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USING LEAF TEMPERATURE TO ASSESS EVAPOTRANSPIRATION AND ADVECTION*

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ABSTRACT

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Results of evapotranspiration research on the energy balance of corn and sorghum plants and their respective leaf and air temperatures are presented. The difference between crop canopy and air temperatures provides the gradient for the flow of sensible heat toward or away from a vegetal surface. Sensible heat flux toward the canopy is an important source of energy for evapotranspiration.

The energy balance of corn (*Zea mays* L. cv. Prairie Valley) and of sorghum (*Sorghum bicolor* L. cv. SG-40 GBR) was determined during the 1978 growing season. Actual evapotranspiration (ET, determined using weighing lysimeters), net radiation (R_n), and soil heat flux (S) were measured. Other data collected were soil water content (θ), stomatal resistance (R_s), leaf-water potential (ψ_L), and air and leaf temperatures (T_A and T_L).

Generally, ET of well-watered crops with full cover nearly equalled R_n. But on days when T_A exceeded 33°C, sensible heat flux was toward the cooler canopy, resulting in ET greater than R_n. Ratios of $ET/(R_n - S)$ were as great as 1.23 and 1.44 for corn and sorghum, respectively. When more than 35% of available soil moisture had been depleted, the leaves lost turgor, stomatal resistance increased, and leaf temperatures rose above air temperatures because of reduced transpiration rate. Leaf—air temperature difference appeared to be a useful indicator of plant stress.

INTRODUCTION

In recent years canopy temperature has become a popular and a practical measurement in evapotranspiration research. Estimating evapotranspiration (ET) by using canopy temperatures has been discussed by Stone and Horton (1974), Heilman et al. (1976), Blad and Rosenberg (1976), Verma et al. (1976) and Jackson et al. (1977). The ET models used require, in addition to canopy temperatures, measurements of air temperatures, solar or net radiation, soil heat flux, and wind velocity.

To better understand water use by vegetation, one must know the complete energy balance of the vegetal surface, of which evapotranspiration is a major component. The surface energy balance can be expressed by the relationship

$$R_n = S + ET + A \quad (1)$$

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where R_n is net radiation, S is soil heat flux, ET is evapotranspiration, and A is sensible heat flux. ET and A are defined as being positive when the flux is away from the canopy.

Net radiation usually provides the upper limit for evapotranspiration, especially in humid regions. In the drier regions, evapotranspiration may exceed net radiation. When $ET > (R_n - S)$, sensible heat flux is toward the canopy (negative) and is an additional source of energy for evapotranspiration (Abdel-Azia et al., 1964; Rosenberg 1969; Brakke et al., 1978; Rosenberg and Verma, 1978). Rosenberg (1969) evaluated the importance of the advective contribution to energy used in evapotranspiration by alfalfa in Nebraska. He reported negative A values as high as 157 W m^{-2} for days when ET exceeded 266 W m^{-2} ($\simeq$ 9 mm day^{-1}). For the same crop, Rosenberg and Verma (1978) gave A estimates of -249 W m^{-2} during the 1976 Midwestern drought.

In this study we relate the rates and patterns of evapotranspiration (lysimeter) by corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) under different soil water contents with the patterns of leaf and air temperatures.

MATERIALS AND METHODS

During the spring of 1978, corn and sorghum were grown under field conditions on Muir silt loam soil (fine—silty, mixed, mesic, pachic and haplustoll) of alluvial deposits with a maximum water-holding capacity of 33.0 cm in the 150-cm rooting zone. The study area, at the Kansas State University Evapotranspiration Research Site, consisted of two adjacent 1-ha plots oriented in a north—south direction. A weighing lysimeter (described by Ritchie and Burnett, 1968), 1.8 × 1.8 m in surface area, was located in the center of each plot.

The north lysimeter plot was planted to corn (*Zea mays* L. cv. Prairie Valley) on 17 May 1978; the south lysimeter plot was planted to sorghum (*Sorghum bicolor* L. cv. SG-40 GBR) on 18 May 1978. The north—south rows were 76 cm apart. Linear densities after plant emergence were 10.5 and 22.0 plants per 2-m row of corn and sorghum, respectively. Commencing 29 July, small areas (6 rows by 3.6 m) of corn and sorghum were kept moist by flood irrigating every three or four days.

Meteorological, hydrological and plant variables were collected from each plot. Soil water content (θ), leaf area index (LAI), and dry matter (DM) accumulation were determined weekly. Soil water contents, determined by using a neutron moisture meter for the 15- to 150-cm soil profile at 15-cm intervals and a gravimetric method for the top 15 cm, were converted to available soil water (θ_{avail}) expressed as percentage of the maximum available soil water (θ_{max}). Two plant samples per plot (3 plants per sample) were collected at random and leaf areas of green leaves were measured with an optical planimeter (Lambda Instruments Corp.). The plant samples were then dried and weighed. Twice a week, two plants were dissected for growth-stage determinations and recorded [using the notation of Vanderlip (1972)

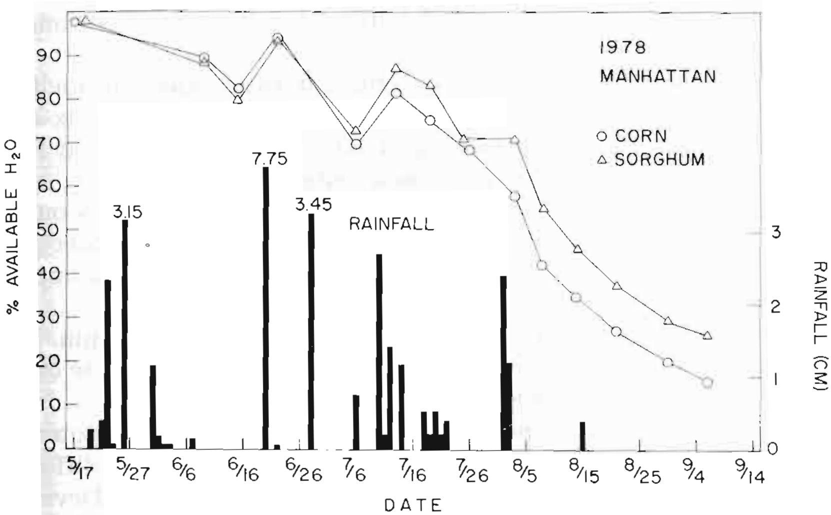


Fig. 1. Seasonal available soil water in the 150-cm profile and seasonal rainfall distribution. Evapotranspiration Research Site, Manhattan, Kansas, 1978.

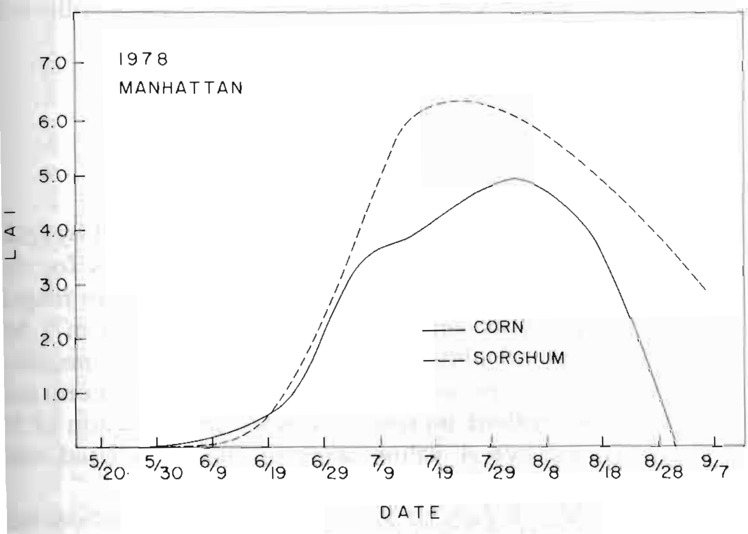


Fig. 2. Corn and sorghum leaf area index (*LAI*), 17 May to 6 September.

and Hanway (1971) for sorghum and corn, respectively]. The plant and soil water measurements and *LAI*, for the season, are summarized in Figs. 1 and 2. Rainfall distribution, which totaled 30.8 cm for the growing season, is also shown in Fig. 1.

Components of the energy balance were measured as follows: total incoming solar radiation (G) with an Eppley pyranometer; net radiation (R_n) with hemispherical net radiometers (Swissteco Pty., Ltd.) located about 2.1 and 3.5 m above ground on the sorghum and corn plots, respectively; and soil heat flux with heat flux plates buried about 2.5 cm deep. Instruments have an accuracy of approximately 5 to 10%.

Profiles of air temperature (T_A) were determined using radiation-shielded, aspirated, copper—constantan thermocouples mounted on masts at six different levels within and above the canopy. Leaf temperatures (T_L) at four and five canopy heights for the corn and sorghum, respectively, were measured with polyvinyl-coated, 38 gage, copper—constantan thermocouples spring-mounted on the undersides of the leaves. Wind speeds and directions at the height of the net radiometers were measured with vane-anemometers (R.M. Young and Assoc.).

Outputs from the above instrumentation were sampled every 10 min. by a data acquisition system, averaged over 30 min. intervals by an on-line calculator, and recorded by a teletypewriter.

Other data collected were stomatal resistance (R_s), leaf-water potential (ψ_L), canopy temperature (T_C). Stomatal resistances of leaves at different heights were determined using an automatic porometer (Delta-T Devices). Two or three porometer readings were taken on each side of the leaf. A pressure bomb was used to estimate ψ_L of leaf numbers 5, 6 or 7 of corn and leaf numbers 2 or 3 of sorghum (top or flag leaf is leaf number 1). A Barnes PRT-5 infrared thermometer was used to measure T_C. Data collected from the irrigated plots were R_s, ψ_L, and T_C.

RESULTS AND DISCUSSION

Evapotranspiration and sensible heat flux

Daily estimates of R_n, S, and actual ET (lysimeter) were obtained by integrating the 30 min. values from 0600 CDT to 1800 CDT. Results for the period between 8 July and 12 August are shown in Table I. ET rates ranged from 196.6 to 584.2 W m^{-2} for corn and from 275.2 to 589.8 W m^{-2} for sorghum. Sensible heat flux was calculated as a residual of (1). The negative A values [i.e., $ET > (R_n - S)$] were as high as 89.9 W m^{-2} for corn and 157.3 W m^{-2} for sorghum — equivalent increases in evapotranspiration of 23 and 44%, respectively, The negative A values were usually associated with high air temperatures ($T_A > 33°$C).

During the period of the study (8 July to 12 August), leaf area indices and soil water availability were not significantly limiting evapotranspiration (Figs. 1 and 2). An earlier study on corn (Ritchie, 1973) and sorghum (Sumayao et al., 1977) indicated that neither carbon dioxide exchange nor transpiration rates were affected by soil water deficits until the soil water in the 150-cm profile was below 30—35% of the maximum available. Available soil water (θ_{avail}) approached 35% on 15 August in the corn plot and 25 August in the sorghum plot.

Hourly components of the energy balance and leaf and air temperature measurements on 17 and 27 July (Figs. 3 and 4) and on 26 July and 10 August (Figs. 5 and 6) are presented to further illustrate the evapotranspiration pat-

Energy balance, maximum air temperature and *LAI* for corn and sorghum during the 1978 growing season. Daily totals are for the 12-h period 0600 to 1800 CDT. *ET* was obtained from lysimeters

Date	$T_{A\ max}$ (°C)	Corn					Sorghum				
		LAI	R_n-S ($W\ m^{-2}$)	*ET* ($W\ m^{-2}$)	*A* ($W\ m^{-2}$)	ET/R_n-S	*LAI*	R_n-S ($W\ m^{-2}$)	*ET* ($W\ m^{-2}$)	*A* ($W\ m^{-2}$)	ET/R_n-S
08/07/78	36.7	3.8	466.2	528.0	−61.8	1.13	5.0	449.4	483.1	− 33.7	1.08
14/07/78	34.4	4.5	477.5	505.6	−28.1	1.06	6.0	438.2	449.4	− 11.2	1.08
15/07/78	32.8	4.6	500.0	476.4	23.6	0.95	6.1	477.5	443.8	33.7	0.93
16/07/78	34.4	4.7	—	—	—	—	6.2	348.3	387.6	− 39.3	1.11
17/07/78	34.2	4.7	471.9	561.7	−89.8	1.19	6.2	449.4	522.4	− 73.0	1.16
18/07/78	35.6	4.8	—	—	—	—	6.3	393.2	449.4	− 56.2	1.14
21/07/78	36.1	4.9	370.8	455.0	−84.2	1.23	6.4	359.5	516.8	−157.3	1.44
23/07/78	25.6	4.9	410.1	348.3	61.8	0.85	6.4	393.2	348.3	39.3	0.89
26/07/78	34.0	4.9	494.3	511.2	−16.9	1.03	6.4	471.9	511.2	− 39.3	1.08
27/07/78	31.8	4.9	471.9	382.0	89.9	0.81	6.4	455.0	460.6	− 5.6	1.10
28/07/78	34.8	4.9	494.3	584.2	−89.9	1.18	6.4	477.5	589.8	−112.3	1.24
29/07/78	33.2	4.9	466.2	471.9	− 5.7	1.01	6.3	433.8	449.4	− 5.6	1.10
31/07/78	33.3	4.9	432.5	432.5	0	1.00	6.2	415.7	438.2	− 22.5	1.05
07/08/78	33.3	4.6	410.1	432.5	−22.2	1.05	6.0	398.8	393.2	5.6	0.99
08/08/78	35.0	4.6	443.8	505.6	−61.8	1.14	5.7	426.9	477.5	− 50.6	1.12
09/08/78	33.3	4.5	191.0	196.6	− 5.6	1.03	5.5	191.0	275.2	− 84.2	1.44
10/08/78	31.2	4.5	321.7	286.5	35.2	0.89	5.5	329.5	314.6	14.9	0.95
12/08/78	38.3	4.3	438.2	477.5	−39.3	1.09	5.3	421.3	511.2	− 89.9	1.21

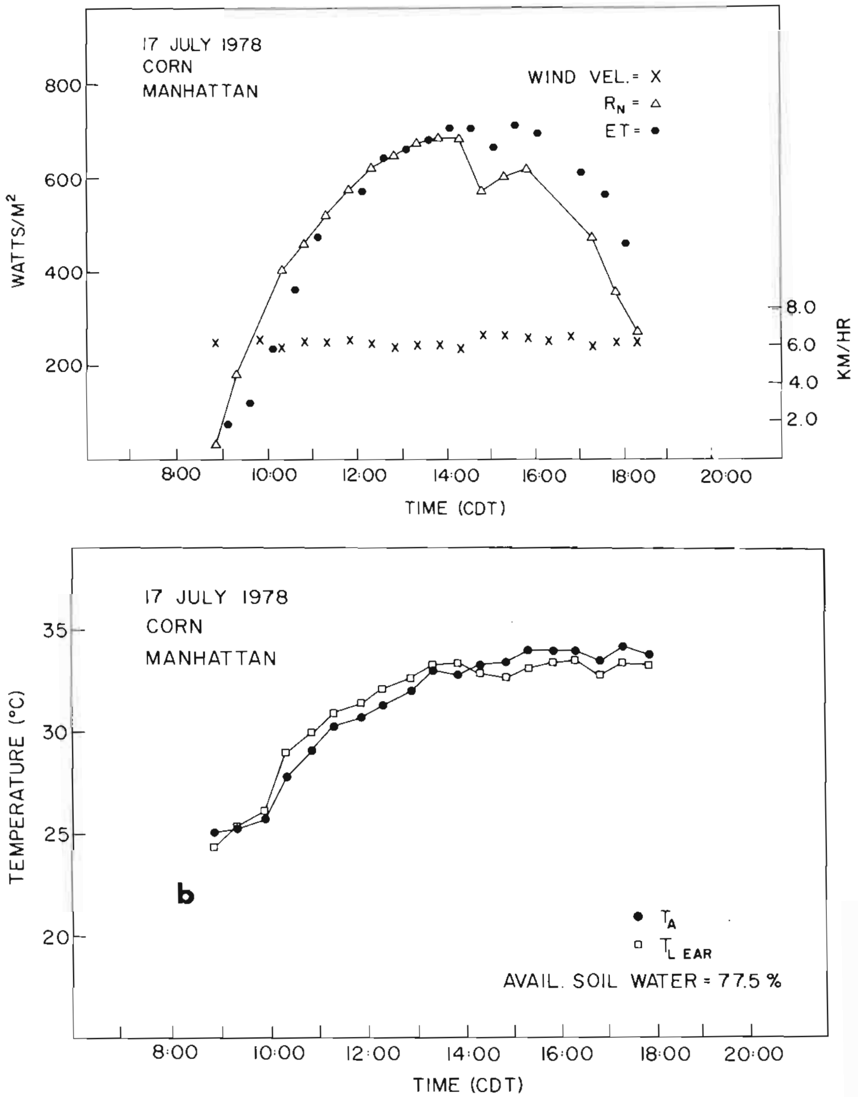


Fig. 3. Corn energy balance (a) and corn-leaf temperature and air temperature at the top of the canopy (b) on 17 July 1978.

terns in relation to meteorological conditions. Crop and environmental information is summarized in Table 2. On 17 and 26 July, days were clear and hot ($T_A > 33°C$), with moderately high evaporative demand ($R_n > 280$ W m^{-2}); on 27 July and 10 August, days were relatively cool ($T_A > 33°C$). The use of $T_A = 33°C$ as a reference in defining a "hot" and a "cool" day is based on observations (Linacre, 1964; Kanemasu et al., 1976; Sumayao et al., 1977) that thin-leaved plants exposed to bright sunshine and non-limiting soil water are warmer than the air at ambient temperatures less than

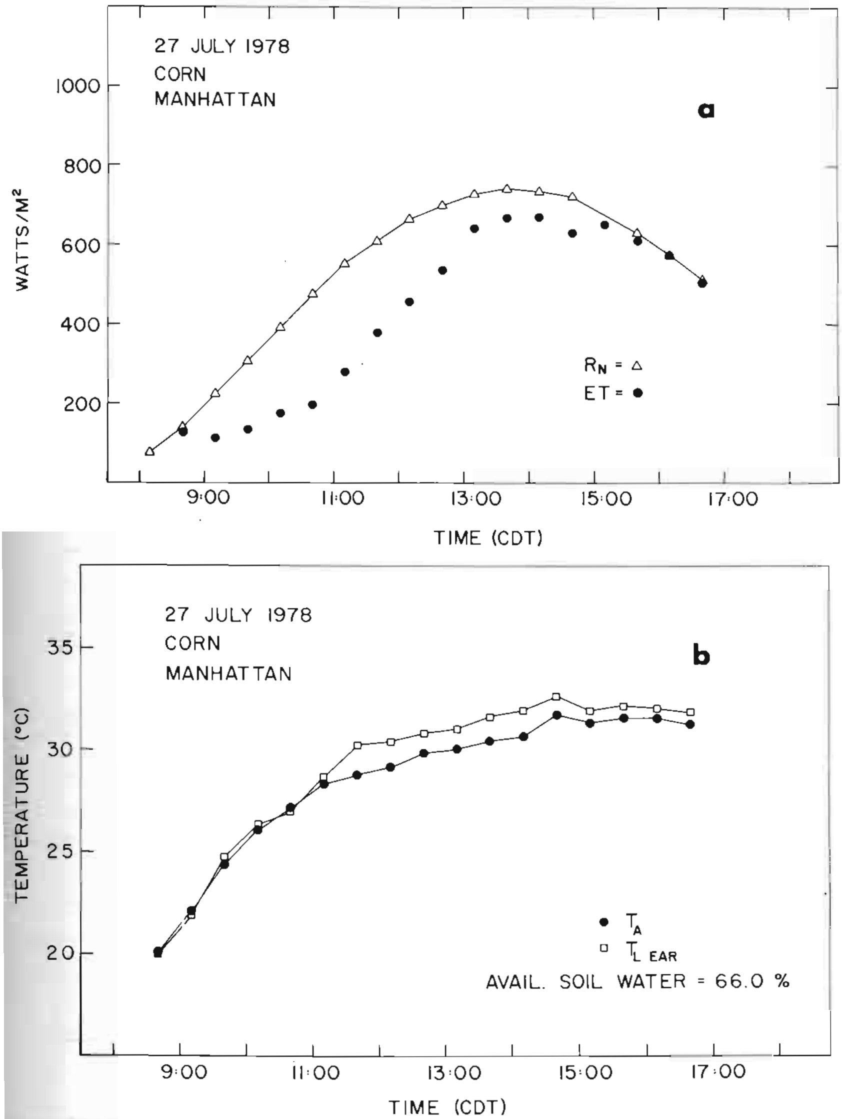


Fig. 4. Corn energy balance (a) and corn-leaf temperature and air temperature at the top of the canopy (b) on 27 July 1978.

33°C and cooler than the air at ambient temperatures above 33°C.

Hourly lysimetric *ET* rates were compared with R_n (Figs. 3 to 6), which, in the absence of sensible heat advection, provides the upper limit for *ET* (Tanner and Pelton, 1960). The *ET* rates on 27 July and 10 August were either less than or equal to R_n (Figs. 4a and 6a). A similar situation was noted during the morning and early afternoon of 17 and 26 July (Figs. 3a and 5a); *ET* exceeded R_n later in the afternoon.

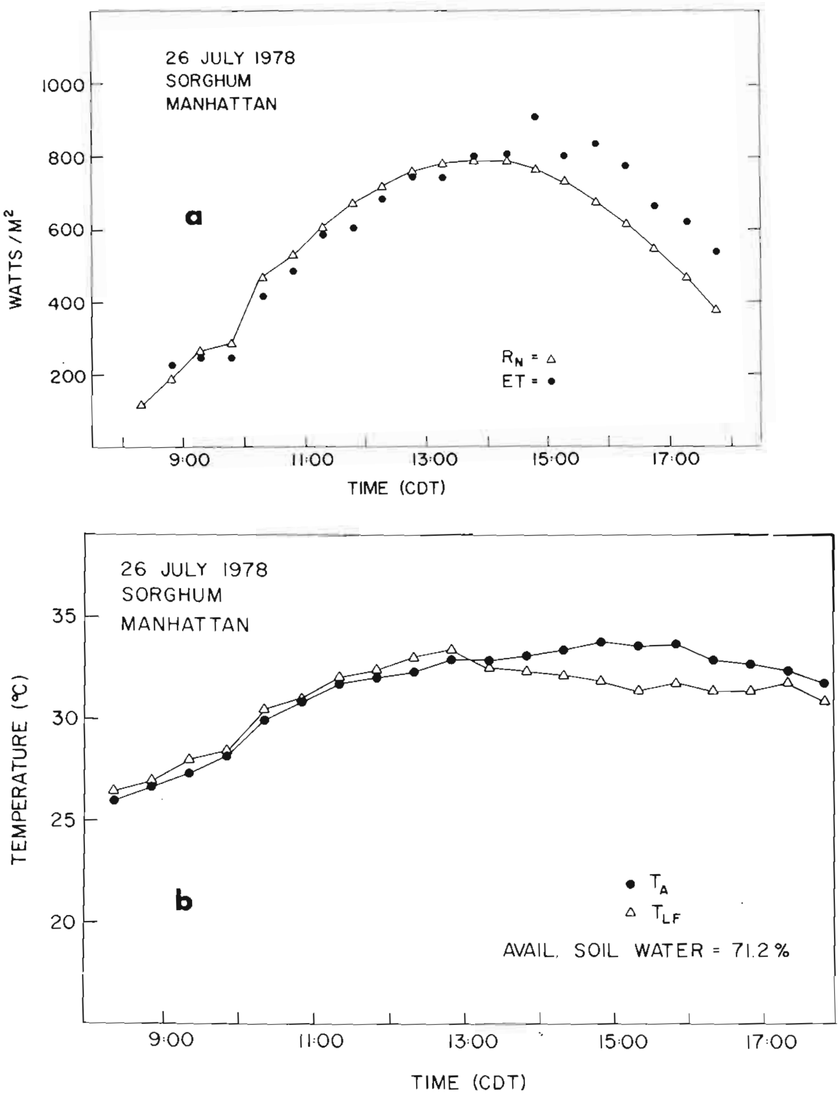


Fig. 5. Sorghum energy balance (a) and sorghum-leaf temperature and air temperature at the top of the canopy (b) on 26 July 1978.

The temperatures of sorghum flag leaf (T_{LF}) and corn ear leaf ($T_{L\ ear}$) are also presented in Figs. 3 to 6. Temperatures of leaves at different canopy heights were similar to T_{LF} and $T_{L\ ear}$; for clarity they are not presented in the figures. Air temperatures were measured at approximately 30 cm above the top of flag leaf. The maximum air temperature (T_A) on 27 July and 10 August were 31.8 and 31.2°C, respectively. Both T_{LF} and $T_{L\ ear}$ were either equal to or greater than T_A. The flow of sensible heat was, therefore, away from the canopy.

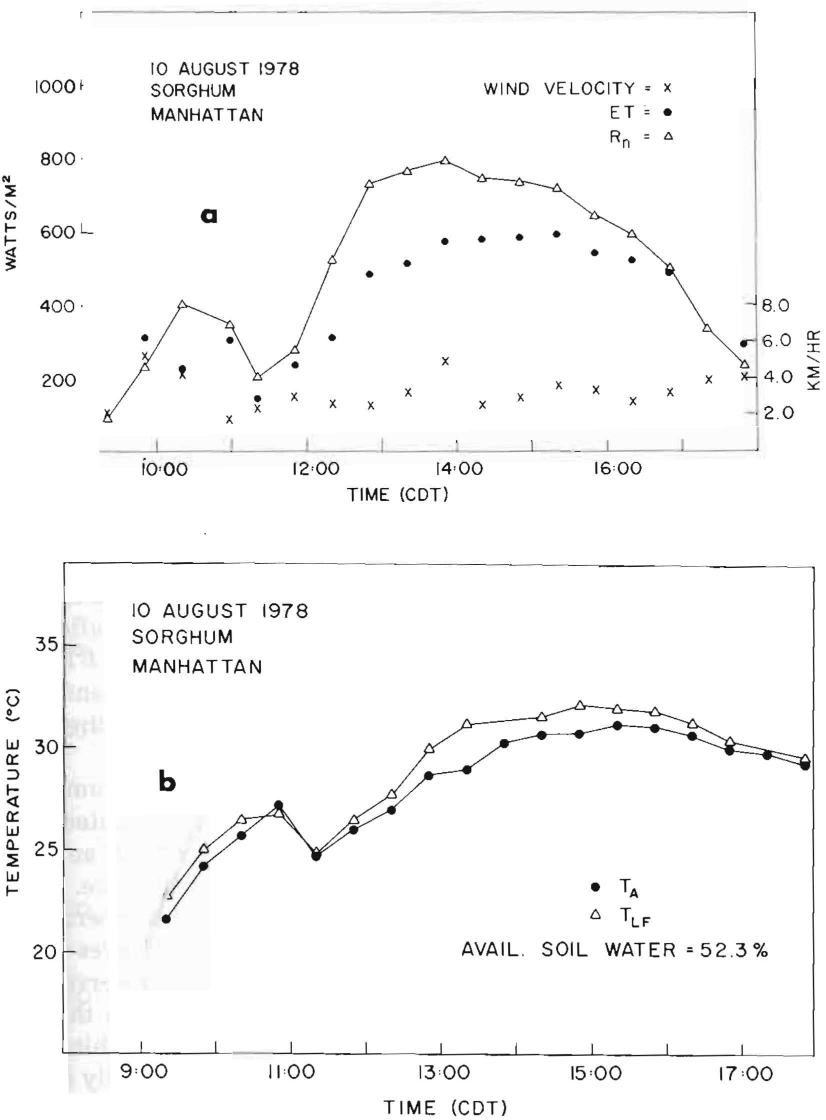


Fig. 6. Sorghum energy balance (a) and sorghum-leaf temperature and air temperature at the top of the canopy (b) on 10 August 1978.

The maximum air temperatures (T_A) on 17 July and 26 July (Figs. 3b and 5b) were 34.2 and 34.0°C, respectively. The corn ear leaf and sorghum flag leaf were warmer than the air early in the day and cooler than the air later in the day. Crossover between the corn ear leaf temperature and air temperature, and between the sorghum flag leaf temperature and air temperature was observed at 33°C. Corn and sorghum leaf temperatures remained near 33°C after the air temperature had exceeded leaf temperature. Hofstra and

TABLE II

Summary of prevailing soil, plant and meteorological conditions on 17, 26, and 27 July and 10 August, 1978

Date	Crop	θ_{avail} (%)	Growth stage	*LAI*	$T_{A\,max}$ (°C)	Daily solar radiation ($W\,m^{-2}$)	Av. wind velocity ($km\,h^{-1}$)
17/07/78	Corn	77.5	4.0	4.7	34.2	526.3	6.6
26/07/78	Sorghum	71.2	6.0	6.4	34.0	570.9	3.8
27/07/78	Corn	66.0	5.5	4.9	31.8	572.8	5.6
10/08/78	Sorghum	52.0	7.5	5.4	31.2	451.8	3.2

Hesketh (1969) observed increasing stomatal apertures with increasing air temperatures up to 36°C (leaf temperatures were not measured) provided that the leaves were not under water stress. Presumably, maximum stomatal opening for corn and sorghum occurs at leaf temperatures of about 33°C. As the air temperature continues to increase well above 33°C ($T_A > 35$°C), which increases the energy load on the leaf, transpiration rate becomes limited and leaf temperature will increase above 33°C under moderate vapor pressure deficits.

The time of the T_L and T_A crossover corresponded to the time ET exceeded R_n. When the air temperature exceeds 33°C, the canopy tends to remain near 33°C, and the sensible heat flux is toward the canopy, thereby resulting in ET greater than R_n.

Prior to the time of temperature crossover on hot days when sorghum and corn provide full ground cover, the sorghum ET closedly approximated R_n while the corn ET were generally lower than R_n. The profiles of leaf and air temperatures (Fig. 7) may partially explain that observed difference. The profiles shown are for periods before and after the times of temperature crossover on 17 and 26 July. Before the crossover times, the corn leaves were generally warmer than the air within and above the canopy. This observation suggests that, in general, the corn plant was losing sensible heat to the air while for sorghum, only the flag leaf was warmer than the air within and above the canopy. The sensible heat lost by the flag leaf was partially compensated for by the sensible heat gained by the cooler lower leaves.

Water stress

Figures 8 and 9 show seasonal trends in the midday values of R_s, ψ_L, and difference between leaf and air temperature ($\Delta T = T_L - T_A$) for both the irrigated and non-irrigated corn and sorghum. The ΔT data presented were for days when $T_A > 33$°C. No significant difference was observed in the R_s and ψ_L values between the irrigated and nonirrigated sorghum (Fig. 8), indicating that no water stress existed in the sorghum plot. Presumably the transpiration rates were not limited and leaf temperature did not rise above air

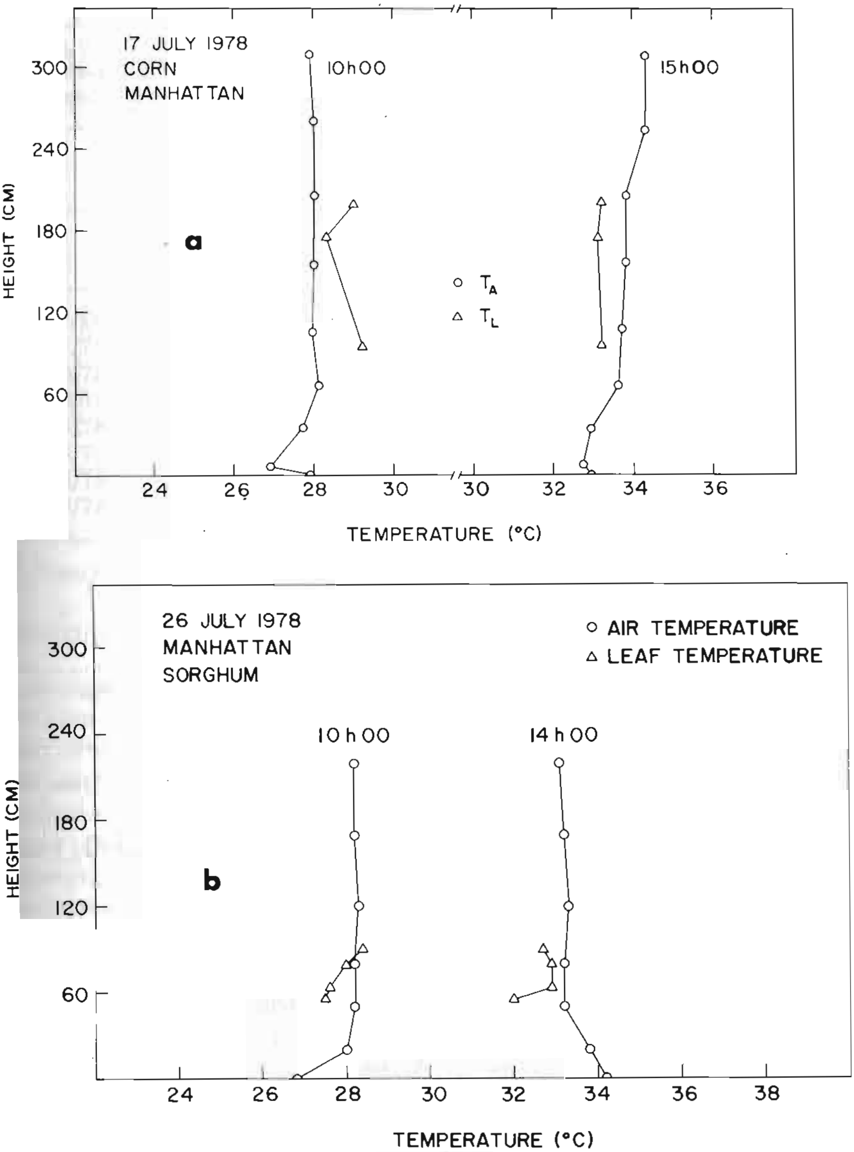
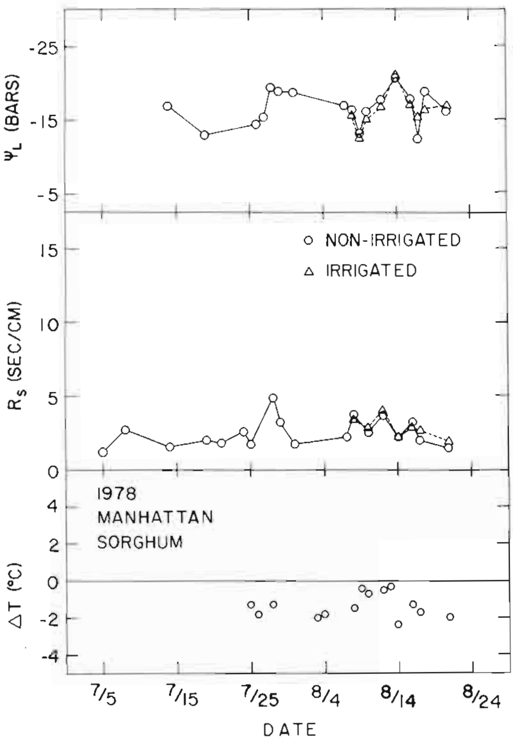


Fig. 7. Profiles of leaf temperatures and air temperatures on 17 July (a) and 26 July (b) 1978. Crop height for corn (a) and sorghum (b) was 220 cm and 110 cm, respectively.

temperature; hence the negative midday ΔT values. The available water in the sorghum plot approached $0.35\,\theta_{max}$ about 25 August (hard dough stage). That is consistent with the finding of Sumayao et al. (1977) that sorghum is not stressed at $\theta_{avail} > 35\%$.

Values of R_s and ψ_L of the non-irrigated corn departed from those of the irrigated corn plants on 12 August (beginning dough stage), indicating that



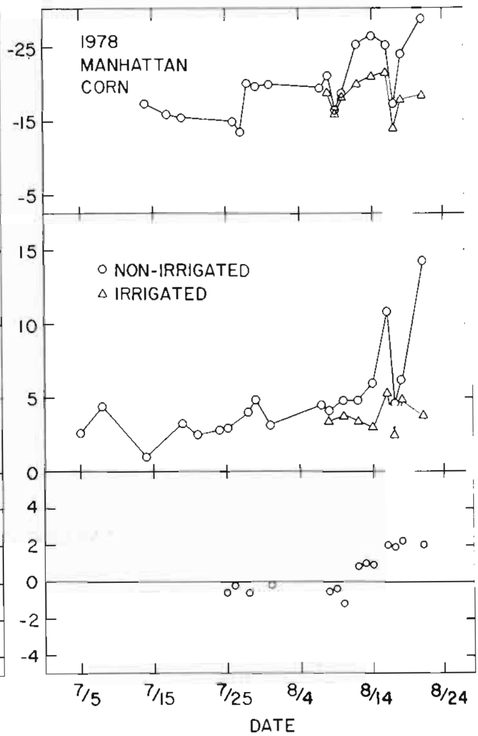


Fig. 8. (left) Midday values of stomatal resistance (R_S), leaf-water potential (ψ_L), and ΔT of sorghum.

Fig. 9. (right) Midday values of stomatal resistance (R_S), leaf-water potential (ψ_L), and ΔT of corn.

the non-irrigated corn plants were stressed. On the same day, the midday values of ΔT switched from negative to positive, indicating reduced transpiration rates. The available soil water on 12 August was 37% — higher than the limiting soil water content reported by Ritchie (1973) for corn. Erie (1962) determined that several crops in Arizona should be irrigated when $\theta_{avail} = 0.6$ to $0.7\,\theta_{max}$ in the top meter of soil. With high soil water, R_s of both corn and sorghum was below 5 s cm^{-1} (Figs. 8 and 9). With limiting soil water content, corn R_s was high as 14.3 s cm^{-1} (Fig. 9).

Table III summarizes measurements of T_C (by infrared thermometry) and the corresponding measurements of T_A (thermocouple) above the canopy. When $T_A > 33°C$, $(T_C - T_A)$ was negative for the irrigated and non-irrigated sorghum and for the irrigated corn, and positive for the non-irrigated corn beginning 12 August. A maximum difference of 0.4°C was observed between the non-irrigated and irrigated sorghum canopy temperatures compared with a 2.7°C difference between the non-irrigated and irrigated corn canopy temperatures. These observations are consistent with Figs. 8 and 9 — sorghum was not under stress while the corn was.

TABLE III

Canopy temperatures (T_C, °C) measured with a Barnes PRT-5 IR thermometer and air temperatures (T_A, °C) measured with copper—constantan thermocouples at midday*

Date	Corn			Sorghum		
	T_A	T_C		T_A	T_C	
		Irrigated	Non-irrigated		Irrigated	Non-irrigated
27/07/78	30.7	—	29.5	31.9	—	29.5
28/07/78	33.6	—	32.0	34.2	—	30.4
07/08/78	30.0	31.1	31.1	29.6	29.5	29.5
08/08/78	32.4	32.3	32.3	33.4	30.2	30.2
12/08/78	32.5	32.7	34.7	33.8	32.5	32.2
14/08/78	35.3	33.5	35.6	35.9	32.4	32.6
16/08/78	33.5	32.4	34.3	34.0	32.1	32.2
17/08/78	34.9	33.1	35.8	35.0	33.2	33.6

* Observation times were between 1100 and 1400 CDT.

SUMMARY AND CONCLUSIONS

Actual ET of corn and sorghum grown under nonlimiting soil water conditions exceeded R_n when air temperatures were greater than 33°C. At midday when air temperatures were above 33°C, the leaves were cooler than the air and sensible heat flux was toward the canopy. Accordingly, evapotranspiration exceeded net radiation during these periods. We observed sensible heat fluxes of $-89.9\,\mathrm{W\,m^{-2}}$ for corn and $-157.3\,\mathrm{W\,m^{-2}}$ for sorghum towards the canopy which are equivalent to increases in ET of 23 and 44%, respectively.

Stomatal resistance, leaf-water potential, and leaf temperature measurements on corn plants indicated a reduction in transpiration at a soil moisture availability of about 0.35 θ_{max}. The results of this experiment suggest that knowledge of leaf and air temperatures, which are relatively easy and inexpensive to determine, can be useful in assessing the water status of corn and sorghum.

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