

Leaf Pubescence Effects on the Mass and Energy Exchange Between Soybean Canopies and the Atmosphere¹

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ABSTRACT

Mass and energy exchanges with the atmosphere were compared in two soybean (*Glycine max* L. Merr. cv. Harosoy) isolines differing in pubescence density. The study was conducted in a field with a Sharpsburg silty clay loam soil (fine, montmorillonitic, mesic Typic Argiudoll) during the summer of 1980 at Mead, Nebr. Mass and energy exchanges were determined by means of micrometeorological techniques. Evapotranspiration (reported in terms of latent heat flux) was reduced in the densely pubescent isolate. Canopy CO₂ exchange was unchanged on a per unit land area basis. Water use efficiency (reported in terms of the CO₂-water flux ratio) was, accordingly, greater in the densely pubescent isolate. The increase in pubescence did not significantly alter the net radiation balance, turbulent mixing, canopy CO₂ exchange, or plant water status. Observed differences in the partitioning of net radiation into latent and sensible heat can be explained by greater penetration of solar radiation into the densely pubescent canopy. Leaf pubescence appears to alter the spectral characteristics of the leaf and, thus, to facilitate the penetration of solar radiation into the canopy.

Additional index words: Photosynthesis, Evapotranspiration, Water use efficiency, Canopy aerodynamics, *Glycine max* L.

CROP productivity is a function of genetic potential interacting with environmental conditions. In recent years, plant breeders have developed near-isogenic lines

of cultivars that differ in morphological characteristics (Bernard and Weiss, 1973). One intent has been to alter the leaf characteristics and, as a consequence, the micro-environment of the leaf. The micro-environment of a leaf can be altered by changing characteristics that affect the radiation balance or the boundary layer resistance to energy and mass exchange.

A morphological change which affects the environment of the leaf and may benefit crop productivity is increased leaf pubescence. Gausman and Cardenas (1973) found that leaf pubescence on detached soybean leaves decreased the reflectance of near-infrared radiation but had no effect on the reflectance of photosynthetically active

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radiation. Ehleringer et al. (1976), Ehleringer and Bjorkman (1978a, 1978b) and Ehleringer and Mooney (1978), on the other hand, reported that leaf pubescence on *Encelia farinosa* caused an increase in the leaf reflectance of solar radiation. Furthermore, Ehleringer and Bjorkman (1978a) showed that leaf pubescence preferentially reflected near infrared radiation more than photosynthetically active radiation.

There is also evidence in the literature suggesting that leaf pubescence may influence the leaf boundary layer. Woolley (1964) reported that leaf pubescence increased the thickness of the boundary layer over soybean leaves. Ehleringer and Mooney (1978), on the other hand, present evidence suggesting that leaf hairs have only a small impact on the leaf boundary layer thickness of *E. farinosa*.

The resultant effect of additional leaf pubescence has been reported to be a reduction in transpiration (Woolley, 1964; Ghorashy et al., 1971; Ehleringer and Mooney, 1978). This effect has been attributed to leaf hairs reducing the radiation load on the leaf. It is not yet clear as to whether photosynthesis is affected by additional leaf pubescence. Ehleringer and Mooney (1978) found that an increase in pubescence reduced photosynthesis of *E. farinosa* while Ghorashy et al. (1971) found no effect on soybean photosynthesis. Soybean yield, however, has been shown to be greater in a pubescent isolate of the Harosoy cultivar (Hartung et al., 1980).

The effects of pubescence on mass and energy exchange are understood on the scale of the leaf. It is uncertain, however, whether these effects are extendable to a full plant because of the complex geometry of the canopy. Here we report measurements of mass and energy exchange between the atmosphere and the canopies of two near-isogenic lines of a soybean cultivar differing only in pubescence density. Mechanistic explanations for the differences found in mass and energy exchange are proposed.

MATERIALS AND METHODS

Experimental Details

This study was conducted between 18 July and 7 Aug. 1980 at the Univ. of Nebraska Agricultural Meteorology Laboratory at Mead, Nebr. (41° 09' N; 96° 30' W; alt. 354 m above msl). Soybeans (*Glycine max* L. Merr. cv. Harosoy) were planted in adjoining portions of an experimental field of Sharpsburg silty clay loam soil (fine, montmorillonitic, mesic Typic Argiudoll). The east side of the field (65 m E-W by 210 m N-S) was planted with an isolate of Harosoy cv. with normal pubescence (HN). The west field (85 m E-W by 210 m N-S) was planted with an isolate possessing as single dominant gene which increases the density of the pubescence on the leaves, stems and pods (HPD). Border fields to the east, south, and west of the main experimental fields were planted with the HN isolate. The soybeans were planted in 0.75 m wide rows oriented north-south.

The soybean isolines were developed by R. L. Bernard (USDA and University of Illinois) and agronomic differences are discussed by Hartung et al. (1980). Bernard and Weiss (1973) state that leaf hairs on the HPD isolate are about four times more numerous per unit leaf area than on the HN isolate. Gausman and Cardenas (1973) reported that pubescent density on soybean leaves is greater on the abaxial side of the leaf.

Air temperature and vapor pressure were measured over both plots at 1.25, 1.50, 1.75, 2.25, 2.75, and 3.25 m above the ground with an automatic, self-checking, multilevel psychrometer (Ro-

senberg and Brown, 1974). Once each hour the psychrometer assembly rotated automatically into a horizontal position for calibration.

Air was sampled to determine CO₂ concentration 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 surface. The manifolds had six air intakes at each level. These intakes were spaced equi-distantly over a horizontal distance of 2.5 m. The 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 calibrated automatically with standard gases of known concentration.

Wind speed was measured over each canopy at 0.25 m intervals between 1.25 and 2.50 m with Cayuga three-cup anemometers.³ The anemometers were calibrated in a wind tunnel before and after the growing season.

Net radiation (R_n) was measured at 1.85 m above the ground with a Swissteco net radiometer.⁴ Net radiation was measured within the canopy at 0.20, 0.40, 0.60, and 0.80 m using strip net radiometers (SNR). Each SNR was 0.35 m long and 45 mm wide. To account for spatial variability within the canopy, R_n was measured at six locations at elevations of 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 with three soil heat flux plates⁵ placed at a depth of 10 mm in the soil.

The output of all micrometeorological sensors was measured with a computer-controlled data acquisition system and data were recorded on magnetic tape. Counts from cup anemometers were integrated over 5 min periods. The CO₂ concentrations were measured once every 7½ min. All other sensor-produced voltages were measured at the rate of about two times per minute. All data were later averaged over the first 45 min of each hour. The remaining 15 min of each hour were reserved for automatic calibrations of the psychrometers and infrared gas analyzers.

Plant water potential was measured with a pressure chamber⁶ on an hourly basis. Four to six sunlit leaves from the upper canopy were selected for this purpose. Each leaf, after excision, was placed in a plastic bag full of moist air. The bag was immediately inserted into the pressure chamber.

Stomatal resistance was measured on the top and bottom sides of six sunlit leaves with a steady state porometer.⁷ The leaves were randomly selected from the upper portion of the canopy. The mean stomatal resistance (r_s) was computed on the assumption that resistances of the tops and bottoms of the leaves act in parallel.

Both soybean isolines had reached full development by the time measurements reported here were started. The HN and HPD isolines were, respectively, about 1.00 and 1.07 m tall and had leaf area indices of about 3.8 and 4.5.

Analytical Considerations

Fluxes of CO₂, latent heat, and sensible heat were computed using flux-gradient theory: fluxes were computed as the products of the appropriate vertical gradients and exchange coefficients. Calculations of both CO₂ flux (F_c) and latent heat flux (LE)

³ Cayuga Development, Ithaca, New York, Model WP-1.

⁴ Swissteco Pty. Ltd., Melbourne, Australia, Type S-1.

⁵ Concept Engineering, Old Saybrook, CN, Model F-080-4.

⁶ Soil Moisture Equipment Corp., Santa Barbara, CA, Model 3005.

⁷ Lambda Instrument Co., Lincoln, NE, Model LI-1600.

⁸ Baldocchi, D.D. 1982. Mass and energy exchanges of soybeans: Microclimate-canopy architecture interactions. Ph.D. Diss. Available from: Ann Arbor, Mich. Univ. of Nebraska-Lincoln. (Diss. Abstr. DA-8228144) 206 p.

⁹ Nielsen, D. C., B. L. Blad, and S. B. Verma. 1981. Influence of soybean pubescence on radiation balance. 15th Conf. on Agriculture and Forest Meteorology, Anaheim, Calif. 46 p.

¹⁰ Negative values indicate that the flux is directed away from the surface. All fluxes were computed on a ground area basis.

Table 1. Statistics from the paired t-tests comparing the HN and HPD soybean isolines. *t* is the computed sample t-statistic, $t_{0.05}$ is the value for one-tailed test at 5% level of significance and *n* is the sample size. Sample means and standard deviations (SD) for the respective isolines are given. Means of the paired differences and their respective 90% confidence intervals (C.I.) are also included.

Variable	Units of variable	<i>t</i>	$t_{0.05}$	<i>n</i>	HN		HPD		Mean of the differences	C.I.
					Mean	SD	Mean	SD		
u_*	$m s^{-1}$	0.68	1.70	28	0.51	0.13	0.51	0.14	-	-
LE	$W m^{-2}$	-4.98	-1.70	28	328	103	306	98	22	7.4
H	$W m^{-2}$	5.73	1.70	28	106	62	132	65	-26	7.7
F_c	$mg m^{-2} s^{-1}$	-1.23	-1.72	21	0.39	0.35	0.44	0.38	-	-
CWFR	$mg g^{-1}$	2.40	1.72	21	2.93	2.58	3.82	2.94	-0.89	0.64
ψ	MPa	-0.99	-1.73	19	-1.50	0.31	-1.48	0.33	-	-
r_s	$s m^{-1}$	0.22	1.66	85	1.89	142	193	151	-	-

were corrected for the effect of water vapor exchange on the density of dry air (Webb et al., 1980). The exchange coefficients for CO_2 (K_c), water vapor (K_w), and sensible heat (K_H) were assumed identical ($K_c = K_w = K_H$) and were computed by means of the Bowen-ratio energy balance (BREB) method. 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. Details of the computational procedures are given in Baldocchi (1982).⁸

A discussion of the errors associated with the BREB method for computing the fluxes of water vapor and CO_2 are given in Blad and Rosenberg (1974) and Verma and Rosenberg (1975). Under non-advective conditions BREB estimates of CO_2 and latent heat flux have accuracies on the order of 10 to 20%.

The manner in which a crop extracts momentum from the air flowing over it can be characterized by means of the friction velocity (u_*). The magnitude of u_* is indicative of the effectiveness of turbulent exchange between the crop and the atmosphere. Friction velocities were computed for both canopies using drag coefficients measured close to the canopy top (see Deacon and Swinbank, 1958; Bradley, 1972; Verma et al., 1976, for further details). The drag coefficients were computed from wind profile measurements.

A common data set was constructed to determine whether leaf pubescence influenced mass and energy exchange. Paired observations (each representing 45 min averages) were selected from periods during which the fetch to height ratio exceeded 70 to 1 and no instrument malfunctions occurred. This data set contains observations made between 18 July and 7 Aug. 1980. The analysis did not include any data collected after 7 August since a storm lodged the crop on 10 August. Variables were compared by means of a paired t-test with significance determined at the 5% level of probability. The comparisons are shown in Table 1.

RESULTS

a) Net Radiation

Additional leaf pubescence can influence the net radiation balance of a canopy if it alters the reflectivity, transmissivity or emissivity of the canopy. The net radiation budget of the two isolines differing in pubescence was compared in an adjunct study by Nielsen et al. (1981).⁹ In that study HN and HPD isolines were grown in adjacent plots. A Swissteco net radiometer mounted on a boom was moved periodically between adjacent plots. In this way the influence of instrumental errors on R_n measurement was minimized. No differences were discerned in the flux density of R_n over the HN and HPD canopies. Gausman and Cardenas (1973) reported small differences in the reflection of near infrared radiation by normal and densely pubescent soybean leaves. In our study, however, the complex geometry of the canopies may have cancelled or concealed such small effects.

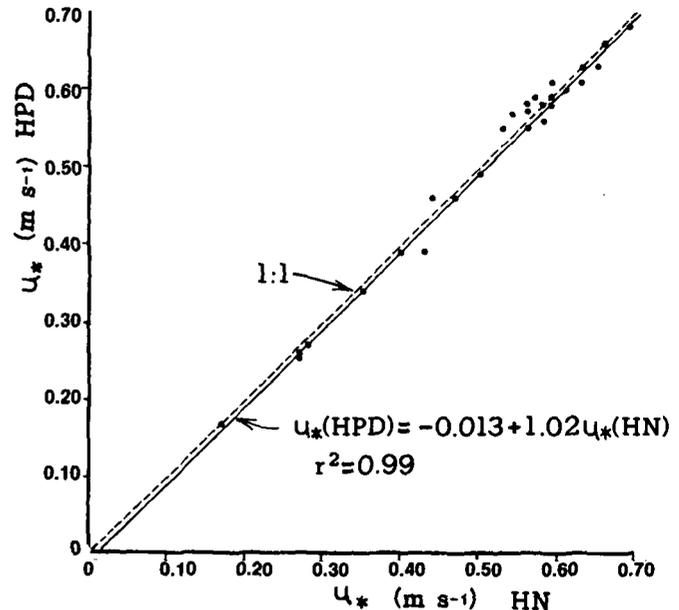


Fig. 1. Friction velocity (u_*) values over the HN and HPD canopies. The solid line is the regression line and the dotted line is the 1-to-1 line. Statistics associated with this comparison are presented in Table 1.

b) Turbulent Mixing

Woolley (1964) reported that pubescence affected the boundary layer thickness of an individual soybean leaf. We did not detect any significant differences in u_* values measured over the HN and HPD canopies (Fig. 1 and Table 1). These results suggest that additional pubescence does not significantly influence the effectiveness of turbulent exchange between the atmosphere and the canopy.

c) Latent Heat Flux

Fluxes of latent heat (LE)¹⁰ measured over the plots of HN and HPD isolines are compared in Fig. 2 and Table 1. These results show that the magnitude of LE fluxes were significantly greater over the HN isolines. For example, LE flux above the HN canopy was $300 W m^{-2}$ —about $22 W m^{-2}$ greater, on the average, than that over the HPD canopy. These results support the work of Ghorashy et al. (1971) and Ehleringer and Mooney (1978) who have shown that additional leaf pubescence reduced transpiration rates.

d) Sensible Heat Flux

Sensible heat flux (H) values measured over the HN and HPD plots are compared in Fig. 3 and Table 1. These

results show greater sensible heat flux above the HPD plot. For example, when the magnitude of the sensible heat flux over the HPD canopy was about 100 W m^{-2} , it was about 26 W m^{-2} more than in the HN plot. These data indicate that leaf pubescence affected the partitioning of net radiation into latent and sensible heat. These effects on partitioning are further discussed later.

e) Canopy CO_2 Flux

Canopy CO_2 fluxes (F_c) measured over the HN and HPD plots are compared in Fig. 4 and Table 1. No significant differences were detected in the values of F_c over the two plots. Ghorashy et al. (1971) also found that pubescence did not affect the photosynthetic rates of soybeans (Clark cv.)

f) CO_2 -water Flux Ratio

The water use efficiency, as indicated by the CO_2 -water flux ratio (CWFR), is compared for the HPD and HN isolines in Fig. 5 and Table 1. The CWFR was significantly greater over the HPD isolate. For example, when CWFR over the HN plot was about $3.0 \text{ mg CO}_2 (\text{g H}_2\text{O})^{-1}$ it was, on the average, about $0.89 \text{ mg CO}_2 (\text{g H}_2\text{O})^{-1}$ greater over the HPD plot. The CWFR values over the HPD canopy were greater due to the lower transpiration rate.

$\text{H}_2\text{O})^{-1}$ greater over the HPD plot. The CWFR values over the HPD canopy were greater due to the lower transpiration rate.

g) Leaf Water Potential and Stomatal Resistance

We have shown differences in LE and H between the two isolines. In an attempt to determine how differences in energy exchange affect the internal water relations of the crop, we compared the leaf water potential (Ψ) and stomatal resistance (r_s) in the two isolines. Data are shown in Fig. 6 and 7 and Table 1. No significant differences were found in Ψ and r_s values. Thus, the greater transpiration in the HN isolines did not, apparently, lead to an increased water stress.

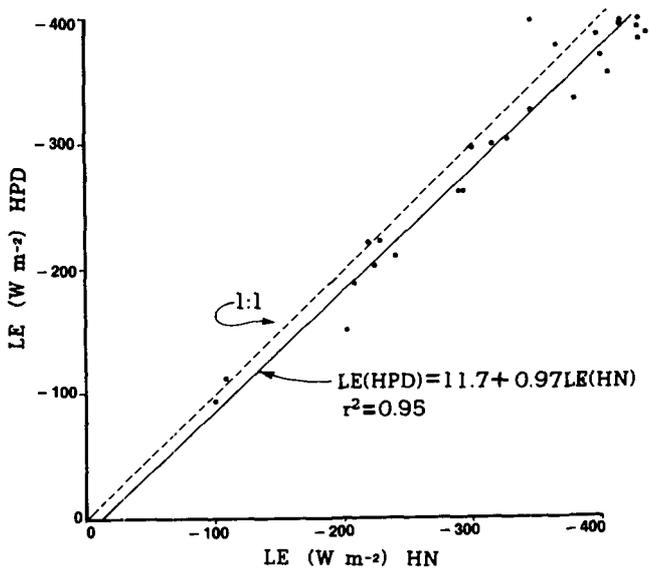


Fig. 2. Same as Fig. 1 except for latent heat flux (LE).

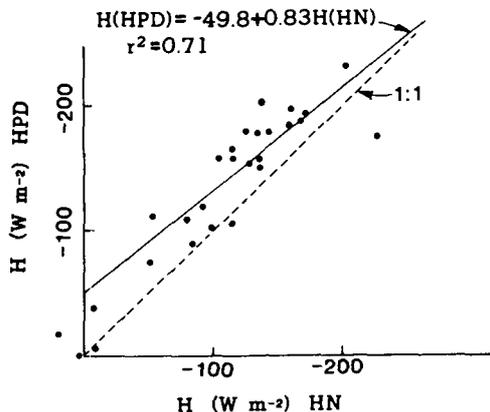


Fig. 3. Same as Fig. 1 except for sensible heat flux (H).

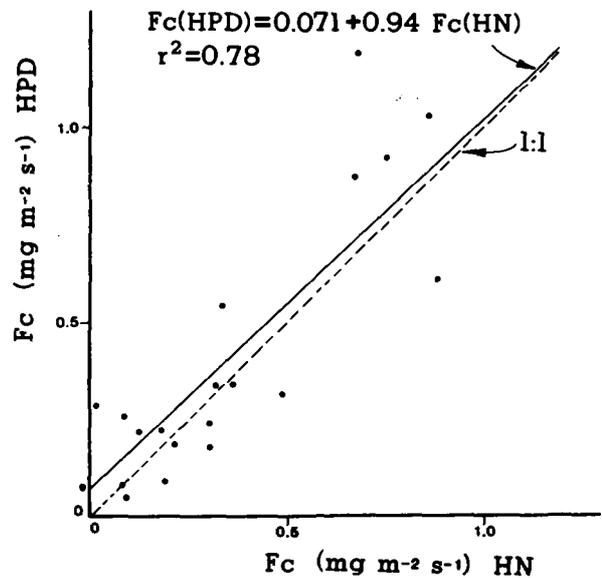


Fig. 4. Same as Fig. 1 except for canopy CO_2 flux (F_c). These values are presented on a unit ground area basis.

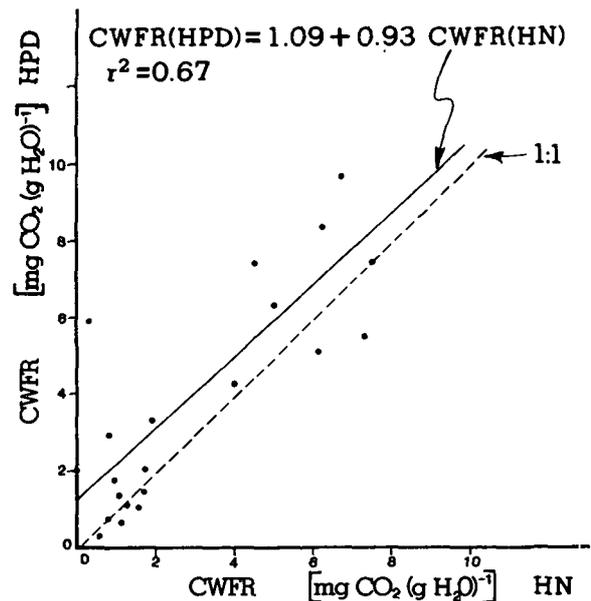


Fig. 5. Same as Fig. 1 except for the CO_2 -water flux ratio (CWFR).

DISCUSSION

Results presented in this paper suggest that greater pubescence did not alter R_n , u_s , F_c , or the internal plant water relations in Harosoy cv. soybeans. The increase in pubescence did, however, affect the partitioning of R_n between latent and sensible heat flux.

After a crop canopy completely covers the inter-row space, R_n is partitioned primarily between H and LE . In

order to understand this partitioning, let us examine the Bowen ratio (β):

$$\beta = H/LE = \frac{\rho C_p \Delta T (r_s + r_v)}{L(\Delta\rho_v)r_a} \quad [1]$$

where ρ is the density of air, C_p is the specific heat of air at constant pressure, L is the latent heat of vaporization, ΔT is the temperature difference between the bulk atmosphere and the crop surface, $\Delta\rho_v$ is the vapor density difference between the crop surface and the bulk atmosphere, r_a is the boundary layer resistance to sensible heat transfer and r_s and r_v are, respectively, the stomatal and boundary layer resistances to vapor transfer.

Three primary factors influencing β are water stress, amount of crop cover, and the manner in which solar radiation penetrates the canopy.

Water stress can increase β by inducing stomatal closure which leads to an increase in r_s . An increase in r_s under high irradiance levels will, in turn, cause $\Delta\rho_v$ to decrease. The ΔT will increase under lapse conditions or decrease with temperature inversions. Since no significant differences were found in the r_s values of these two isolines (Fig. 7) it is likely that water stress was not the cause of the differential partitioning of R_n .

Differences between the isolines in amount of crop cover could account for the observed differential partitioning of the net radiation if other environmental and physiological variables are not consequential. With greater crop cover we expect a greater proportion of R_n to be partitioned into LE . Crop cover was not measured directly but, since the leaf area index (LAI) for the HPD isolate was 4.5 as compared to 3.8 for the HN isolate, we can infer that, if anything, the crop cover should have been

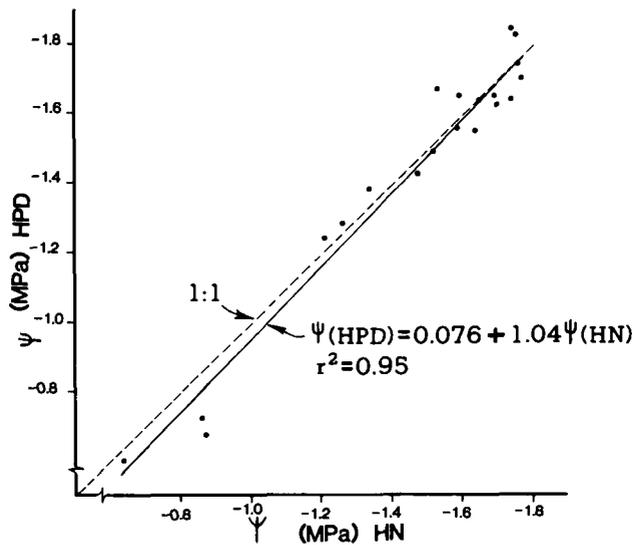


Fig. 6. Leaf water potential values (Ψ) measured in the HN and HPD canopies. Each value is the average of four to six measurements on leaves measured.

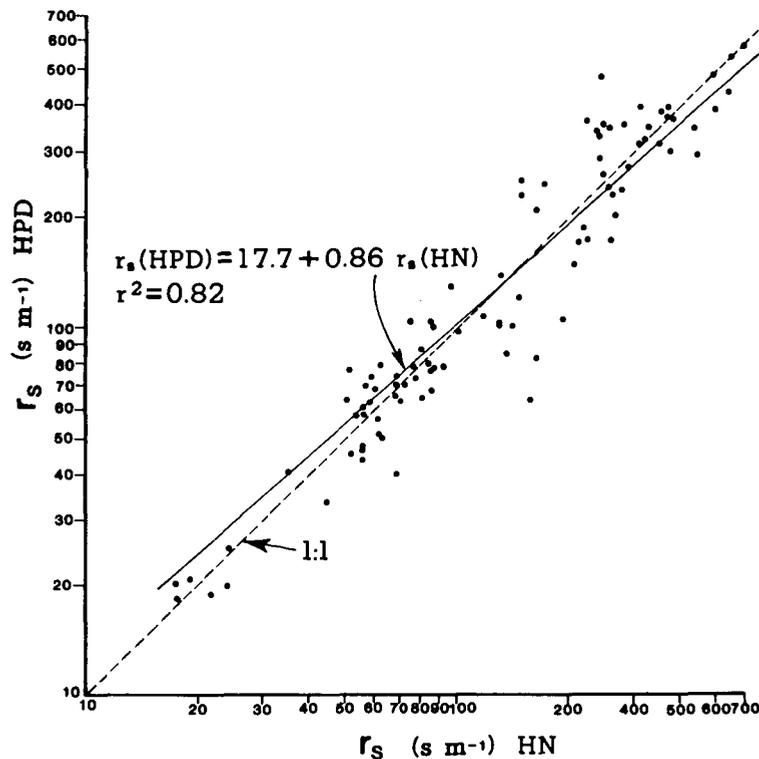


Fig. 7. Mean stomatal resistance values (r_s) measured in the HN and HPD canopies. Each value is the average of measurements on six sunlit leaves.

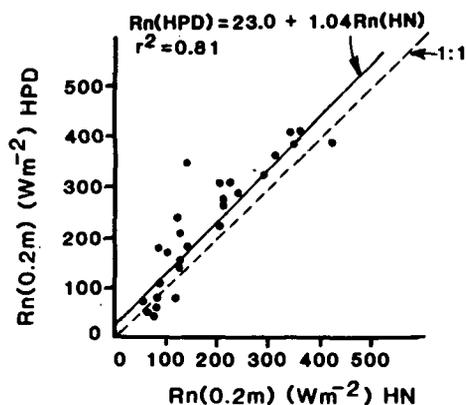


Fig. 8. Same as Fig. 1 except for net radiation values measured at 0.20 m within the HN and HPD canopies.

higher in the HPD isolate. Ritchie (1972), however, found that beyond an LAI of 2.7 the ratio of LE/Rn became essentially constant. We conclude, therefore, that the observed differences between the two isolines in the partitioning of Rn was probably not caused by the differences in either crop cover or leaf area index.

An increase in β can occur if solar radiation penetrates more deeply into the canopy. For example, an increase in solar radiation penetration will result in greater net radiation at lower levels in the canopy. Most of this radiation will be consumed in heating of the air and soil. Latent heat exchange will be relatively small since the evaporative surface area is sparse in the lower canopy. Latent heat flux may also be reduced because the stomatal resistance is substantially greater in the lower portion of a soybean canopy. Such an effect on r_s has been reported by Hatfield and Carlson (1978).

Comparison of Rn values at 0.20 m in HN and HPD canopies indicates that throughout the period of observations, Rn penetrated more deeply into the HPD canopy (Fig. 8). The Rn at 0.20 m was significantly greater in the HPD canopy.

Leaf area index (LAI) and the spectral characteristics of the canopy influence the penetration of radiation. As discussed above, LAI was greater in the HPD canopy. Had the spectral characteristics of the two isolines been similar, Rn would have been more effectively attenuated by the HPD canopy. Since greater attenuation of Rn was not observed in the HPD isolines (see Baldocchi et al., 1983), we hypothesize that greater solar radiation penetration into the HPD canopy was facilitated by increased leaf pubescence affecting the spectral characteristics of the leaves.

Such an effect is possible if pubescence increased the scattering coefficient or reflectivity of leaves. For example, a model of Lemeur and Blad (1974) indicates that the penetration of radiation into a canopy increases with increased scattering coefficient of a leaf.

Altering leaf reflectivity can also enhance the penetration of Rn into the canopy. Lemeur and Rosenberg (1975) presented experimental evidence showing that net radiation penetration into a soybean canopy increased with increased leaf reflectivity. In this case, increased reflectivity was achieved by coating the crop with a reflectant material. In view of these observations, it seems that the enhanced penetration of Rn into the HPD canopy was

due, primarily, to pubescence either increasing leaf reflectivity or the leaf scattering coefficient.

SUMMARY AND CONCLUSIONS

We have examined the influence of pubescence on the exchange of mass and energy between a soybean crop and the atmosphere. Additional pubescence in an isolate of Harosoy cv. soybeans decreased latent heat flux and increased sensible heat flux from the crop. The Rn, turbulent mixing, and CO₂ exchange over the normal and densely pubescent isolines were similar. No differences were found in internal plant water potential or stomatal resistance. We suggest that the differential partitioning of Rn by the isolines was due to differential penetration of solar radiation into the canopies—more solar radiation penetrated into the HPD canopy. The CWFR was greater in the HPD isolate since additional pubescence reduced LE. This observation suggests that increasing pubescence density improves water use efficiency.

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LITERATURE CITED

- Baldocchi, D.D., S.B. Verma, and N.J. Rosenberg. 1983. Microclimate within soybeans. *Agric. Meteorol.* (In press).
- Bernard, R.L., and M.G. Weiss. 1973. Qualitative genetics. p. 117-154. *In* B.E. Caldwell (ed.) *Soybeans: improvement, production and uses*. Am. Soc. Agron., Madison, Wis.
- Blad, B.L., and N.J. Rosenberg. 1974. Lysimetric calibration of the Bowen ratio-energy balance method for evapotranspiration estimation in the central Great Plains. *J. Appl. Meteorol.* 13:227-236.
- Bradley, E.F. 1972. The influence of thermal stability on a drag coefficient measured close to the ground. *Agric. Meteorol.* 9:183-190.
- Deacon, E.L., and W.C. Swinbank. 1958. Comparison between momentum and water transfer. p. 38-41. *In* Proc. Symp. Arid Zone Res. UNESCO, Canberra, Australia.
- Ehleringer, J.R., and O. Bjorkman. 1978a. Pubescence and leaf spectral characteristics in a desert shrub, *Encelia farinosa*. *Oecologia* 36:151-162.
- , and ———. 1978b. A comparison of photosynthetic characteristics of *Encelia* species possessing glabrous and pubescent leaves. *Plant Physiol.* 62:185-190.
- , ———, and H.A. Mooney. 1976. Leaf pubescence: effects on absorptance and photosynthesis in a desert shrub. *Science* 192:376-377.
- , and H.A. Mooney. 1978. Leaf hairs: Effects on physiological activity and adaptive value to a desert shrub. *Oecologia* 37:183-200.
- Gausman, H.W., and R. Cardenas. 1973. Light reflectance by leaflets of pubescent, normal and glabrous soybean lines of soybeans. *Agron. J.* 65:837-838.
- Ghorashy, S.R., J.W. Pendleton, R.L. Bernard, and M.E. Bauer. 1971. Effect of leaf pubescence on transpiration, photosynthetic rate and seed yield of three near-isogenic lines of soybeans. *Crop Sci.* 11:426-427.
- Hartung, R.C., J.E. Specht, and J.H. Williams. 1980. Agronomic performance of selected soybean morphological variants in irrigation culture with two row spacings. *Crop Sci.* 20:604-609.
- Hatfield, J.L., and R.E. Carlson. 1978. Photosynthetically active radiation, CO₂ uptake and stomatal diffusive resistance profiles within soybean canopies. *Agron. J.* 70:592-596.
- Lemeur, R., and B.L. Blad. 1974. A critical review of light models for estimating the shortwave radiation regime of plant canopies. *Agric. Meteorol.* 14:255-286.

- , and N.J. Rosenberg. 1975. Reflectant induced modification of the radiation balance for increased crop water use efficiency. p. 479–488. *In* D.A. deVries and N.H. Afgan (ed.) Heat and mass transfer of the biosphere. Scripta Book Co., Washington, DC.
- Rosenberg, N.J., and K.W. Brown. 1974. "Self-checking" psychrometer system for gradient and profile determinations near the ground. *Agric. Meteorol.* 13:215–226.
- , and S.B. Verma. 1976. A system and program for monitoring CO₂ concentration, gradient and flux in an agricultural region. *Agron. J.* 68:414–418.
- Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with complete cover. *Water Resour. Res.* 8:1204–1213.
- Verma, S.B., and N.J. Rosenberg. 1975. Accuracy of lysimetric, energy balance and stability-corrected aerodynamic methods of estimating above-canopy flux of CO₂. *Agron. J.* 67:699–704.
- , ———, B.L. Blad, and M.W. Baradas. 1976. Resistance-energy balance method for predicting evapotranspiration: Determination of boundary layer resistance and evaluation of error effects. *Agron. J.* 68:776–782.
- Webb, E.K., G.I. Pearman, and R. Leuning. 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. *Q. J. Roy. Meteorol. Soc.* 106:85–100.
- Woolley, J.T. 1964. Water relations of leaf hairs. *Agron. J.* 56:569–571.