-response CO_2 sensor with a 0.2-m path length (constructed by the Lawrence Livermore National Laboratory; Bingham *et al.*, 1978). Information on the performance of these sensors (including the observations on turbulence spectra) is available elsewhere (e.g., Anderson, 1983; Anderson *et al.*, 1984, 1986; Anderson and Verma, 1986; Verma *et al.*, 1986). These sensors were mounted 2.25 m above ground. Mean air temperature and humidity were measured with an aspirated ceramic wick psychrometer. Mean horizontal wind speeds at several elevations were measured with three-cup aneomometers (Cayuga Development, Ithaca, NY, Model WP-1). Net radiation was measured with Swissteco net radiometers (Swissteco Pty. Ltd., Melbourne, Australia, Type S-1). Photosynthetically active radiation (PAR, 0.4–0.7 μm) was measured with a quantum sensor (Lambda Instrument Co., Lincoln, NE, LI-190SB). Soil heat flux was measured with four heat-flow transducers (Micromet System, Beaverton, OR, Model HFT-1), buried at a depth of 50 mm. The average soil temperature from the surface to 50 mm at each location was measured with a set of three platinum resistance thermometers (0.2 m long) buried at an angle of 15 deg. Surface soil heat flux was computed employing a combination method described by Kimball *et al.* (1976). Micrometeorological data were collected when the wind direction was from south to east, allowing an upwind fetch of about 200 m.

* C_4 plants utilize the C_4-dicarboxylic acid chemical pathway for photosynthesis. C_4 species are generally the tropical grasses, for example, corn, sorghum, millet, sugar cane and the grasses discussed here. C_3 plants utilize a photosynthetic pathway involving a three-carbon intermediate product. The C_3 group includes small grains (wheat, barley); leguminous species (e.g., alfalfa, soybean). For further details, see Rosenberg *et al.* (1983).

† LAI was measured in a concurrent study by P. J. Starks and B. L. Blad (personal communication).

Volumetric soil water content was determined gravimetrically in the upper 0.6 m soil layer.

Signals from the eddy correlation sensors were lowpass filtered with 8-pole Butterworth active filters (12.5 Hz cutoff frequency) and sampled at 25 Hz. These signals were recorded on an IBM PC-AT microcomputer. The slow-response micrometeorological signals were recorded on an IBM PC-XT microcomputer. Data were averaged for the first 45 min of each solar hour. The last 15 min were reserved for sensor calibration and checks. Fluxes of carbon dioxide were corrected for the variation in air density due to simultaneous transfers of latent and sensible heat, employing a method described in Webb *et al.* (1980).

The energy balance over prairie vegetation can be approximated by:

$$Rn \approx LE + H + S \tag{1}$$

where Rn is the net radiation, S is the soil heat flux and LE and H are the fluxes of latent and sensible heat, respectively. Values of Rn and S were measured with slow-response sensors (net radiometers and heat flow transducers). On the other hand, LE and H were measured with fast-response eddy correlation sensors. Ideally, $(LE + H)$ should be balanced by $(Rn - S)$. As indicated in Figure 1, the

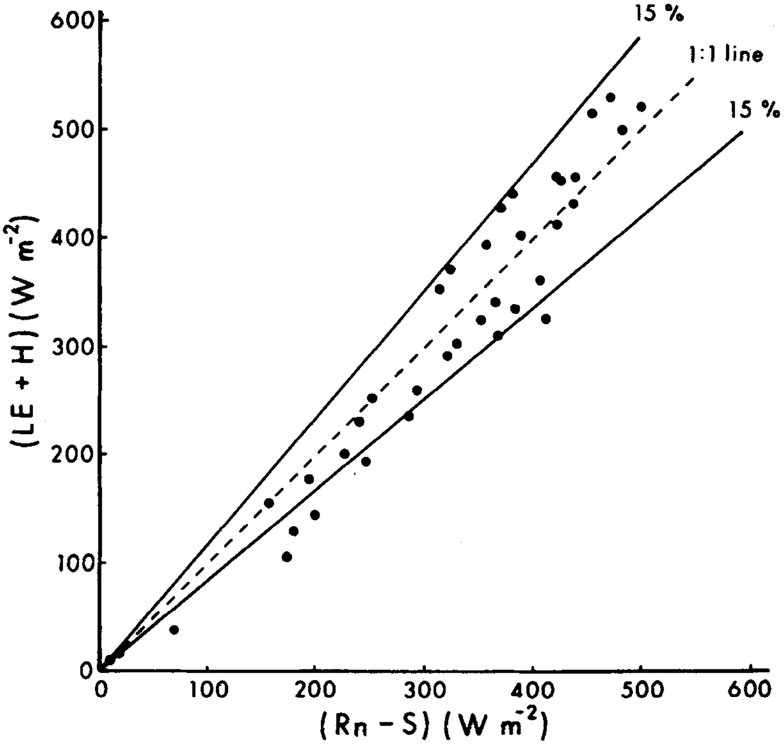


Fig. 1. Balance of energy budget terms. LE and H measured by eddy correlation. Rn and S measured with net radiometer and soil heat transducer. Dotted lines indicate ±15% deviation from 1:1 line.

sum of latent and sensible heat fluxes $[(LE + H)]$ measured by the eddy correlation technique generally agreed well with $(Rn - S)$.

3. Results

3.1. Environmental Conditions

3.1.1. *Atmospheric Conditions*

A wide range of atmospheric conditions occurred between 30 July and 6 August, 1986. Values of mean air temperature ($\bar{T}$), vapor pressure deficit ($\bar{D}$) and wind speed ($\bar{U}$) on four selected days are given in Figure 2 and Table I. Moderate conditions prevailed on 5 and 6 August (midday $\bar{T} \approx 23$ to 31 C, $\bar{D} \approx 0.2$ to 1.4 kPa and $\bar{U} \approx 1.3$ to 3.1 m s^{-1}). August 5 was overcast in the early morning hours and became partly cloudy after about 0900 hr. August 6 was mostly-to-partly cloudy in the morning and clear in the afternoon. As compared to 5 and 6 August, 4 August was a day with higher evaporative demand. While the air temperature on 4 August was similar to that on 5 and 6 August, the vapor pressure defiicit (midday $\bar{D} \approx 1.3$ to 2.6 kPa) and wind speed (midday $\bar{U} \approx 4.9$ to 5.5 m s^{-1}) were substantially higher. August 4 was mostly cloudy in the early morning and became partly cloudy later in the day. July 30 had the greatest atmospheric evaporative demand, with high air temperature (midday $\bar{T} \approx 31$ to 38 C), high vapor pressure deficit (midday $\bar{D} \approx 2.8$ to 4.7 kPa) and strong winds (midday $\bar{U} \approx 1.4$ to 4.7 m s^{-1}). Except for a few early morning clouds, the sky was fairly clear throughout the day.

3.1.2. *Soil Water Conditions*

Profiles of volumetric soil water content, measured during 29 July–6 August 1986, are shown in Figure 3 [surface (0 to 0.05 m) volumetric soil water contents corresponding to −1/30 MPa and −1.5 MPa were approximately 39.4% and 15.0%, respectively]. Of the four days discussed above, 4 August was a day with the least available soil water.

Precipitation of about 7 mm during each of the previous nights resulted in a

TABLE I

Midday (1000–1400) mean air temperature ($\bar{T}$), vapor pressure deficit ($\bar{D}$), wind speed ($\bar{U}$), LE/Rn and β on selected days

	$\bar{T}$ (C)	$\bar{D}$ (kPa)	$\bar{U}$ (m s^{-1})	LE/Rn	β
				Average	
30 July	31 to 38	2.8 to 4.7	1.4 to 4.7	0.67	0.28
4 August	25 to 32	1.3 to 2.6	4.9 to 5.5	0.53	0.61
5 August	23 to 28	0.2 to 1.2	2.0 to 3.1	0.54	0.59
6 August	26 to 31	0.6 to 1.4	1.3 to 2.9	0.54	0.56

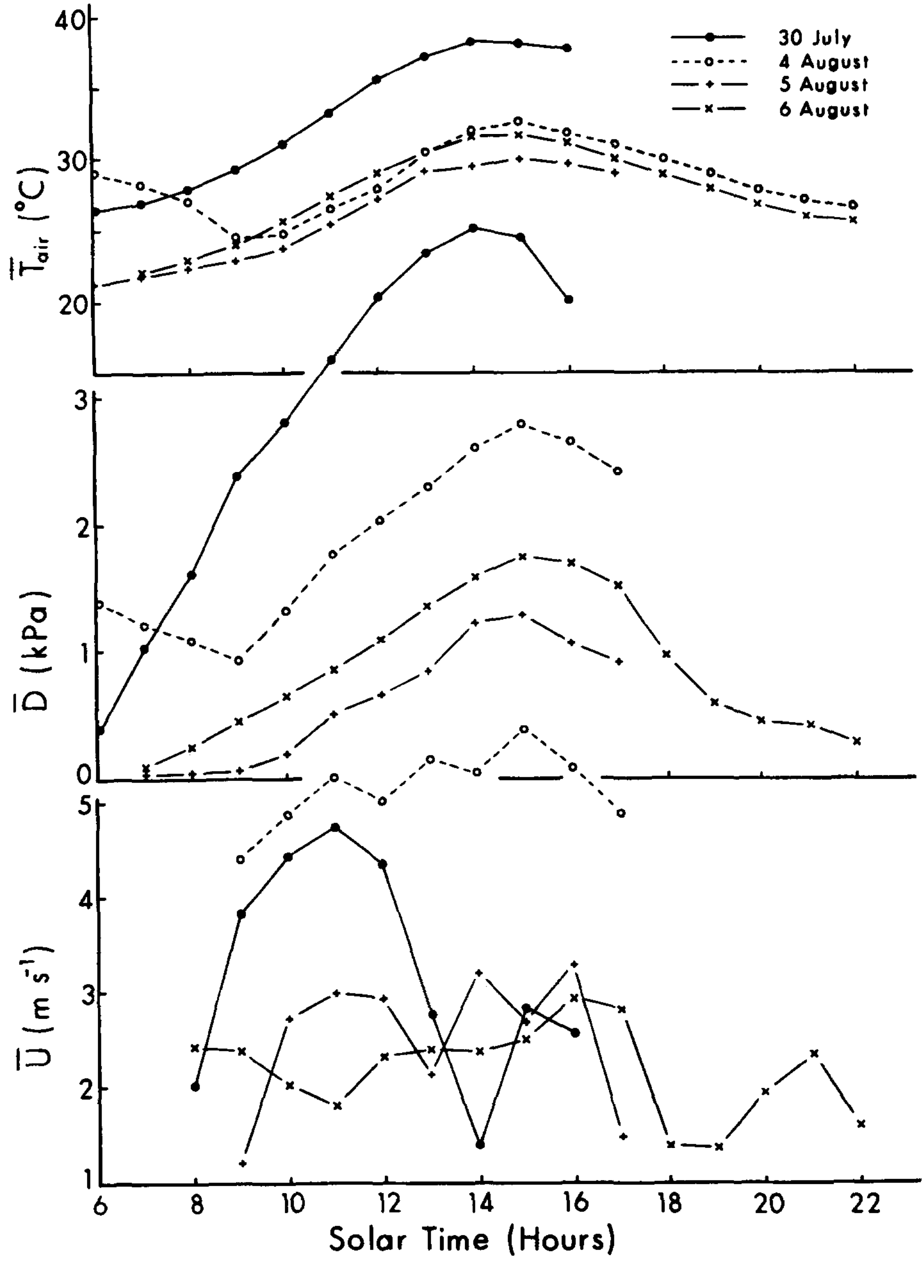


Fig. 2. Diurnal patterns of mean air temperature ($\bar{T}$), mean vapor pressure deficit ($\bar{D}$), and mean wind speed ($\bar{U}$) over a tall-grass prairie near Manhattan, Kansas. These measurements were made at 1.25 m above ground. 30 July, 4, 5 and 6 August 1986.

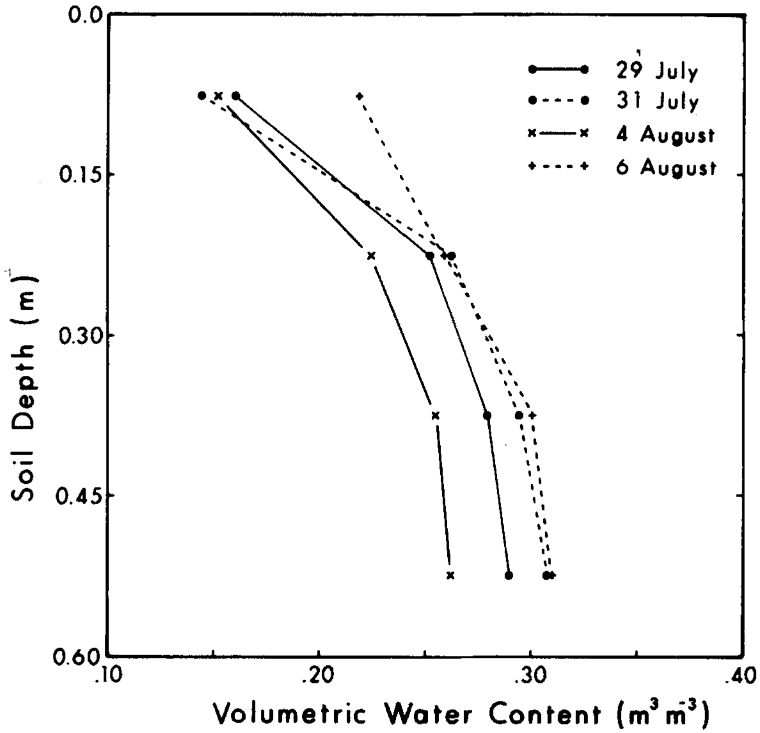


Fig. 3. Change in volumetric water content at selected depths measured during the experimental period in a tallgrass prairie. Surface (0 to 0.05 m) volumetric soil water contents corresponding to $-1/30$ MPa and -1.5 MPa were approximately 39.4% and 15.0%, respectively.

greater amount of available soil water on 5 and 6 August. Based on the measurements on 29 and 31 July, it appears that the volumetric water contents at lower depths (below 0.15 m) on 30 July were similar to those on 6 August, the surface soil layer (0 to 0.15 m) was drier, however.

3.2. Energy fluxes

The diurnal patterns of the energy balance components over the tallgrass prairie on two days (5 and 6 August 1986) with low to moderate atmospheric evaporative demand are shown in Figures 4a and b. On 5 August, values of Rn varied depending on the degree of cloud cover and ranged from 200 to 500 W m^{-2} during the midday (Figure 4a). Diurnal patterns of LE, H and S followed that of Rn quite closely. The midday magnitude of H varied from 60 to 170 W m^{-2}. The midday magnitude of LE ranged between 130 to 270 W m^{-2}, while that of S ranged from 20 to 70 W m^{-2}. The midday averages of LE/Rn and the Bowen ratio ($\beta = H/LE$) were 0.54 and 0.59, respectively. The diurnal patterns of the energy balance components on 6 August (Figure 4b) were similar to those on 5 August. Midday values of H, LE and S varied from 130 to 180, from 230 to 330,

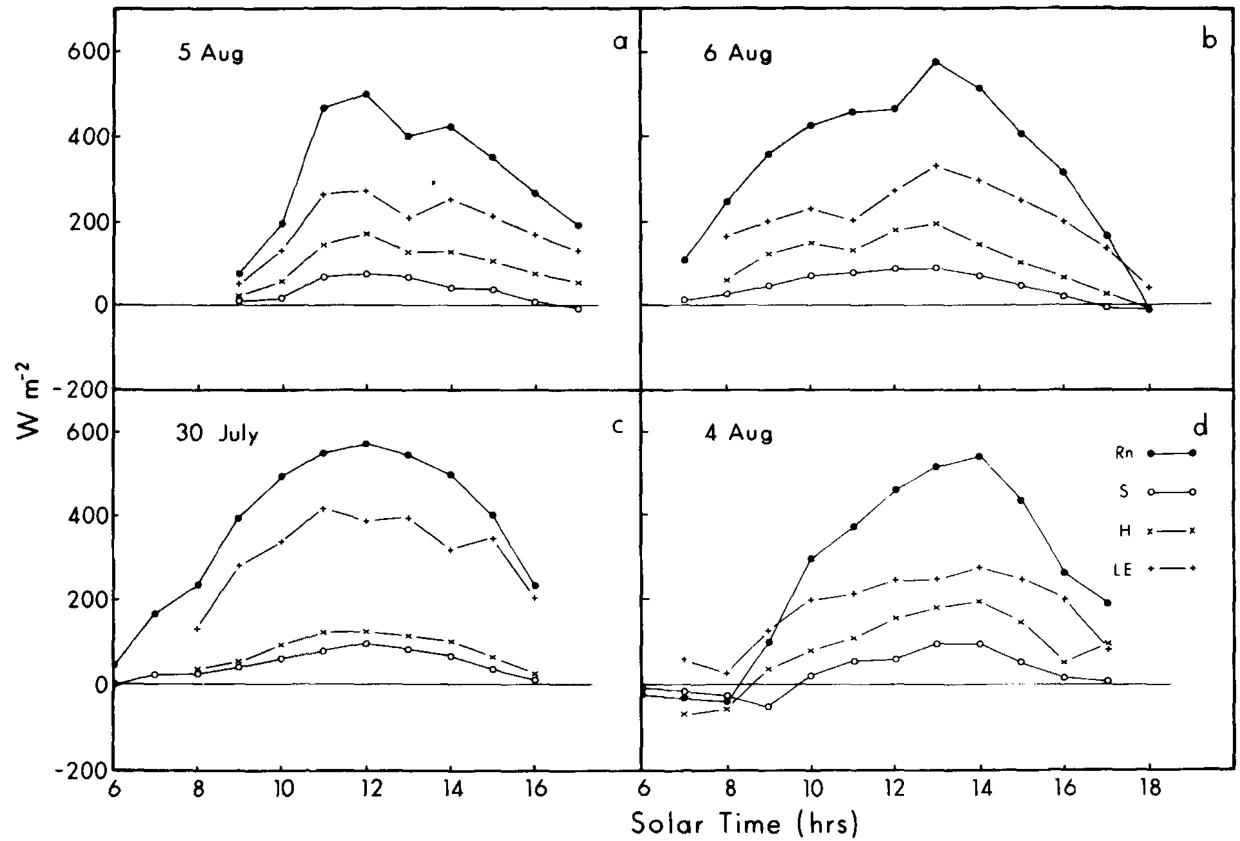


Fig. 4. Diurnal patterns of net radiation (*Rn*), soil heat flux (*S*), sensible heat flux (*H*), and latent heat flux (*LE*) over a tallgrass prairie near Manhattan, Kansas. (a) 5 August, 1986; (b) 6 August, 1986; (c) 30 July, 1986; (d) 4 August, 1986.

and from 60 to 80 W m^{-2}. Average values of LE/Rn and β during the midday were 0.54 and 0.56.

Figure 4c shows diurnal patterns of the energy balance components measured on 30 July, a day with relatively high atmospheric evaporative demand (Figure 2 and Table I). Fluxes of sensible (H), latent (LE) and soil heat (S) followed diurnal patterns similar to that of net radiation (Rn). Net radiation reached its maximum of about 570 W m^{-2} at solar noon. Sensible and soil heat fluxes reached peak magnitudes of about 130 W m^{-2} and 90 W m^{-2} at solar noon, respectively. The latent heat flux reached a peak magnitude of 410 W m^{-2} around 1100 hr and then decreased later in the day. Midday average values of LE/Rn and β were about 0.67 and 0.28, respectively. As compared to 5 and 6 August, LE was higher on this day due to greater net radiation and substantially higher air temperature, vapor pressure deficit and wind speed (Figure 2). Accordingly, a greater proportion of Rn was partitioned into LE and β was smaller (Table I).

The energy balance components on 4 August are shown in Figure 4d. The midday magnitude of Rn ranged from 300 to 540 W m^{-2} while those of H and LE varied from 90 to 180 W m^{-2} and from 200 to 270 W m^{-2}, respectively. The midday average values of LE/Rn and β were 0.53 and 0.61, respectively. As discussed in Section 3.1, the atmospheric evaporative demand on 4 August was higher than that on 5 and 6 August. Partitioning of Rn into LE and H (Table I) on 4 August, however was similar to that on 5 and 6 August. This may have resulted from lower availability of soil water on 4 August (Figure 3).

3.3. CO_2 FLUX

3.3.1. *Diurnal Patterns*

Figures 5a and b show diurnal patterns of carbon dioxide flux* (F_c) and photosynthetically active radiation (PAR) for 5 and 6 August 1986, respectively. The CO_2 flux on 5 August varied in response to changing PAR (Figure 5a). A peak F_c value of 0.8 mg m^{-2} s^{-1} was reached at solar noon (PAR = 1660 μEi m^{-2} s^{-1}). Similarly, on 6 August the diurnal pattern of F_c followed that of PAR. The maxima in F_c and PAR of 0.6 mg m^{-2} s^{-1} and 1990 μEi m^{-2} s^{-1}, respectively, occurred at about 1300 hr (Figure 5b). Even though the amount of incoming PAR was higher on 6 August, the maximum value of F_c on 6 August was slightly lower than that on 5 August, probably due to higher vapor pressure deficit throughout the day (Figure 2).

Diurnal patterns of F_c and PAR for 30 July and 4 August 1986 are shown in Figures 5c and d, respectively. On 30 July, F_c did not follow the pattern of PAR and reached a peak of about 0.5 mg m^{-2} s^{-1} in mid-morning and decreased in the remainder of the day. Photosynthetically active radiation reached a peak of 2032 μEi m^{-2} s^{-1} at solar noon. The diurnal pattern of F_c on 4 August (Figure

* CO_2 fluxes directed toward the surface are considered positive. CO_2 fluxes are reported on a per ground area basis.

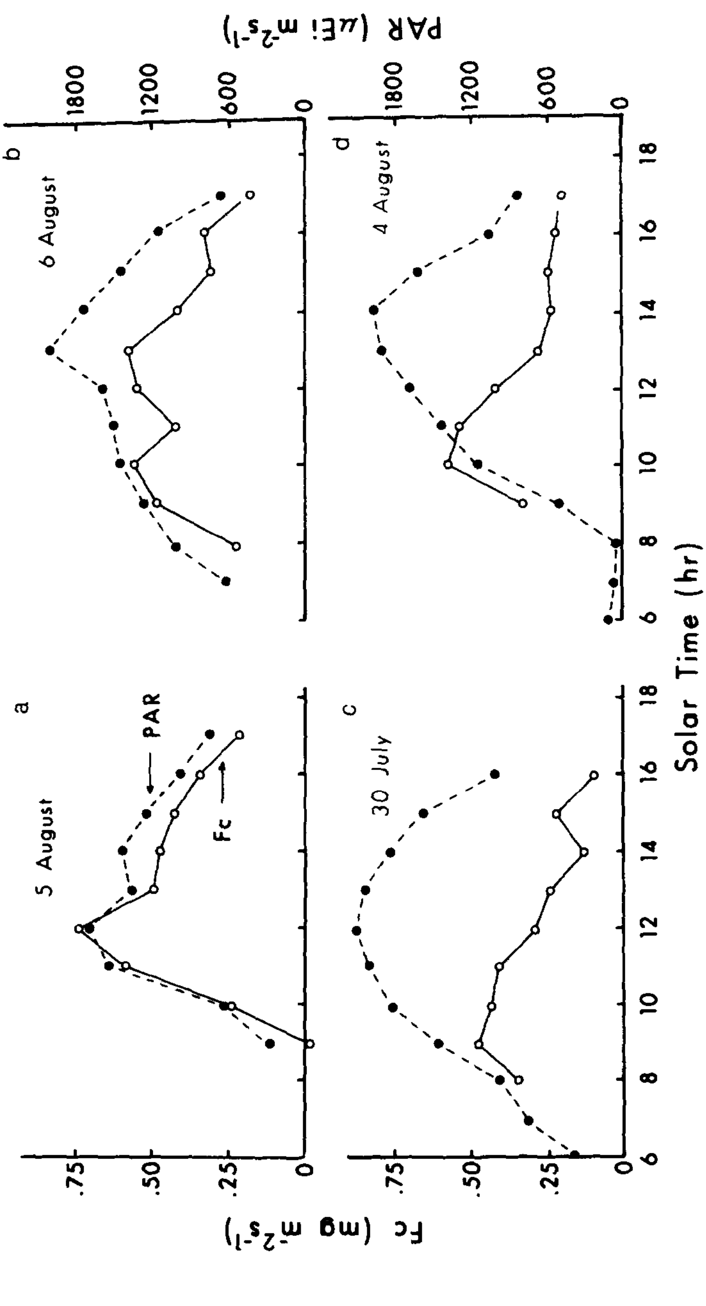
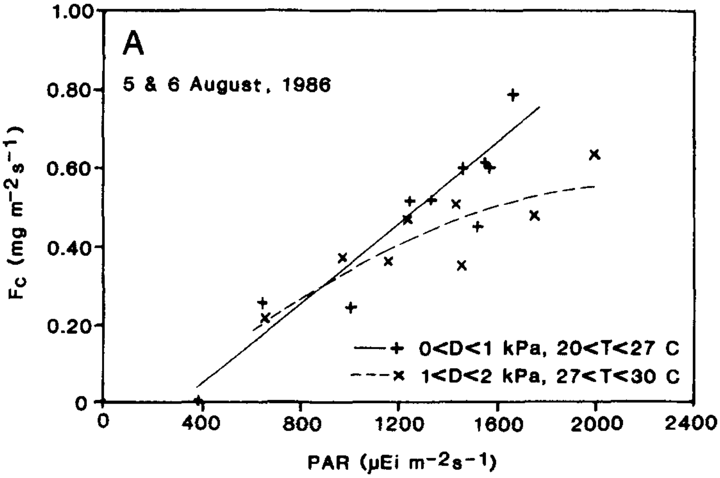


Fig. 5. Diurnal patterns of CO_2 flux (F_c: on ground area basis) and photosynthetically active radiation (PAR) over a tallgrass prairie near Manhattan, Kansas. (a) 5 August, 1986; (b) 6 August, 1986; (c) 30 July, 1986; (d) 4 August, 1986.

5d) was similar to that on 30 July. The maximum value of F_c, observed in mid-morning, was about 0.6 mg m^{-2} s^{-1}. The maximum in PAR of 1880 μEi m^{-2} s^{-1} occurred at about 1400 hr.

3.3.2. F_c-*Light Response*

The dependence of F_c on PAR is more clearly shown in Figure 6. The data included in Figure 6A are from 5 and 6 August, days with low to moderate



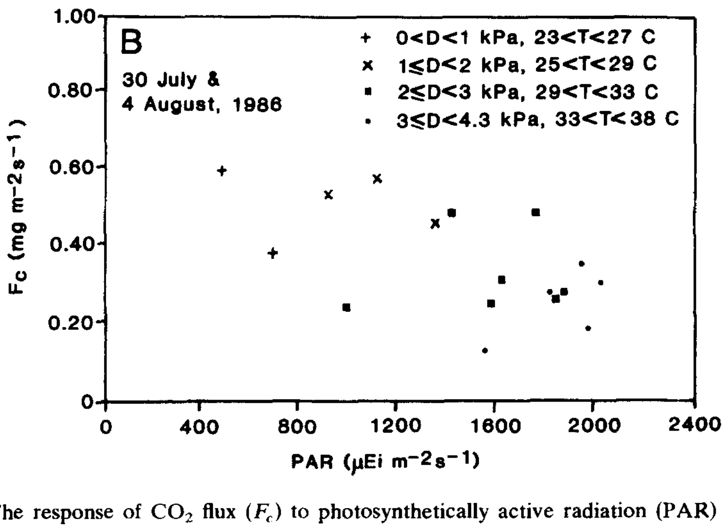


Fig. 6. The response of CO_2 flux (F_c) to photosynthetically active radiation (PAR) over different ranges of vapor pressure deficit (D) and air temperature (T). (A) 5 and 6 August and (B) 30 July and 4 August 1986. Data in Figure 6A were fitted with rectangular hyperbolae (commonly used in physiological studies – see e.g., Landsberg, 1977).

atmospheric evaporative demand and more available soil water. At low D (0 to 1 kPa) and T (20 to 27 C), F_c increased with PAR. For larger D (1 to 2 kPa) and T (27 to 30 C), a similar relationship was observed; however, the increase in F_c appears to have been suppressed due to high D. The data in Figure 6A do not indicate light saturation* of the tallgrass prairie canopy up to PAR levels of 1800 μEi m^{-2} s^{-1}. This observation seems reasonable since the vegetation at the site is dominated by warm season C_4 grasses.

The relationship between F_c and PAR on 30 July and 4 August is shown in Figure 6B. High vapor pressure deficit and air temperature, and lower surface soil water content strongly affected the rates of CO_2 exchange. These effects are further considered in Section 4.

3.3.3. F_c-*Canopy Conductance Response*

Canopy conductance (g_c) was calculated using measured values of *Rn*, *LE*, *T*, *D* and estimated values of aerodynamic resistance in the Penman–Monteith equation (Monteith, 1965). Figure 7 shows the relationship between F_c and g_c. Data were selected for periods when PAR > 1200 μEi m^{-2} s^{-1} to minimize the influence of low PAR on g_c. Data suggest that the canopy conductance did not limit the exchange of CO_2 for high values of g_c. However, as the stomata began to close partially at higher vapor pressure deficit and temperature, F_c decreased almost linearly with decreasing g_c. Knapp (1985) reported a strong positive correlation between net photosynthesis and leaf conductance of *Andropogon gerardii* and *Panicum virgatum* in a tallgrass prairie.

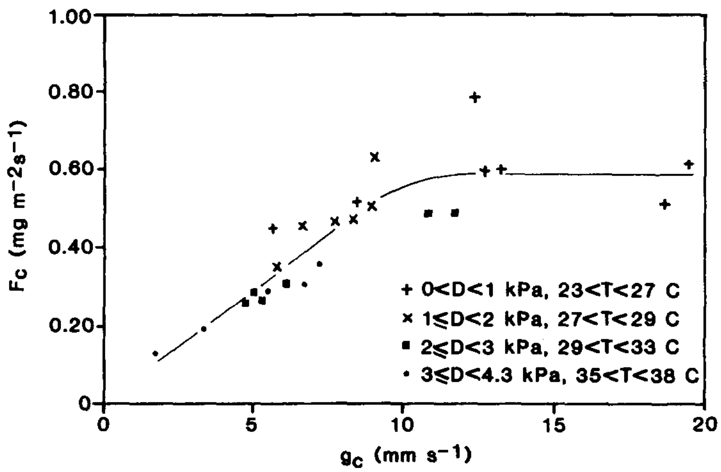


Fig. 7. The response of CO_2 flux (F_c) to canopy conductance (g_c) for four days (30 July, 4, 5, and 6 August, 1986). Eye-fit curve is shown.

* The level at which the photosynthetic rate becomes independent of irradiance is called the light saturation point. For further details on the concept of light saturation, see Rosenberg *et al.* (1983).

4. Discussion

As expected, the energy partitioning was controlled by vapor pressure deficit (D) and air temperature (T). A greater portion of net radiation was consumed in evapotranspiration as D and T increased (Figure 8). This effect was not observed when the availability of soil water was low (see circled data points from 4 August in Figure 8).

At low to moderate vapor pressure deficits and air temperatures, the exchange of CO_2 (F_c) was limited primarily by the incoming PAR and was generally independent of g_c (Figures 6A and 7). The strong dependence of F_c on PAR observed on 5 and 6 August also may have been aided by the rainfall (about 7 mm) during each of the previous nights. Sala and Lauenroth (1982) reported a rapid response of enhanced leaf water potential and leaf conductance in *Bouteloua gracilis* (Blue grama, C_4) to a small rainfall event of 5 mm. They indicated that the effect of this small rainfall was observed in less than 12 hr and lasted for up to two days.

The F_c–PAR relationship (Figure 6B) was strongly influenced by the effect of high atmospheric evaporative demand on g_c (Figure 7). The smaller magnitudes and the mid-morning maximum of F_c observed on 30 July and 4 August were likely due to the combined effects of high D and T, and lower availability of soil water. Although it was not possible to separate the effect of vapor pressure deficit and air temperature, high vapor pressure deficit appeared to decrease F_c through reduction in stomatal conductance on these two days. High air temperatures may have also affected photosynthetic rates and caused increased soil and plant respiration, thereby decreasing F_c after mid-morning. Sala *et al.* (1982) suggested that the shift of the peak F_c toward mid-morning is an adaptation of grass species

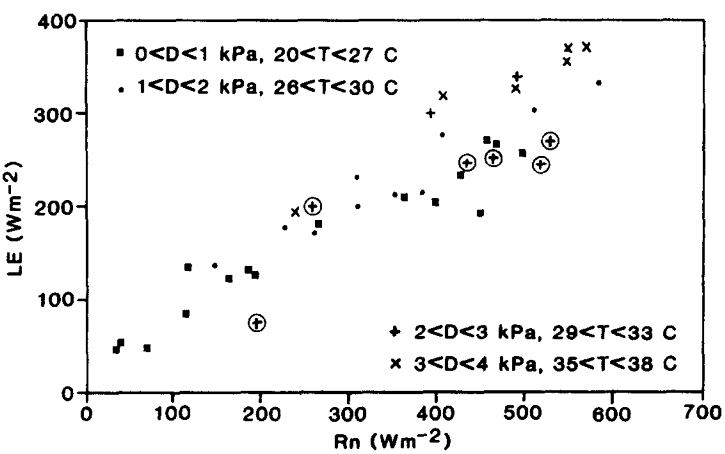


Fig. 8 The relation between latent heat flux (LE) and net radiation (Rn). Data are distinguished for four different ranges of vapor pressure deficit (D) and air temperature (T). Circled data points are from 4 August, a day with low availability of soil water.

to water stress and that it is a consequence of physiological characteristics such as high stomatal conductance and high leaf water potential in the morning.

Lower availability of soil water, particularly on 4 August, may have also affected the CO_2 exchange rates. Brown and Trlica (1977) found that the rates of net photosynthesis of *Bouteloua gracilis* decreased with increasing water stress at all temperatures. As has been suggested by Moore (1977), the decline in F_c may have also resulted from the inhibition of photosynthesis due to rapid carbohydrate accumulation with increasing water stress and high air temperature. For Zea mays L. (Maize, C_4), Raschke (1970) indicated that increased carbohydrate in epidermal tissue or increased apoplast sucrose concentration may prevent full stomatal opening.

5. Summary and Conclusions

Eddy correlation measurements were made of CO_2, latent heat and sensible heat fluxes during late July and early August, 1986 over a tallgrass prairie in northeastern Kansas. Fluxes of latent, sensible and soil heat followed diurnal patterns similar to that of net radiation. Midday magnitudes of sensible and latent heat fluxes were 60 to 180 and 130 to 410 W m^{-2}, respectively. The partitioning of *Rn* into *H* and *LE* depended on the atmospheric evaporative demand and the availability of soil water.

Midday values of carbon dioxide flux ranged from 0.3 to 0.8 mg m^{-2} (ground area) s^{-1}. The CO_2 flux followed a diurnal pattern similar to that of incoming photosynthetically active radiation (PAR), when the atmospheric evaporative demand was not high. On days with higher atmospheric evaporative demand (high air temperature, vapor pressure deficit and strong winds) and lower availability of soil water, the CO_2 flux reached its peak in mid-morning and then decreased thereafer regardless of the amount of incoming PAR. The vegetation did not appear to be light-saturated at PAR flux densities <1800 μEi m^{-2} s^{-1}.

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