CHARACTERISTICS OF AIR FLOW ABOVE AND WITHIN SOYBEAN CANOPIES*

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Abstract. Air flow was observed above and within canopies of a number of kinds of soybeans. The Clark cultivar and two isolines of the Harosoy cultivar were studied in 1979 and 1980, respectively. Wind speed above the canopy was measured with cup anemometers. Heated thermistor anemometers were used to measure air flow within the canopy.

Above-canopy air flow was characterized in terms of the zero-plane displacement (d), roughness parameter (z_0) and drag coefficient (C_d). d and z_0 were dependent on canopy height but were independent of friction velocity in the range 0.55 to 0.75 m s^{-1}. C_d for the various canopies ranged from 0.027 to 0.035. Greater C_d values were measured over an erectophile canopy than over a planophile canopy. C_d was not measurably affected by differences in leaf pubescence.

Within-canopy wind profiles were measured at two locations: within and between rows. The wind profile was characterized by a region of great wind shear in the upper canopy and by a region of relatively weak wind shear in the middle canopy. Considerable spatial variability in wind speed was evident, however. This result has significant implications for canopy flow modeling efforts aimed at evaluating transport in the canopy.

In the lower canopy, wind speed within a row increased with depth whereas wind speed between two rows decreased with depth. The wind speeds at the two locations tended to converge to a common value at a height near 0.10 m.

The attenuation of within-canopy air flow was stronger in canopies with greater foliage density. Canopy flow attenuation seemed to decrease with increasing wind speed, suggesting that high winds distorted the shape of the canopy in such a manner that the penetration of wind into the canopy increased.

1. Introduction

Wind influences crop growth by providing a mechanism for the exchange of CO_2, water vapor and sensible heat between the atmosphere and the crop. Wind also distorts the shape of the canopy. This distortion can affect the aerodynamic roughness of the canopy and the penetration of radiation and wind into it. Hence, the exchange of mass and energy between the crop and atmosphere is also affected.

The importance of the interaction between wind and crop canopy has been recognized for many years. This recognition has led to the investigation of air flow above and within several types of canopies (e.g., beans: Thom, 1971; Legg *et al.*, 1981; corn: Uchijima and Wright, 1964; cotton: Bache and Unsworth, 1977; potato: Legg *et al.*, 1981; soybeans, Perrier *et al.*, 1970, 1972, Hicks and Wesely, 1981; wheat: Penman and

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Long, 1960, Legg and Long, 1975, Finnigan, 1979). An excellent review of air flow above and within crop canopies is presented by Raupach and Thom (1980). These cited works present useful results. However, more work is needed before we can fully understand how variation in such factors as crop height, roughness, flexibility and foliage distribution affect above- and within-canopy air flow.

Here we report observations from a study of air flow above and within different soybean (*Glycine max* L. Merrill) canopies. The influence of canopy height and wind speed on aerodynamic characteristics such as the zero-plane displacement, the roughness parameter and the drag coefficient are investigated. The general shape of within-canopy profiles measured at different locations (within the row and between rows) is examined. The dependence of attenuation of air flow in the canopy on such factors as foliage density and canopy distortion is also evaluated.

2. Materials and Methods

2.1. Experimental details

Observations reported here were obtained during the 1979 and 1980 growing seasons at the University of Nebraska Agricultural Meteorological Laboratory near Mead, Nebraska (41° 09′ N; 96° 30′ W; 354 m above msl). The experimental fields were planted with soybeans (*Glycine max* L. Merrill) in 0.75 m wide, north-south rows (about 375 000 plants ha^{-1}). Clark cultivar soybeans were planted on May 25, 1979, in a 105 m E-W by 210 m N-S experimental field. Border fields to the east, west and south were planted with Woodworth cultiver soybeans.

In 1980 we studied the wind flow characteristics above and within canopies of two Harosoy cultivar isolines differing in pubesence (leaf hairs). This study was part of a comprehensive experiment conducted to investigate the effects of pubescence on canopy energy and mass exchanges. Observations were made in two fields planted on May 22, 1980. The east field (65 m E-W by 210 m N-S) was planted to an isoline of the Harosoy cultivar which had normal pubescence (HN). The adjacent west field (85 m E-W by 210 m N-S) was planted to another isoline of the Harosoy cultivar which was densely pubescence (HPD). Border fields were planted with the HN isoline.

Data presented in this paper are selected from periods when the fetch-to-height ratio exceeded 75 to 1 with wind flowing down the rows. The thermal stability above the canopy was near-neutral (the absolute value of the Richardson number was less than 0.005).

Horizontal wind speed was measured above the crop canopies with Cayuga three-cup anemometers.* Wind speed profiles were measured in 0.25 m intervals between 1.25 and 2.50 m. Within the canopy, wind speed was measured with heated thermistor anemometers (HTA) designed and constructed by Bergen (1971a). These instruments were quite sensitive to wind speeds in the range between 0.30 and 2.50 m s^{-1}. The time

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

constant was on the order of 2 s (Bergen, 1971a). Wind speed profiles were determined using five HTAs spaced equidistantly between 0.10 and 0.90 m. Within-canopy wind profiles were measured both in the row and midway between two rows in order to investigate spatial variability. Cup anemometers and HTAs were calibrated in a wind tunnel before and after the field experiments. The HTA calibrations were corrected for the effects of variable air temperature.

Air temperature and vapor pressure profiles were measured above each canopy using automatic, self-checking, multi-level psychrometers (Rosenberg and Brown, 1974). Once each hour the psychrometers were rotated into a horizontal position for calibration. Within-canopy profiles of air temperature were measured with mini-psychrometers adapted from a design by Stigter and Welgraven (1976). Within-canopy psychrometers were installed at the same levels as the HTAs.

All micrometeorological data were recorded with a computer-controlled data acquisition system. Counts from the cup anemometers were integrated over 5-min periods. Output of all emf-producing sensors were sampled two times per minute and were recorded on magnetic tape as 5-min averages. The count and emf data were later converted to meteorological parameters and were then time-averaged over the first 45 min of each solar hour.

Thermal stability was characterized by the Richardson number (Ri), derived from profile measurements of wind speed, air temperature and vapor pressure (e.g., see Thom, 1975).

2.2. Crop characteristics

Data presented in this paper are from periods following full canopy development when full ground cover had been achieved. The canopy of the Clark cultivar was about 1.00 m tall and had a leaf area index* (LAI) of about 4.1. Crop height (h) and LAI data for the two Harosoy canopies are presented in Table I. The Harosoy canopies were erect until a storm caused both canopies to lodge on August 10, 1980. Measurements of within-canopy wind flow were made only when the Harosoy canopies were erect. Vertical

TABLE I

Canopy characteristics for the normal (HN) and densely pubescent (HPD) isolines of the Harosoy cultivar of soybean. Mead, Nebraska, 1980

	HN	HPD
Leaf area index		
Before lodging (July 29–August 8)	~3.8	~4.5
After lodging (August 12–19)	~3.3	~3.3
Crop height		
Before lodging (July 29–August 8)	1.02 m	1.08 m
After lodging (August 12–19)	0.80 m	0.80 m

* LAI is the ratio of leaf surface area (one side) to ground area.

profiles of leaf area index for the periods during which within-canopy wind profile data were examined are presented in Figure 1.

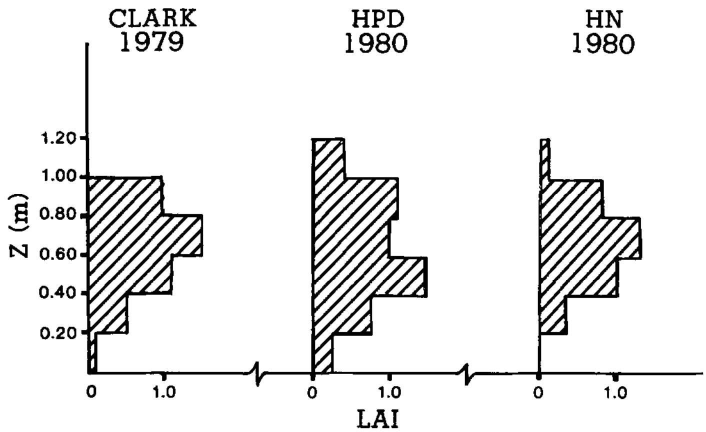

Fig. 1. Vertical distribution of leaf area index (LAI). Values are presented for discrete 0.20 m intervals. These data were characteristic of the canopies when they were erect.

3. Results and Discussion

3.1. Above–canopy air flow

3.1.1. *Roughness Parameter and Zero-Plant Displacement*

Under near-neutral stability, wind speed at a height z can be described as:

$$U(z) = \frac{u_*}{k} \ln [(z - d)/z_o], \tag{1}$$

where u_* is friction velocity, k is von Karman's constant (0.4), d is the zero-plane displacement and z_0 is the roughness parameter. d and z_0 were determined from wind profiles measured under near-neutral conditions, using an iterative eye-fit technique described by Monteith (1973).

Over vegetative surfaces, z_0 and d are affected by crop height (h), element flexibility and foliage density and distribution. Figures 2a and b show z_0 and d, respectively, as functions of crop height (h) for the HPD soybean canopy. Both parameters increased linearly with increasing h in the range 0.80 to 1.10 m. Our values of z_0 and d fall within the range of values presented by Perrier *et al.* (1970, 1972) for a 1.10 m tall soybean canopy. Their z_0 values ranged from 0.03 to 0.14 m and d ranged from 0.45 to 0.69 m. Our results are also close to z_0/h and d/h values resulting from the numerical modeling effort by Shaw and Pereira (1982). Their model predicts $z_0/h \approx 0.11$ and $d/h \approx 0.57$ for a canopy with characteristics similar to the fully-developed HPD canopy reported in

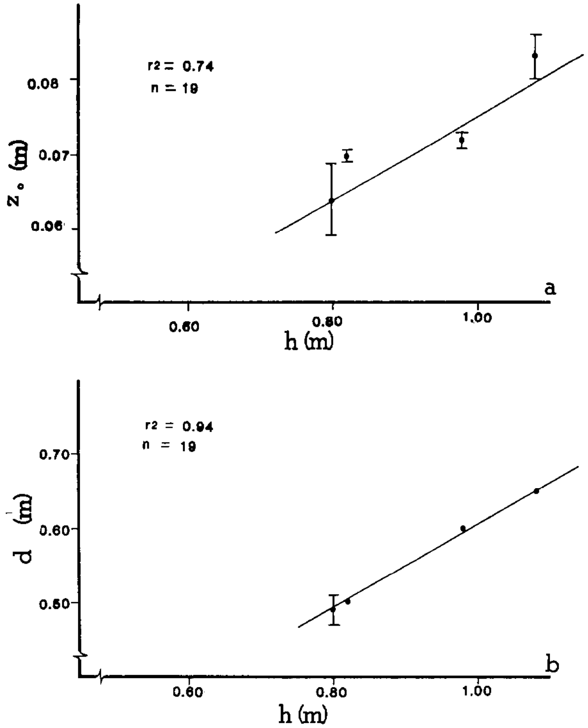

Fig. 2. (a) Roughness parameter (z_0) as a function of crop .height (h). (b) Zero plane displacement (d) as a function of crop height (h). Data were from both a lodged and erect HPD soybean canopy. Standard deviations are indicated by error bars about each point. r^2 is the coefficient of determination and n is sample size.

this study. Hicks and Wesely (1981), on the other hand, found d and z_0 to be about 90% and 5%, respectively, of the average canopy height.

The dependency of z_0 and d on wind speed is the subject of some controversy. Denmead (1966) and Perrier *et al.* (1972) report that z_0 decreases and d increases with increasing wind speed, while Uchijima (1976) considers the converse to be true. Tani (1963) and Bache and Unsworth (1977) found that, depending on the wind speed regime, either situation can occur. Legg *et al.* (1981) report that z_0/h decreased with increasing wind speed when d was held constant. However, since z_0 is correlated with d, they were unable to discern which of the parameters was actually dependent on the wind speed. Munro and Oke (1973), Legg and Long (1975) and Leuning *et al.* (1978), on the other hand, report that z_0 and d are independent of wind speed.

It is difficult to ascertain whether z_0 and d are dependent on wind speed since these three variables are correlated (Equation (1)). In order to examine the above mentioned dependency, we used friction velocity (u_*) as an independent measure of wind speed. u_* was obtained by the eddy correlation technique:

$$u_* = (\overline{-u'w'})^{1/2} \tag{2}$$

where u' and w' are instantaneous fluctuations in the horizontal and vertical wind speeds, respectively, and the overbar denotes time averaging. Friction velocity (u_*) was determined in a concurrent study with a three-dimensional drag anemometer. Details on the $\overline{-u'w'}$ measurements are provided in an earlier paper (Redford *et al.*, 1981). z_0/h and d/h are plotted as functions of u_* in Figure 3. Both z_0/h and d/h were independent of u_* in the range 0.55 to 0.75 m s^{-1}.*

3.1.2. *Canopy Drag Coefficient*

The canopy drag coefficient (C_d) is described by:

$$C_d = \frac{\tau}{\rho_a U(z)^2}, \tag{3}$$

where τ is the shear stress, ρ_a is the density of dry air and $U(z)$ is the mean wind speed at height z (z = 1.25 m in this case). C_d is an indicator of the overall effectiveness with which the canopy extracts momentum from the air flow (Thom, 1975). In this study, the drag coefficient (C_d) was computed for near-neutral conditions using wind speed profiles measured at levels close to the canopy. Techniques described by Deacon and Swinbank (1958), Bradley (1972), and Verma *et al.* (1976) were used.

Values of C_d computed for two soybean cultivars and the two isolines differing in pubescence are presented in Table II. C_d values for the period during which the Harosoy

TABLE II

Mean drag coefficient (C_d) values and standard deviations for the soybean cultivars and isolines studied. Mead, Nebraska, 1979–1980

Cultivar	$C_d \pm$ std. dev.
Clark	0.027 ± 0.005
Harosoy, HPD	0.037 ± 0.006
Harosoy, HN	0.035 ± 0.008
Harosoy, HPD[a]	0.030 ± 0.006
Harosoy, HN[a]	0.038 ± 0.005

[a] After the crop lodged.

isolines were lodged are also presented. C_d for the Clark cultivar was lower than for the unlodged Harosoy isolines. The lower C_d associated with the Clark cultivar is consistent with the morphology of that cultivar. The Clark cultivar canopy is essentially planophile in structure, whereas the Harosoy canopies are essentially erectophile.† The C_d values for the normal and densely pubescent Harosoy isolines were not significantly different.

* u_* values ranging from 0.55 to 0.75 m s^{-1} corresponded to wind speeds at z = 1.25 m ranging from about 2.7 to 4.0 m s^{-1}.

† Personal Communication with Dr James E. Specht, Department of Agronomy, University of Nebraska, Lincoln. Also see deWit (1965) for erectophile vs planophile canopy classification.

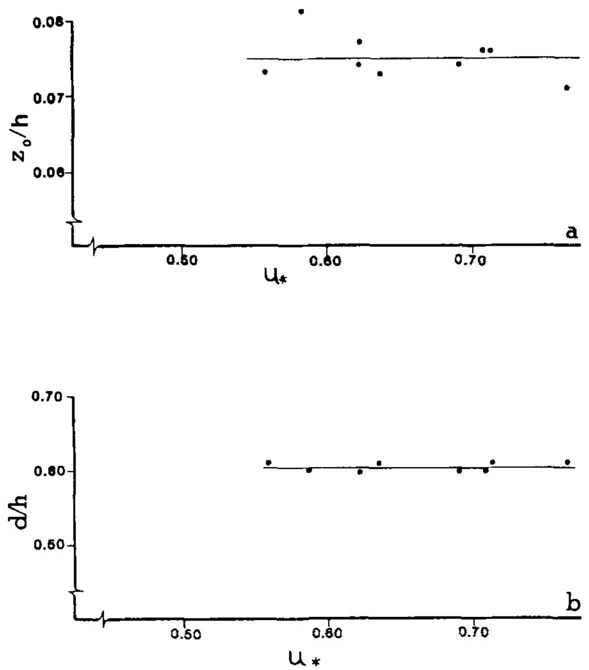

Fig. 3. (a) The dependence of z_0/h on friction velocity (u_*). (b) The dependence of d/h on friction velocity (u_*). Data in this figure are for the HPD soybean canopy.

These results suggest that additional leaf pubescence did not affect the bluff body characteristics of the canopies.

In general, C_d for the unlodged soybean canopies ranged from 0.027 to 0.035. For comparison, Perrier *et al.* (1972) reported that C_d for a soybean canopy was 0.020. Thom (1971) found C_d for a bean canopy to range from 0.035 to 0.055, while Legg *et al.* (1981) report that C_d for a bean canopy is 0.022.

No general conclusions regarding the influence of lodging on C_d can be obtained from these results. Lodging reduced C_d in the HPD isoline while increasing it in the HN isoline.

3.2. Within-Canopy Air Flow

3.2.1. *Profile Shapes*

Within-canopy wind profiles, measured within a row and between two rows, are presented in Figure 4a and b for the HN and HPD isolines, respectively. Above 0.30 m, two distinct regions of air flow can be discerned: (a) an upper region (0.70 m $< z < h$) where wind shear was great and (b) a middle region (0.30 m $< z <$ 0.70 m) where wind shear was relatively weak. Considerable spatial variability was also evident for wind speeds within the canopy. Wind speed was greater at the between-row location than at the within-row location. This difference in wind speed was on the order of 0.50 m s^{-1} between the heights 0.30 and 0.90 m.

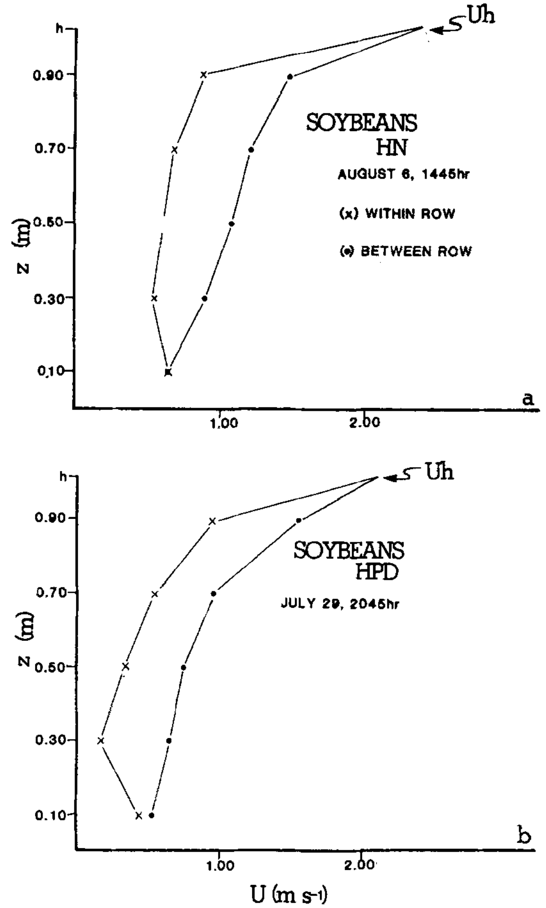

Fig. 4. (a) Wind speed profile within the HN soybean canopy. (b) Wind speed profile within the HPD soybean canopy. (×) indicates wind speeds measured within a row. (•) indicates wind speeds measured between two rows. U_h is the wind speed at the top of the canopy. U_h was determined by extrapolation from the above canopy wind profile.

Many workers (e.g., Penman and Long, 1960; Inoue, 1963; Uchijima and Wright, 1964; Thom, 1971; Landsberg and James, 1971; Perrier *et al.*, 1970; Cionco, 1972, 1978; Shaw *et al.*, 1974; Legg and Long, 1975; Bache and Unsworth, 1977; Finnigan, 1979) have reported that wind shear is great in the upper canopy and weak in the mid-canopy. Bergen (1971b) reported that the spatial variability in the wind field within a pine forest stand was appreciable. Observations of spatial variability of wind speed in a crop canopy, however, are rare.

In a row crop such as soybeans, foliage elements are denser and stiffer near the row than they are between two rows. This horizontal difference in foliage density and stiffness probably led to greater drag being induced on the within-row air flow than on the between-row air flow. Results from a two-dimensional model by Kondo and Akashi (1976) seem to substantiate this hypothesis. They show that the shape of the within-canopy wind profile is similar to our within-row case when the drag induced by the foliage elements is substantial. On the other hand, when the drag induced by the foliage elements is relatively small, the shape of their within-canopy wind profile is similar to our between-row case.

The shape of the wind profile in the lower canopy is not well established. Workers have reported cases where wind speed in the lower canopy: (a) increased with depth (Landsberg and James, 1971; Legg and Long, 1975), (b) is relatively constant (Perrier *et al.*, 1970; Thom, 1971; Finnigan, 1979) and (c) decreased exponentially with depth (Uchijima and Wright, 1964; Cionco, 1978). Our observations indicate that the shape of the within-canopy wind profile in the lower canopy ($0.10 \text{ m} < z < 0.30 \text{ m}$) is dependent on location (Figure 4a and b). Wind speed within a row increased with depth, whereas wind speed between two rows decreased with depth. Wind speed at both locations tended to converge to a common value near 0.10 m. This observation of a reversal of the wind gradient in the lower canopy at the within-row location is supported by the results of within-canopy air flow models of Shaw (1977), Kondo and Akashi (1976) and Wilson and Shaw (1977). Shaw (1977) and Wilson and Shaw (1977) show that a reversal in the wind gradient occurs when the value of the term representing the vertical turbulent transport of Reynolds stress exceeds that of the pressure-velocity gradient correlation. Kondo and Akashi (1976) suggest that a reversal in the wind gradient is related to canopy drag and to canopy geometry.

3.2.2. *Within-canopy air flow attenuation*

The attenuation of air flow within the canopy has been quantified by various workers (Inoue *et al.*, 1963; Cionco, 1972, 1978) using the canopy flow index (α) defined as:

$$\alpha = \frac{\ln (U(z)/U_h)}{(z/h - 1)} \tag{6}$$

where $U(z)$ is the mean wind speed at height z and U_h is the mean wind speed at the canopy height h. α increases in magnitude as the ability of the canopy to attenuate within-canopy air flow increases (Cionco, 1978). Cionco (1972) reported that, for a wide range of vegetation, α ranges from 0.30 to 3.00.

TABLE III

Canopy flow index (α) at two positions for the normal and densely pubsecent isolines of Harosoy cultivar soybeans

Isoline	Location of measurement	α
HPD	In row	2.72 ± 0.44
	Between row	1.58 ± 0.26
HN	In row	1.64 ± 0.47
	Between row	1.27 ± 0.22

We computed α as the slope of the least-square fit between $\ln (U(z)/U_h)$ and $(z/h - 1)$ at four elevations between 0.90 and 0.30 m. Mean values of α for the two different soybean isolines and locations in the canopy are presented in Table III. The α values ranged from 1.27 ± 0.22 to 2.72 ± 0.44, with greater values of α being in the row where foliage elements were denser and stiffer. Larger α values were observed in the HPD isolines since the foliage density of this isoline was greater. These observations are in agreement with the results of a numerical study by Pereira and Shaw (1980), which showed that canopy flow attenuation increased with increasing foliage density.

Strong winds and associated wind gusts can distort the canopy shape by opening temporary gaps and by inducing a waving motion in the canopy. To determine whether this phenomenon affects wind flow attenuation, we plotted α as a function of u_* in Figure 5. It is seen that as u_* increased, α decreased. This relationship suggests that strong winds distorted the canopy in such a manner that the penetration of wind into the canopy increased. Figure 5 also shows that the effect of u_* on α was greater for air flow within the row than for that between two rows. The penetration of wind into the canopy at the within-row location was probably facilitated by wind gusts causing the foliage elements to bend away from the row.

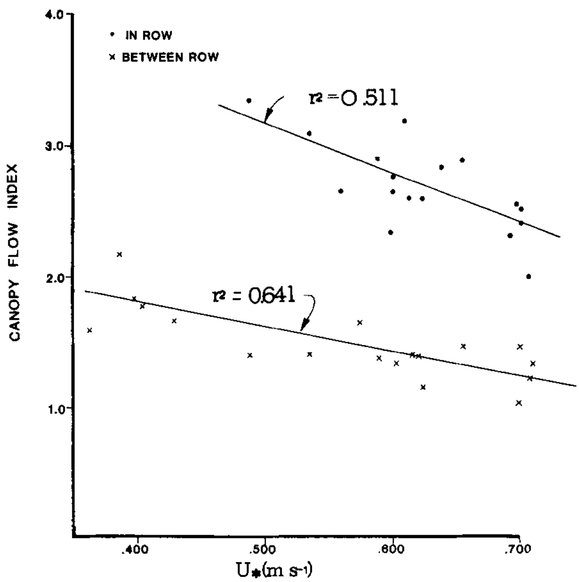

Fig. 5. Influence of friction velocity (u_*) on the canopy flow index (α). u_* was determined above the HPD canopy by the eddy correlation technique.

4. Summary

Characteristics of air flow above and within different soybean canopies were examined. z_0 and d were related to crop height but were independent of friction velocity in the range 0.55 to 0.75 m s^{-1}. Drag coefficient (C_d) for the different soybean canopies ranged from

0.027 to 0.035, with greater C_d values observed for an erectophile canopy than a planophile canopy. Canopies with different leaf pubescence did not affect C_d.

Within-canopy wind profiles showed that wind shear was great in the upper canopy and weak in the middle canopy. Considerable spatial variability in wind speed was also evident in the upper and middle canopy. Wind speed was greater between two rows than within a row. This difference was due to the foliage element being stiffer and denser at the within-row location.

In the lower canopy, the shape of the wind profile was location dependent. Wind speed within a row increased with depth, whereas wind speed between two rows decreased with depth. Furthermore, wind speed at both locations tended to converge to a common value near 0.10 m.

The attenuation of within-canopy wind speed was enhanced in the canopy with greater foliage density, whereas higher wind speeds seemed to reduce the ability of the canopy to attenuate within-canopy air flow.

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References

Bache, D. H. and Unsworth, M. H.: 1977, 'Some Aerodynamic Features of a Cotton Canopy', *Quart. J. Roy. Meteorol. Soc.* **103**, 121–134.

Bergen, J. D.: 1971a, 'An Inexpensive Heated Thermistor Anemometer', *Agric. Meteorol.* **8**, 395–405.

Bergen, J. D.: 1971b, 'Vertical Profiles of Windspeed in a Pine Stand', *Forest Sci.* **17**, 314–321.

Bradley, E. F.: 1972, 'The Influence of Thermal Stability on a Drag Coefficient Measured Close to the Ground', *Agric. Meteorol.* **9**, 183–190.

Cionco, R. M.: 1972, 'Intensity of Turbulence within Canopies with Simple and Complex Roughness Elements', *Boundary-Layer Meteorol.* **2**, 453–465.

Cionco, R. M.: 1978, 'Analysis of Canopy Index Values for Various Canopy Densities', *Boundary-Layer Meteorol.* **15**, 81–93.

Deacon, E. L. and Swinbank, W. C.: 1958, *Comparison between Momentum and Water Transfer*, Proc. Symp. Arid Zone Res. UNESCO Canberra, Australia, pp. 38–41.

Denmead, O. T.: 1976, 'Temperate Cereals', in J. L. Monteith (ed.), *Vegetation and the Atmosphere*, Vol. 2. Academic Press, pp. 1–33.

deWit, C. T.: 1965, Photosynthesis of Leaf Canopies, Agr. Res. Report No. 663, Centre Agr. Publ. Doc., Wageningen, The Netherlands, p. 1–57.

Finnigan, J. J.: 1979, 'Turbulence in Waving Wheat I', *Boundary-Layer Meteorol.* **16**, 181–211.

Hicks, B. B. and Wesely, M. L.: 1981, 'Heat and Momentum Transfer Characteristics of Adjacent Fields of Soybeans and Maize', *Boundary-Layer Meteorol.* **20**, 175–185.

Inoue, E.: 1963, 'On the Turbulent Structure of Air Flow within Crop Canopies', *J. Meteorol. Soc. of Japan* **41**, 317–325.
Kondo, J. and Akashi, S.: 1976, 'Numerical Studies on the Two-Dimensional Flow in Horizontally Homogeneous Canopy Layers', *Boundary-Layer Meteorol.* **10**, 255–272.
Landsberg, J. J. and James, G. B.: 1971, 'Wind Profiles in Plant Canopies: Studies on an Analytical Model', *J. Appl. Ecol.* **8**, 729–741.
Legg, B. J. and Long, I. F.: 1975, 'Turbulent Diffusion within a Wheat Canopy. II. Results and Interpretation', *Quart. J. Roy. Meteorol. Soc.* **101**, 611–628.
Leuning, R. and Attiwill, P. M.: 1978, 'Mass, Heat and Momentum Exchange between a Mature Eucalyptus Forest and the Atmosphere', *Agric. Meteorol.* **19**, 215–241.
Monteith, J. L.: 1973, *Principles of Environmental Physics*, Edward Arnold Limited, London. 241 pp.
Munro, D. S. and Oke, T. R.: 1975, 'Aerodynamic Boundary Layer Adjustment over a Crop in Neutral Stability', *Boundary-Layer Meteorol.* **9**, 53–61.
Penman, H. L. and Long, I. F.: 1960, 'Wheather in Wheat: An Essay in Micrometeorology', *Quart. J. Roy. Meteorol. Soc.* **86**, 16–50.
Pereira, A. and Shaw, R. H.: 1980, 'A numerical Experiment on the Mean Wind Structure Inside Canopies of Vegetation', *Agric. Meteorol.* **22**, 303–318.
Perrier, E. R., Millington, R. J., Peters, D. B., and Luxmoore, R. J.: 1970, 'Wind Structure above and within a Soybean Canopy', *Agron. J.* **62**, 615–618.
Perrier, E. R., Robertson, J. M., Millington, R. J., and Peters, D. B.: 1972, Spatial and Temporal Variation of Wind above and within a Soybean Canopy', *Agric. Meteorol.* **10**, 421–442.
Raupach, M. R. and Thom, A. S.: 1981, 'Turbulence in and above Plant Canopies', *Ann. Rev. Fluid Mech.* **13**, 97–129.
Redford, T. G., Jr., Verma, S. B., and Rosenberg, N. J.: 1981, 'Drag Anemometer Measurements of Turbulence over a Vegetated Surface', *J. Appl. Meteorol.* **20**, 1222–1230.
Rosenberg, N. J. and Brown, K. W.: 1974, 'Self-Checking Psychrometer System for Gradient and Profile Determination near the Ground', *Agric. Meteorol.* **13**, 215–226.
Shaw, R. H.: 1977, 'Secondary Wind Speed Maxima Inside Plant Canopies', *J. Appl. Meteorol.* **16**, 514–521.
Shaw, R. H., Den Hartog, G., King, K. M., and Thurtell, G. W.: 1974, 'Measurements of Mean Wind Flow and Three Dimensional Turbulence Intensity within a Mature Corn Canopy', *Agric. Meteorol.* **13**, 419–425.
Shaw, R. H. and Pereira, A. R.: 1982, 'Aerodynamic Roughness of a Plant Canopy: A Numerical Experiment', *Agric. Meteorol.* **26**, 51–65.
Stigter, C. J. and Welgraven, A. D.: 1976, An Improved Radiation Protected Differential Thermocouple Psychrometer for Crop Environment', *Arch. Met. Geoph. Biokl.* **B, 24**, 177–181.
Tani, N.: 1963, 'The Wind over the Cultivated Field', *Bull. Natl. Inst. Agric. Sci.*., Tokyo A **10**, 99 pp.
Thom, A. S.: 1971, 'Momentum Absorption by Vegetation', *Quart. J. Roy. Meteorol. Soc.* **97**, 414–418.
Thom, A. S.: 1975, 'Momentum, Mass and Heat Exchange of Plant Communities', in J. L. Monteith (ed.), *Vegetation and the Atmosphere*, Vol. 1. Academic Press, N.Y., pp. 57–109.
Uchijima, Z.: 1976, 'Maize and Rice', in J. L. Monteith (ed.), *Vegetation and the Atmosphere*, Vol. 2. Academic Press, N.Y., pp. 33–64.
Uchijima, Z. and Wright, J. L.: 1964, 'An Experimental Study of Air Flow in a Corn Plant-Air Layer', *Bull. Nat. Inst. Agric. Sci.* (Japan) SerA **11**, 19–65.
Verma, S. B., Rosenberg, N. J., Blad, B. L., and Baradas, M. W.: 1976, 'Resistance-Energy Balance Method for Predicting Evapotranspiration: Determination of Boundary Layer Resistances and Evaluation of Error Effects, *Agron. J.* **68**, 776–782.
Wilson, N. R. and Shaw, R. H.: 1977, 'A Higher Order Closure Model for Canopy Flow', *J. Appl. Meteorol.* **16**, 1197–1205.