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MICROCLIMATE—PLANT ARCHITECTURAL INTERACTIONS: INFLUENCE OF LEAF WIDTH ON THE MASS AND ENERGY EXCHANGE OF A SOYBEAN CANOPY*

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ABSTRACT

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Two isolines of soybean (*Glycine max* L. Merrill, cv. Clark) differing only in leaf width were studied to ascertain the effects of leaf width on the canopy microclimate and mass and energy exchanges. The study was performed during the 1981 growing season at Mead, Nebraska. Mass and energy exchanges were determined by means of micrometeorological techniques.

Turbulent mixing was affected in a complex manner. Before full cover was achieved, turbulent mixing (expressed in terms of friction velocity, u_*) was slightly greater over the isoline with narrower leaves (denoted CLN). After full-cover was achieved, turbulent mixing was greater over the isoline with normal leaves (CN). Analysis of data indicated that greater u_* values in the CN canopy were due to greater canopy density which caused greater bluff-body effects.

Differences in leaf width did not affect the above-canopy radiation balance, but did affect the within-canopy profile of net radiation (R_n). R_n was greater deep inside the CLN isoline since this isoline established a canopy with less leaf area. This difference in the vertical profile of R_n affected the canopy microclimate and the partitioning of this radiation. Higher air temperatures, lower vapor pressures, lower latent heat exchange and greater sensible and soil heat flux were observed in the CLN canopy. Greater CO_2 concentrations were also measured within the CLN canopy because warmer soil temperatures caused greater soil efflux of CO_2 . Also, less leaf area of that canopy prevented a stronger drawdown in $[\text{CO}_2]$.

Canopy CO_2 exchange was greater over the CLN isoline when expressed on a leaf area basis, whereas no differences in CO_2 exchange were observed between fluxes expressed on a ground area basis. The CO_2 -water flux ratio, an index of water use efficiency, was improved in the CLN crop because of its lower evapotranspiration rates.

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INTRODUCTION

Altering leaf width influences momentum, mass and energy exchanges on a leaf and canopy basis. For example, reducing leaf width decreases the leaf boundary layer resistance to momentum transfer (Parkhurst et al., 1968; Baker and Myhre, 1969; Campbell, 1977; Zangerl, 1978; Grace, 1980) and facilitates the penetration of light into the crop canopy (Hicks et al., 1969). This latter result led Hicks et al. (1969) to speculate that a reduction in leaf width might increase CO₂ uptake in canopies of C₃ species, since better light distribution would increase the amount of light available to the lower light-unsaturated leaves. Results from a modeling effort by Waggoner et al. (1969) indicate that deeper light penetration into a canopy with narrow leaves could result in reduced latent heat exchange.

In the late seventies, chamber techniques were used in several field studies to investigate the influence of leaf width on the CO₂ and water vapor exchange of several species. In one such study, Pegelow et al. (1977) found that a reduction in leaf width causes a decrease in CO₂ exchange but does not affect the rate of transpiration. Zangerl (1978), on the other hand, reported that a more complex relationship occurs between leaf width, photosynthesis and transpiration. He found in *Abutilon theopasti* that leaf width could, depending on conditions, either increase or decrease photosynthesis and transpiration. Zangerl (1978) argued that his results were due to 'trade-offs' between leaf temperature and the leaf boundary resistance, since both are affected by leaf width. Egli et al. (1970) and Hiebsch et al. (1976) reported that, on a leaf area basis, photosynthesis is greater in a soybean canopy with narrower leaves. They attributed this increase in photosynthesis to greater availability of light to the lower light unsaturated leaves. Photosynthetic rates of the normal and narrow-leafed soybean canopies did not differ when expressed on a ground area basis, since narrow-leafed soybeans establish a canopy with less leaf area. Egli et al. (1970) also reported that a reduction in leaf width reduced transpiration. Hiebsch et al. (1976) found no such effect.

As mentioned above some disagreement prevails on the question of how alteration in leaf width may affect momentum, mass and energy exchanges between a canopy and the atmosphere. Many of the uncertainties reported in the literature might have been resolved had detailed observations been made of microclimatic and physiological conditions. Here we attempt to improve the understanding of the influence of leaf width on the canopy microclimate and mass and energy exchanges between canopies of two near-isogenic lines of a soybean cultivar differing only in leaf width.

MATERIALS AND METHODS

The study was conducted during the summer of 1981 at the University of Nebraska Agricultural Meteorology Laboratory at Mead, Nebraska (41° 09' N; 96° 30' W; alt. 354 m above msl). Soybeans (*Glycine max* L. Merrill, cv.

Clark) were planted on May 27, 1981 in an adjoining portion of an experimental field. The western portion (75 m E-W by 210 m N-S) was planted with the normal Clark isoline (CN). The east side of the field (85 m E-W by 210 m N-S) was planted with a Clark cv. isoline differing only in leaf width (CLN). The leaf width of the CLN isoline was between 0.015 and 0.03 m. The leaf width of the CN isoline was between 0.04 and 0.06 m. The narrow leaf isoline was developed by Dr. R.L. Bernard (USDA and University of Illinois) and is described in Bernard and Weiss (1973).

The crops were planted in 0.75 m wide rows oriented north-south. Because of limited seed supply, border fields extending 600 m to the south and 200 m to the east and west of the main experimental plot were planted with the Calland cv. The soil at the site is Typic Argiudoll (Sharpsburg silty clay loam).

Air temperature and vapor pressure were measured at 1.25, 1.50 and 1.75 m above the ground with an automatic self-checking psychrometer (Rosenberg and Brown, 1974). Once each hour the psychrometer assembly rotated automatically into a horizontal position for calibration.

Air temperature and vapor pressure were also measured inside the canopy. 'Mini-psychrometers' adapted from a design by Stigter and Welgraven (1976) were used for this purpose. Profiles were measured at three locations within the canopy to account for horizontal heterogeneity. Profiles were measured in the row, 0.10 m from the row and midway between two rows at 0.10, 0.30, 0.50, 0.70 and 0.90 m above the ground.

Air was sampled to determine CO₂ concentrations in both fields with multilevel manifolds at 0.30, 0.50, 0.70, 0.90, 1.25, 1.50 and 1.75 m above the ground. The manifolds had six air intakes at each level. These were spaced equidistantly over a horizontal distance of 2.5 m. CO₂ concentrations were measured with a system which employed an absolute and a differential infrared gas analyzer (see Rosenberg and Verma, 1976 for details). Once each hour both analyzers were automatically calibrated with standard gases of known concentration. These gases are traceable to the CO₂ standards maintained by Dr. C.D. Keeling of the Scripps Institute of Oceanography, La Jolla, California.

Net radiation (R_n) was measured above each canopy with a Swissteco net radiometer.* Net radiation was measured within each canopy at 0.20, 0.40, 0.60, and 0.80 m with strip net radiometers.** These were 0.35 m long and 45 mm wide. Impens et al. (1970) reported that great spatial variation of R_n occurs within crop canopies. To account for this variability R_n was measured at six locations at 0.60 and 0.80 m, at four locations at 0.40 m and at two locations at 0.20 m. Soil heat flux was measured in each plot with three soil heat flux plates.*** These plates had a sensitivity of 0.25 W m^{-2}

* Swissteco Pty. Ltd., Melbourne, Australia, Type S-1.

** Manufactured and calibrated at the University of Nebraska.

*** Concept Engineering, Old Saybrook, CT, Model F-080-4.

(μv^{-1}) and an accuracy of $\pm 2\%$. The plates were buried 10 mm below the soil surface and were spaced equidistantly between the rows to minimize bias due to the diurnal change in the sun's azimuth.

Wind speed profiles were measured above the canopy with sensitive three-cup anemometers.* These anemometers were placed above each canopy at 0.25 m intervals between 1.25 and 2.50 m. Wind profiles were measured within the canopy using heated thermistor anemometers. Profiles were measured between the rows at 0.10, 0.30, 0.50, 0.70 and 0.90 m. Details of these instruments and measurement procedures are provided in Bergen (1971) and Baldocchi et al. (1983a).

Plant water potential (ψ) was measured hourly with a Scholander-type chamber.** Four to six sunlit leaves from the upper canopy were selected for this purpose. Immediately after excision, each leaf was placed into a plastic bag, full of moist air, and then placed into the pressure chamber for measurement. Stomatal resistance was measured with a steady-state porometer.*** Leaves were randomly selected from the upper sunlit portion of the canopy. Mean stomatal resistance (r_s) was computed on the assumption that resistances of the top and bottom sides of the leaf act in parallel.

Leaf water potential and stomatal resistance measurements were made to provide an index of crop water status. Measurements of actual canopy water status require weighted measurements of both shaded and sunlit leaves at various levels inside the canopy. Such intensive sampling was not feasible in our experiment. However, since the upper sunlit leaves are the first to experience water stress, we feel that these measurements provide an adequate indication of the water status of the crop.

Both canopies grew substantially during the period of observation. *LAI* of the CN canopy increased from 2.3 to 5.6 and that of the CLN canopy increased from 1.9 to 4.4. Vertical profiles of *LAI* are shown in Fig. 1 for several periods during the growing season.

Analytical considerations

Fluxes of CO_2 , latent heat and sensible heat were determined using the flux-gradient theory. Application of this theory allows computation of fluxes as the product of the turbulent exchange coefficient and the vertical gradient of the entity of interest. Turbulent exchange coefficients for CO_2 , water vapor and sensible heat were assumed identical and were computed by means of the Bowen-ratio energy balance technique (see Rosenberg et al., 1983 for details). Gradients were determined between the heights 1.25 and 1.75 m. Calculations of CO_2 flux (F_c) and latent heat (LE) were corrected for the effects of moisture exchange on air density (Webb et al., 1980).

* Cayuga Development, Ithaca, NY, Model WP-1.

** Soil Moisture Equipment Corp., Santa Barbara, CA, Model 3005.

*** Lambda Instrument Co., Lincoln, NE, Model LI-1600.

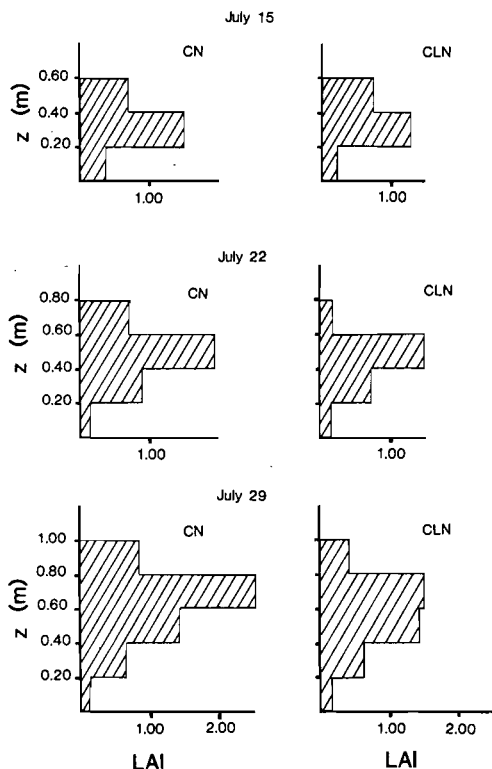


Fig. 1. Vertical profiles of leaf area index in CN and CLN canopies during the growing season.

These fluxes were measured during periods of southerly winds (135 to 225 degrees), providing a fetch to height ratio exceeding 70 to 1.

Water use efficiency was expressed in terms of an index, the CO_2 -water flux ratio ($CWFR$), which is the ratio of the mass flux of CO_2 to that of water vapor. $CWFR$ values are lower than water use efficiency values since canopy CO_2 exchange (F_c) underestimates canopy photosynthesis and canopy water vapor exchange (LE) overestimates canopy transpiration. This index, however, can provide useful information on the overall effect of an alteration in leaf width on water use efficiency.

Turbulent mixing was characterized by the friction velocity (u_*) which was computed using drag coefficients measured close to the canopy (see Deacon and Swinbank, 1958; Bradley, 1972; Verma et al., 1976; for details).

The general shape of the net radiation profile was described using an analogue of the Beer-Bouguer Law (see Brown and Covey, 1966; McCaughy and Davies, 1974; Ross, 1981):

$$Rn(z) = Rn_0 \exp[-\gamma f(z)] \quad (1)$$

where Rn_0 is net radiation at the top of the canopy, γ is the extinction coefficient for net radiation and $f(z)$ is the cumulative leaf area index at

height z . Measurements of Rn and computations of γ were used to infer the solar radiation environment within the canopy since Rn is highly correlated with solar radiation.

A common data set was constructed to permit examination of the influence of leaf width on mass and energy exchanges. Paired observations (each representing 45 min averages) were selected from periods with the fetch to height ratio exceeding 70 to 1 and when no instrument malfunctions occurred. This data set contains observations made between July 10 and July 30, 1981. The analysis did not include any data collected after July 30 since a thunderstorm on August 1 lodged the crop. Variables were compared by means of a one-tailed, paired t -test, with significance determined at the 5% level of probability.

RESULTS AND DISCUSSION

Turbulent mixing

Friction velocities (u_*) measured over the CN and CLN canopies are compared in Fig. 2 and Table I. These data fall into two distinct groups: before the canopy was fully developed u_* values were slightly greater over the CLN canopy, whereas, after full cover u_* was greater over the CN isolate.

Differences in u_* can be explained by examining the momentum balance above and within the canopy (see Thom, 1975; Grace, 1980; Raupach and Thom, 1981). Momentum transfer to a canopy (τ) can be expressed in terms of friction velocity by the following equation:

$$\tau = \rho u_*^2 \quad (2)$$

where ρ is air density. With the aid of the following one-dimensional re-

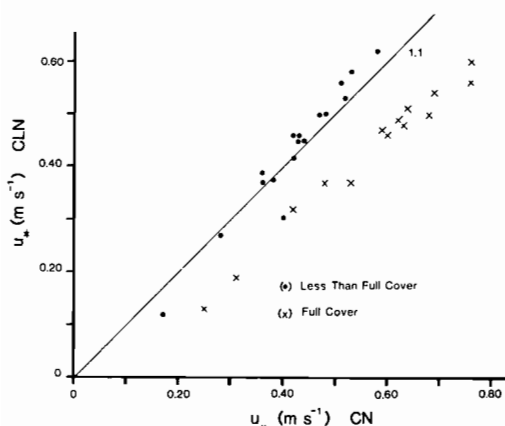


Fig. 2. Friction velocity (u_*) measured over the CN and CLN canopy. Each datum represents a 45-min average.

TABLE I

Statistics from paired t -tests comparing measurements made over normal leafed (CN) and narrow leafed (CLN) isolines of Clark cv. soybeans. 'n' is the sample size, 't' is the computed sample t -statistic, and $t_{0.05}$ is the t value for the one-tailed test at the 5% level of significance. Sample means and standard deviations (std. dev.) for the respective isolines are given. Means of the paired differences and their respective 90% confidence intervals (CI) are also given.

Variable	Units of variable	n	t	$t_{0.05}$	CN Mean	CN Std. Dev.	CLN Mean	CLN Std. Dev.	Mean of the difference	90% CI
u_s^a	$m s^{-1}$	16	2.86	1.73	0.42	0.10	0.44	0.12	-0.018	0.011
u_s^b	$m s^{-1}$	14	-18.9	-1.76	0.57	0.16	0.43	0.14	0.14	0.007
Rn	$W m^{-2}$	46	0.23	1.68	265	163	265	162	-0.031	1.91
γ	-	39	15.2	1.68	0.26	0.05	0.38	0.07	-0.12	0.013
[LE]	$W m^{-2}$	30	5.55	1.70	280	143	204	99.1	76.0	23.2
ψ	MPa	41	0.51	1.68	-0.63	0.34	-0.63	0.35	0.004	0.019
[H]	$W m^{-2}$	30	-6.02	-1.70	23.4	45.2	96.2	79.9	-72.8	20.6
[S]	$W m^{-2}$	30	8.01	1.70	31.2	22.0	38.8	26.6	-7.6	5.4
r_s	$s m^{-1}$	20	-0.16	-1.73	87.7	77.0	86.8	74.6	0.9	9.8
F_c	$mg m^{-2} s^{-1}$	16	0.20	1.75	0.70	0.50	0.72	0.12	-0.02	0.15
F_c/LAI	$mg m^{-2} s^{-1}$	16	2.01	1.75	0.24	0.19	0.29	0.16	-0.05	0.04
CWFR	$mg g^{-1}$	16	3.56	1.75	5.99	3.50	11.1	3.84	-5.11	2.52

^a These data were obtained between July 10 and July 17, before either canopy had achieved full cover.

^b These data were obtained between July 24 and July 30, after both canopies had achieved full cover.

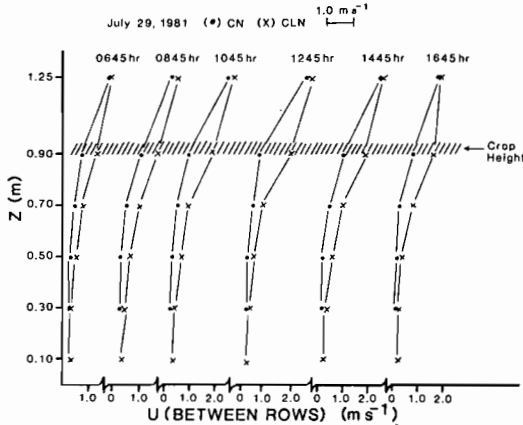


Fig. 3. Profile of wind speed within the CN and CLN canopies after full-cover was achieved. These profiles were measured between rows.

relationship, momentum transfer within the canopy can be described as:

$$\tau(z) = \int_z^h \rho C_c(z) a(z) u^2(z) dz \quad (3)$$

where h is canopy height, $C_c(z)$ is the effective drag coefficient at height z , $a(z)$ is the leaf area density at z and $u(z)$ is the within-canopy wind speed at z .

Applying eq. 2 to the data presented in Fig. 2 indicates that after full cover was achieved, momentum transfer (τ) was, on the average, greater by about 40% for the CN canopy. Examination of eq. 3 suggests three factors that can account for this greater momentum exchange (τ) for the CN crop: (a) greater within-canopy wind speeds, (b) greater canopy density and (c) greater elemental drag. The influence of these factors on momentum transfer (τ) and u_* is discussed below.

Figure 3 shows a comparison of wind speed profiles measured within the two canopies. Wind speed was lower in the CN canopy than in the CLN canopy. In the upper half of the crop wind speeds were generally 0.40 to 1.00 m s^{-1} less in the CN canopy. This factor does not account for greater u_* values over the CN canopy.

Leaf area densities were computed from the leaf area index profiles presented in Fig. 1. Computations show that leaf area density in the fully-developed crops was about 25% greater in the CN canopy.

The effective drag coefficient is often assumed to be independent of height (Thom, 1975). Using this assumption, C_c can be expressed as:

$$C_c = u_*^2 / \int_0^h a(z) u(z)^2 dz \quad (4)$$

We computed values of C_c based on eq. 4 for a typical period (July 29, 1245 hours, see Fig. 3). Computations show that C_c for the CN and CLN

canopies was 0.305 and 0.072, respectively. C_e in the CN canopy was greater than that of the CLN canopy because the higher foliage density of the CN canopy increases the sheltering of leaves, which increases C_e (see Landsberg and Thom, 1971). The factor of four difference between the C_e values may be debated since it is difficult to measure leaf area index profile with precision. Furthermore, the computations of C_e were based on wind speed measurements made midway between two rows. Baldocchi et al. (1983a), however, show that there is a considerable spatial variability in wind speed across a row of soybeans. Differences in C_e may have been reduced had spatially-averaged wind speeds been used in these computations.

The analysis presented above can be summarized as follows: greater u_* values measured over the mature CN canopy resulted from that canopy having a greater foliage density, which caused greater effective drag or "bluff-body" effects.

Friction velocities over a fully-developed canopy with narrow leaves are much different than those expected based on measurements of momentum transfer over leaves of varying widths. Many workers (e.g., Parkhurst et al., 1968; Baker and Myhre, 1969; Campbell, 1977; Zangerl, 1978; Grace, 1980) report that the resistance to momentum transfer increases with decreasing leaf width. This would translate into an increase in momentum transfer and friction velocity as leaf width is reduced. Under wind tunnel conditions, most momentum transfer is due to "skin-friction" effects since the wind blows parallel to the leaf. Our results, however, deal with whole canopies in the field environment. Under field conditions most momentum transfer is due to "bluff-body" effects, since leaves in a canopy are randomly oriented and are often perpendicular to the wind flow (Grace, 1980; Raupach and Thom, 1981). "Skin-friction" effects, under field conditions, are quite minimal in comparison.

As stated above, u_* values were slightly greater over the CLN canopy before full-cover was attained. The mean difference was 0.02 m s^{-1} . Within-canopy wind speed measurements are not available for the early period of the season so a momentum balance analysis is not possible. *LAI* of the two canopies were similar, however, suggesting that differences in "bluff-body" effects were small.

Net radiation

Net radiation (R_n) measurements above the CN and CLN canopies are compared in Table I. No significant differences in R_n were observed between the two isolines as the two canopies grew from sparse to full cover. This suggests that differences in leaf width had no influence on the flux densities of outgoing shortwave and longwave radiation.

Net radiation profiles within the CN and CLN canopies are presented in Figs. 4a and 4b for two stages of growth: (a) on a day before either canopy had achieved full-cover (*LAI* for the CN and CLN canopies were 2.7 and 2.3,

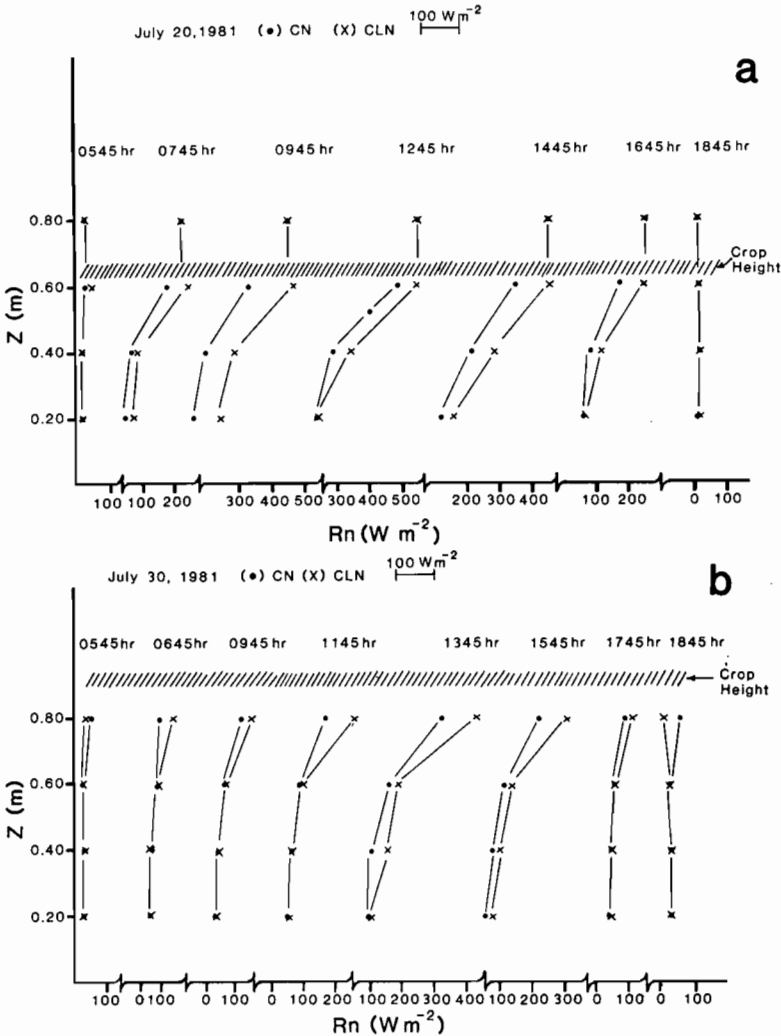


Fig. 4(a) Profiles of net radiation (R_n) within the CN and CLN canopies before full-cover was achieved. (b) Profiles of net radiation (R_n) within the CN and CLN canopies after full-cover was achieved.

respectively); and (b) on a day after both canopies had achieved full-cover (LAI for the CN and CLN canopies were 5.6 and 4.4, respectively). Both figures show that R_n decreased with depth into the canopy, in accordance with eq. 1.

Prior to full-cover (Fig. 4a) R_n within the CLN canopy was generally greater by 60 to 130 W m^{-2} during the day. Differences in R_n profiles diminished after both canopies achieved full-cover (Fig. 4b). For example, above 0.60 m R_n was only about 50 to 100 W m^{-2} greater in the CLN crop, whereas below 0.60 m differences were of the order 20 to 50 W m^{-2} . Because

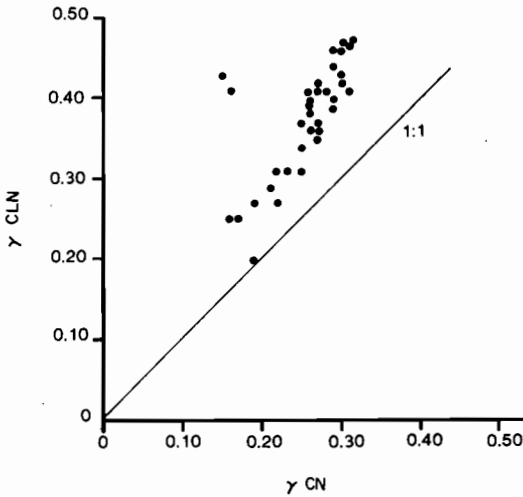


Fig. 5. Net radiation attenuation coefficient (γ) measured within the CN and CLN canopies.

of the exponential dependence of R_n on cumulative LAI (see eq. 1), differences between R_n profiles were smaller after full-cover.

Net radiation profiles are affected by the optical properties, orientation and distribution of leaves (Ross, 1981). Differences between the R_n profiles were primarily due to lesser leaf area in the CLN isoline. Leaf optical properties were not affected by differences in leaf width and, therefore, are unlikely to have contributed to these observations.

Isogenic differences in leaf width can affect leaf distribution. We investigated the effect of alterations in leaf distribution on the vertical profile of R_n by examining the attenuation coefficient, γ , defined by eq. 1. Coefficients of net radiation attenuation were computed using data obtained on July 23, 24, 29, and 30, 1981, between 0600 and 1800 hours. Figure 5 shows a comparison of γ measured inside the CN and CLN canopies. Values of γ were significantly greater in the CLN canopy; mean γ values for the CN and CLN isolines were 0.26 and 0.38, respectively (see Table I).

From these observations we can infer that the CLN canopy, on a normalized leaf area basis, attenuated net radiation more effectively. The explanation for this observation is as follows. Phytoactinometric theory suggests that the attenuation of solar radiation is more effective when leaves are distributed in a uniform rather than a clumped pattern (Lemeur and Blad, 1974; Norman and Jarvis, 1975; Goudriaan, 1977; Ross, 1981). By visual inspection, we established that the leaves of the CLN isoline were arranged more uniformly (or mosaically) than those of the CN isoline, suggesting a mechanism for the more effective attenuation of solar radiation in that crop.

Profiles of air temperature, vapor pressure and CO₂ concentration

Profiles of air temperature above and within fully-developed CN and CLN canopies are presented in Fig. 6a. LAI values for the CN and CLN canopies were 5.6 and 4.4, respectively. The soil surface was dry and both isolines were well-supplied with water. Air temperatures were about 0.5°C higher within the CLN canopy. Since no differential water stress was observed (see ψ and r_s values in Table I) we attribute this observation to greater levels of net radiation, deep inside the CLN canopy, heating the soil surface and adjacent air layer. This contention is based on energy balance considerations (see Rosenberg et al., 1983) and is supported by the measurement of latent, sensible and soil heat fluxes (see Figs. 7, 9 and 10) discussed below.

Although the leaf boundary layer resistance to sensible heat transfer is affected by leaf width, it is not likely to have had a significant effect on within-canopy air temperature. Waggoner et al. (1969), for example, reported that a ten times reduction in the characteristic length of a leaf results in an air temperature change in the forest canopy of less than 0.2°C.

Profiles of vapor pressure above and within fully-developed and well-watered canopies of the two isolines are shown in Fig. 6b. In general, vapor pressures were greater both above and within the CN canopy during the daytime. Above 0.50 m, these vapor pressure differences were of the order 0.05 to 0.1 kPa, whereas below 0.50 m the differences were smaller. These observations are consistent with the greater rates of evapotranspiration in the CN canopy (discussed below).

Better penetration of solar radiation did not affect humidity via its effect on stomatal resistance. This is because the threshold light level for the stomatal opening of soybeans is about 10 W m⁻² of photosynthetically active radiation (Hatfield and Carlson, 1978), a value exceeded inside the lower canopy.

Profiles of CO₂ concentration ([CO₂]) above and within the well-watered CN and CLN canopies are shown in Fig. 6c. Concentrations were generally greater above and within the CLN canopy even though CO₂ uptake (on a ground area basis) from the atmosphere was similar for the two isolines (see Fig. 11a). These concentration differences can be explained by examining the sources of CO₂ above and below the canopy. First, greater penetration of solar radiation into the CLN canopy resulted in greater soil heat flux (see Fig. 10). This effect caused warmer soil temperatures which, in turn, increased the efflux of CO₂ from the soil (see Rosenberg et al., 1983). This process accounts for higher [CO₂] in the lower half of the CLN canopy. Second, lower leaf area in the CLN canopy reduced the drawdown in [CO₂] in the upper portion of that canopy by providing a weaker sink for CO₂.

Fluxes of latent, sensible and soil heat

Latent heat fluxes (*LE*) measured over the CN and CLN canopies are compared in Fig. 7 and Table I. Results show significantly greater *LE* over the

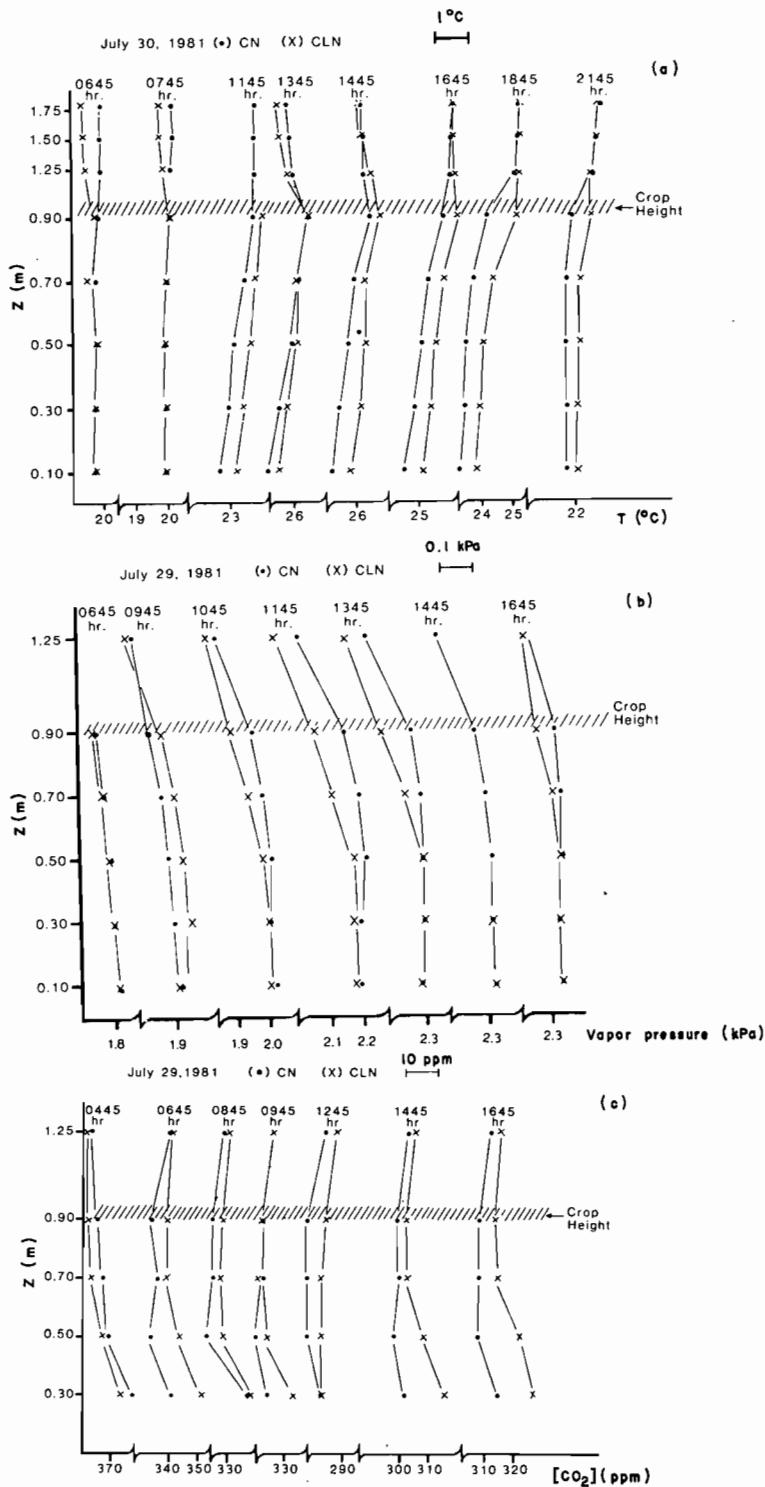


Fig. 6(a) Profiles of air temperature (T) within the CN and CLN canopies. (b) Profiles of vapor pressure within the CN and CLN canopies. (c) Profiles of CO_2 concentration $[\text{CO}_2]$ within the CN and CLN canopies.

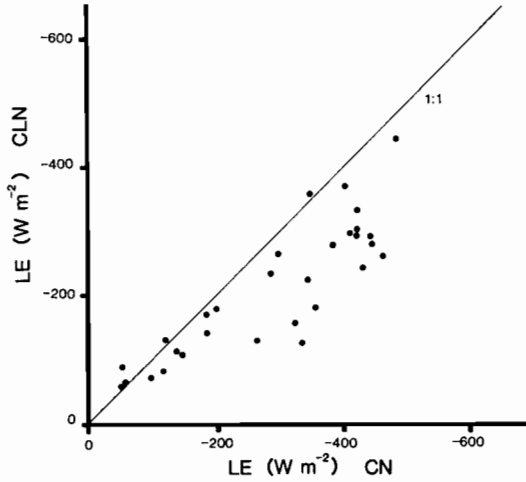


Fig. 7. Latent heat fluxes (LE) measured over the CN and CLN canopies. Each datum represents a 45-min average.

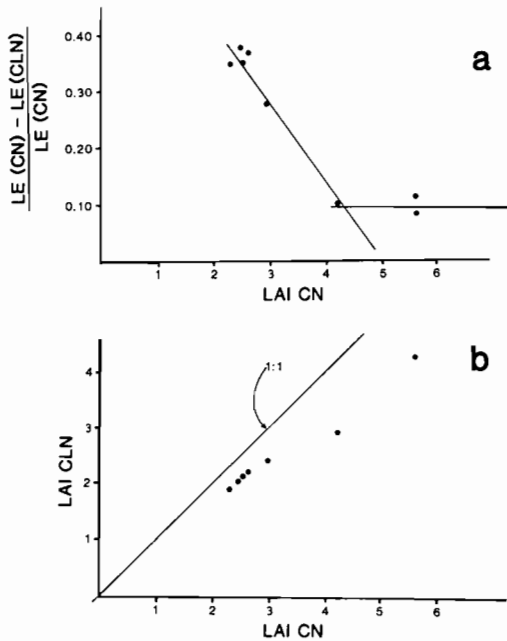


Fig. 8(a) Relative difference between LE measured over the CN and CLN canopies as a function of LAI . Each datum is the mean of hourly observations taken during a daily period. (b) Comparison between LAI measured in the CN and CLN canopies.

CN canopy. Differences in LE between the two canopies, however, diminished as the two canopies developed. Figure 8a shows that LE was about 35% greater over the CN canopy when the LAI of that crop was less than

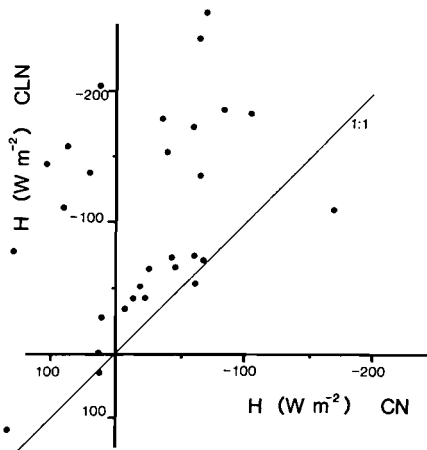


Fig. 9. Sensible heat fluxes (H) measured over the CN and CLN canopy. Each datum represents a 45-min average.

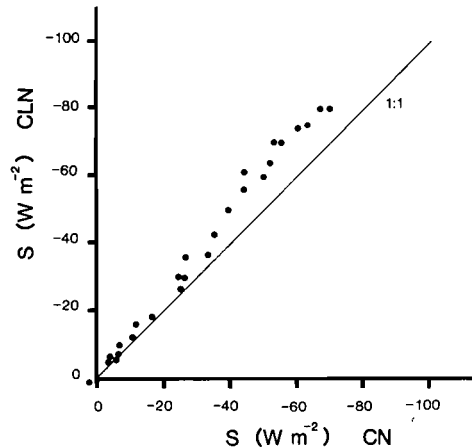


Fig. 10. Soil heat fluxes (S) measured under the CN and CLN canopy. Each datum represents a 45-min average.

three (see Fig. 8b). The differences in LE diminished to about 10% after both canopies achieved full-cover.

Sensible heat (H) and soil heat flux (S) in the two isolines are compared in Figs. 9 and 10, respectively, and in Table I. Both fluxes were greater in the CLN crop.

Results presented in Figs. 1, 7, 9 and 10 indicate that differences in leaf width affected canopy architecture which, in turn, affected the partitioning of net radiation. Greater penetration of solar radiation into the CLN canopy accounts for this differential partitioning. Most of the additional energy in the lower portion of that canopy was likely consumed in heating the soil and adjacent air (see Fig. 6) since the soil surface was dry and leaf area was sparse there (Fig. 1). The modeling efforts of Waggoner et al. (1969) and the experimental work of Baldocchi et al. (1983b) also support this contention. Both groups report that an enhancement in the penetration of solar radiation into a crop canopy alters the partitioning of net radiation by reducing latent heat transfer and increasing sensible and soil heat transfer.

Differences in leaf area are not likely to account for differences in LE after the canopies had achieved full-cover. Brun et al. (1972) and Meyer and Green (1981) report that evapotranspiration of soybeans is independent of leaf area indices greater than three. Stomatal resistances also did not cause the differential partitioning of net radiation since stomatal resistances were similar in the two canopies (see Table I).

Hiebsch et al. (1976) and Pegelow et al. (1977) found no evidence that

differences in leaf width affected canopy transpiration. However, in both of these studies the canopies were fully-developed ($LAI > 3.0$). Egli et al. (1970), on the other hand, reported that transpiration in a narrow-leaved soybean isolate was about 30% less than in the normal isolate. Absolute LAI values were not reported, although the normal isolate had 30% more leaf area than did the narrow leaf isolate.

Values of leaf water potential (ψ) in the CN and CLN isolines are compared in Table I to determine whether the differences in LE , reported above, affected crop water status. No significant difference was found in ψ values. This suggests that the CN isolate was able to take up soil water effectively, thus preventing excessive water stress despite its greater rates of evapotranspiration.

CO_2 flux

CO_2 fluxes (F_c) measured above the two isolines are presented on a ground area and leaf area basis in Fig. 11. No significant differences were found in F_c when expressed on the ground area basis. However, on a leaf area basis F_c values were, on the average, greater over the CLN canopy by about $0.05 \text{ mg m}^{-2} (\text{leaf area}) \text{ s}^{-1}$ (Table I). A better distribution of solar radiation throughout that canopy, providing more light to the lower light-unsaturated leaves, explains this effect. Egli et al. (1970) and Hiebsch et al. (1976) also found that CO_2 exchange rates of soybean canopies, when expressed on a leaf area basis, were greater for the narrow leaf isolate due to a better distribution of light in that canopy. Baker and Myhre (1969) and Pegelow et al. (1977) reported similar results for normal and narrow-leaf cotton isolines.

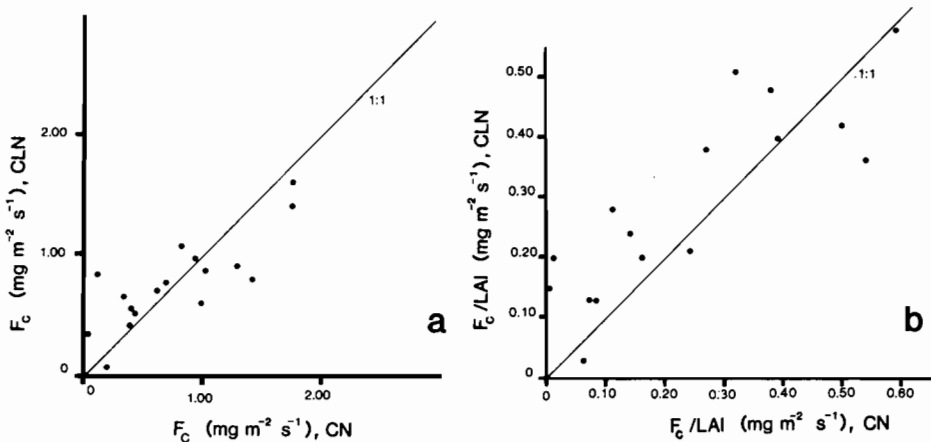


Fig. 11. Canopy CO_2 fluxes (F_c) measured over the CN and CLN canopy. Each datum represents a 45-min average. (a) F_c is on a ground area basis. (b) F_c is presented on a leaf area basis.

CO_2 -water flux ratio

CO_2 -water flux ratio ($CWFR$) measured over the CN and CLN canopies are compared in Fig. 12 and Table I. Greater values of $CWFR$ were found over the CLN isoline. This results from leaf width affecting the canopy architecture, which enhances the penetration of light into the canopy and reduces evapotranspiration. These results seem reasonable in view of our earlier findings (Baldocchi et al., 1983b) that $CWFR$ increases when a morphological modification (additional leaf pubescence in that case) facilitates the penetration of light into the canopy.

Hiebsch et al. (1976) and Pegelow (1977), on the other hand, examined the ratio between canopy photosynthesis and transpiration of soybean and cotton isolines, respectively, differing in leaf width. They found no difference in this ratio.

Tanner (1981), Tanner and Sinclair (1983) and Sinclair et al. (1984) derived the following expression for water use efficiency (WUE):

$$WUE = k_1 / VPD \quad (5)$$

where k_1 is a function of CO_2 concentration in the air and intercellular spaces, and the stomatal and boundary layer resistances to CO_2 and water vapor transfer and the mesophyll resistance to CO_2 transfer. For a given crop k_1 is generally assumed to be constant and, therefore, WUE is expected

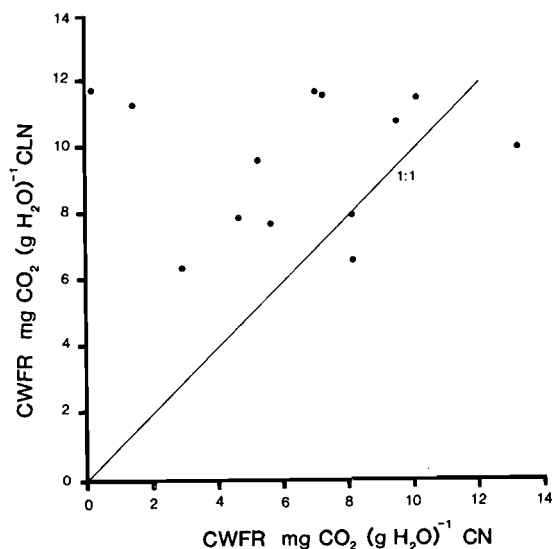


Fig. 12. CO_2 -water flux ratios ($CWFR$) measured over the CN and CLN canopy. Each datum represents a 45-min average.

to decrease with increasing vapor pressure deficits (*VPD*). From Fig. 6 it can be inferred that *VPD* was greater in the CLN canopy since the humidity was lower and the air temperature was greater than in the CN canopy. Yet, as shown in Fig. 12, *CWFR* was greater in the CLN canopy. It appears that the differential penetration of solar radiation and partitioning of net radiation between the two isolines might have altered the overall resistances to transfers of water vapor and CO_2 . This would indicate that k_1 is not the same for the two isolines.

A reduction in leaf width may not lead to an increase in productivity. However, it may be a desirable trait since it appears to cause a reduction in evapotranspiration and an increase in *CWFR*. Such an adaptation may be especially advantageous for rainfed crops or where irrigation water is expensive or in limited supply.

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