Variability of Reflectance Measurements with Sensor Altitude and Canopy Type[1]

C. S. T. Daughtry, V. C. Vanderbilt, and V. J. Pollara[2]

ABSTRACT

Use of portable, ground-based sensors for measuring crop reflectance has created a need for comparable and reliable measurement procedures capable of providing calibrated and reproducible canopy reflectance data. In this field experiment we determined how canopy reflectance varies as a function of sensor altitude above the crop and what minimum altitude is needed to acquire repeatable reflectance measurements with a 15 degree field of view instrument. Data were acquired in 1979 on three canopies grown on a Typic Argiaquoll; mature corn (*Zea mays* L.) planted in 76 cm rows, mature soybeans [*Glycine max* (L.) Merr.] planted in 96 cm rows with 71% soil cover, and mature soybeans planted in 76 cm rows with 100% soil cover. Spectral data were acquired using a Landsat band radiometer (Exotech 100) at 10 altitudes ranging from 0.2 to 10 m above the canopy. At each altitude, measurements were taken at 15-cm intervals along a 2.0 m transect perpendicular to the crop row direction.

The variance of reflectance factor measurements at low altitudes was attributable to row effects which disappeared at higher altitudes where the sensor integrated across several rows. The coefficient of variation of reflectance factor in both visible and near infrared bands decreased exponentially as the sensor was elevated. Systematic sampling (at odd multiples of 0.5 times the row spacing interval) required fewer measurements than simple random sampling over row crop canopies. Extreme care must be exercised in analyzing and interpreting data acquired at sensor altitudes where the diameter of the sensor's FOV at the top of the canopy is smaller than several multiples of the row spacing.

Additional index words: **Remote sensing, Radiometer, Sampling errors, *Zea mays* L., *Glycine max* (L.) Merr.**

Use of portable, ground-based sensors for measuring reflectance of crops has created a need for comparable and reliable measurement procedures capable of providing calibrated and reproducible canopy reflectance data. Acquisition of reproducible data is assured in part if the field of view (FOV) of the measuring sensor contains a representative sample of the canopy. The particular portion of the canopy in the sensor FOV changes with the altitude of the sensor above the canopy. For example, readings taken at low altitudes might tend to be erratic, because the sensor may view only vegetation or only soil, biasing the measurements. As the sensor altitude above the canopy increases, the repeatability of the measurements should improve because the composition, the relative abundance of bright and dark areas, of the sensor FOV tends to represent the canopy better.

Previous researchers working with field crops have positioned their radiometers from less than 2.0 m to more than 9.0 m above the soil (Table 1). Some researchers have held their radiometers at arm's length for relatively short crops (e.g., wheat and soybeans) while others have used ladders, hand-held booms, truck-mounted booms, and aerial lift towers to position their radiometers above relatively tall crops (e.g., corn). Jackson et al. (1980) described and discussed techniques for operating radiometers in a hand-held mode. There appears to be little consensus about what altitude a radiometer should be positioned or how many measurements per plot are required to acquire reliable spectral data.

In this experiment we determined how canopy reflectance varies as a function of sensor altitude above the crop and what minimum altitude is needed to acquire repeatable reflectance measurements with a desired precision over fully developed corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] canopies.

MATERIALS AND METHODS

Data were acquired at the Purdue University Agronomy Farm, West Lafayette, Ind. on 10 Sept. 1979 for three crop canopies: (1) corn, (2) soybeans with complete soil cover, and (3) soybeans with incomplete soil cover. All three canopies were grown on Chalmers silty clay loam (Typic Argiaquoll) which has a dark gray (10 YR 4/1) surface when dry.

Pioneer 3780 corn was planted in 76-cm wide north-south (N-S) rows on 31 May 1979 and thinned to 54,000 plants/ha. On 10 Sept. the corn was 2.9 m high, covered more than 95% of the soil, and was in the beginning dent stage of development (Hanway, 1963).

Amsoy 71 soybeans were planted in 76-cm wide, N-S rows on 20 May 1979 and developed a closed or full canopy with 100% soil cover. On 10 September these soybeans were 1.1 m high, slightly lodged, and were beginning to mature, stage R7, (Fehr et al., 1971). A few yellow leaves were visible among the upper leaves of the canopy.

A second field of Amsoy 71 soybeans was planted in 96-cm wide, N-S rows on 10 June 1979. These soybeans were 0.9 m tall, and covered 71% of the soil with a 20 to 30-cm strip of bare soil between the rows. At the time of these measurements the soybeans were in the full seed, stage R6, development stage (Fehr et al., 1971).

Spectral data were acquired with an Exotech 100 radiometer in four wavelength bands, 0.5 to 0.6-, 0.6 to 0.7-, 0.7 to 0.8-, and 0.8 to 1.1-μm, corresponding the four spectral bands of the Landsat multispectral scanner (MSS). Measurements in all bands were taken simultaneously and recorded by a printing data logger. The radiometer and a camera were mounted on the boom of an aerial lift truck and were elevated to altitudes ranging from 0.2 to 10 m above the crop canopy (Table 2). At altitudes less than 0.6 m above the canopy, 26 measurements were taken at 7.5-cm intervals along a 2.0 m transect perpendicular to the crop's row direction. At all other altitudes, 13 measurements were taken at 15-cm intervals. Less than 2.0 min were required to collect two replications of spectral data along the transect at each altitude. Spectral data were acquired on 10 Sept. 1979 under clear skies during an interval from 1.5 hours before to 2.5 hours after solar noon. The corresponding solar zenith angles were 42 to 36, 35 to 37, and 42 to 53 for the soybean full, soybean row, and corn canopies, respectively.

A 1.2 m square panel painted with highly reflecting barium sulfate was used as a reference surface for determination of reflectance factor (Robinson and Biehl, 1979). This reflectance standard provided a field calibration reference with stable, known reflectance properties. A dark level response

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[2] Research agronomist, research engineer, and graduate student, respectively.

Table 1. Examples of sensor altitudes used by various researchers.

Investigator	Crop	Maximum canopy height	Row spacing	Sensor altitude	Sensor FOV	No. rows in FOV† At soil surface	At canopy surface	Number of observations per plot
		m			degrees			
Aase and Siddoway (1980)	Wheat	(0.9)‡	0.30	1.9	15	1.7	0.9	6
Daughtry et al. (1980)	Wheat	0.9	0.18	3.4	15	5.0	3.7	2
Hinzman et al. (1981)	Wheat	1.1	0.18	6.0	15	8.8	7.3	1§
Pinter et al. (1981)	Wheat	1.0	0.18	2.0	15	3.0	1.5	6
Tucker et al. (1981)	Wheat	1.2	0.18	2.2	25	5.7	2.6	4
Kollenkark et al. (1982)	Soybeans	1.1	0.25	5.2	15	5.5	4.3	2
		1.0	0.75	5.2	15	1.8	1.4	2
		1.1	0.15	3.4	15	6.0	4.0	2
		1.0	0.45	3.4	15	2.0	1.4	2
		1.0	0.90	3.4	15	1.0	0.7	2
Tucker et al. (1979)	Corn	(2.5)	0.91	3.5	25	1.7	0.3	24
	Soybeans	(1.0)	0.76	2.0	25	1.2	0.4	16
Holben et al. (1980)	Soybeans	(1.0)	0.76	2.0	25	1.2	0.4	4
Nash et al. (1981)	Corn	3.0	0.76	5.2	15	1.8	0.8	2
Walburg et al. (1982)	Corn	3.2	0.71	9.1	15	3.4	2.2	1§
Kimes et al. (1982)	Corn	(2.5)	0.76	3.6	28	2.5	0.8	4

† Diameter (d) of the FOV was calculated using $d = 2\,h \tan(\theta/w)$, where h is the altitude of the sensor in meters and θ is the sensor FOV in degrees.
‡ Values in parenthesis are estimated.
§ Two observations per plot were acquired for a random subset of plots to estimate within plot variance.

of the instrument was also obtained by holding an opaque light-tight apparatus against the instrument's optical ports to measure the amplifier offset. The response of the reference panel was measured about every 20 min during the data collection period and the dark level every 40 min. These values were then used in the following equation to calibrate readings taken over the plots:

$$RF(\lambda) = (Ds(\lambda) - ds(\lambda))/(Dr(\lambda - ds(\lambda))*Rr(\lambda) \quad [1]$$

Where, $RF(\lambda)$ = reflectance factor (%) at a specific wavelength interval (λ),

$Ds(\lambda)$ = response of instrument to scene (crop canopy),

$ds(\lambda)$ = dark level response of instrument,

$Dr(\lambda)$ = response of instrument to painted barium sulfate reference standard,

$Rr(\lambda)$ = reflectance (%) of painted barium sulfate reference standard (measurement made in laboratory by comparison with pressed barium sulfate).

The reflectance data were plotted as a function of altitude and horizontal distance across the row to verify that the variance of reflectance at low altitudes was attributable to row effects. Since the two visible wavelength bands are highly correlated, as are the two near infrared bands, the 0.6 to 0.7 μm band 0.8 to 1.1 μm band were selected as representatives of the visible and near infrared bands, respectively. The change in the coefficient of variation (CV) for reflectance in each band was described as a function of sensor altitude above the crop using stepwise regression. The number of replications (measurements) required for a 90% probability of obtaining a significant result at the alpha = 0.10 level can be estimated using the following equation from Cochran and Cox (1957):

$$r \geq 2\,(s/d)^2\,(t_1 + t_2)^2 \quad [2]$$

where, r = number of replications,

d = true difference that is desired to detect,

s = true standard error per unit,

t_1 = significant value of t in the test of significance,

t_2 = value of t in the ordinary table corresponding to $(1 - P)$.

Since the value of r depends only on the ratio of s/d, coefficient of variation and percent difference were substituted for s and d, respectively, in Eq. [2]. In application of Eq. [2] the number of degrees of freedom in t_1 and t_2 depends on r. In order to start the calculations, r was assumed to be infinity and then adjusted in subsequent calculations until the smallest number of replications that would satisfy the condition in Eq. [2] was determined.

An alternative to a random sampling scheme for row crops might be to sample at half row spacing intervals across the canopy. In the extreme case at low altitude, the sensor would view only the crop when centered over the row and only soil when positioned between the rows. The mean of these two observations may more nearly represent the overall canopy reflectance than either alone. To evaluate this stratified sampling approach the coefficients of variation for pairs of measurements at half row spacing intervals for each altitude were calculated and regressed as a function of sensor altitude. The number of paired observations needed to obtain the desired precision was estimated using Eq. [2], but was converted to the number of individual measurements for comparison.

RESULTS AND DISCUSSION

Variation Due to Rows

Mean reflectance factor of the canopy (the average of all measurements taken at one altitude along the 2.0 m transect) varied slightly with sensor altitude (Table 2). A portion of this variation in the mean is associated with experimental technique which, for each sensor altitude, did not always position identically the beginning of the 2.0 m transect above the same spot of the canopy. The portion of the canopy in the sensor FOV increased with sensor altitude and changed if and when the horizontal position of the 2.0 m transect changed. During data acquisition, obser-

Table 2. Mean reflectance factor as a function of sensor altitude for three crop canopies.

Sensor altitude			Wavelength band, μm			
Above soil	Above canopy	n	0.5–0.6	0.6–0.7	0.7–0.8	0.8–1.1
m			Reflectance, %			
			Corn canopy			
3.1	0.2	52	4.4	4.2	21.5	31.6
3.5	0.6	52	3.7	3.8	20.5	31.8
3.8	0.9	26	4.2	4.2	21.6	32.8
4.2	1.3	26	3.7	3.7	20.1	30.9
4.6	1.7	26	4.2	4.2	21.5	33.2
5.0	2.1	26	3.9	3.7	20.7	31.1
6.2	3.3	26	5.0	4.8	26.9	39.8
7.7	4.8	26	4.9	4.6	26.2	38.7
9.2	6.3	26	4.7	4.4	25.0	36.9
10.7	7.8	26	4.7	4.4	24.8	36.9
12.2	9.3	26	4.7	4.1	23.9	35.8
13.8	10.9	26	4.8	4.2	24.5	36.8
			Soybean row canopy			
1.1	0.2	52	5.5	4.3	33.2	43.6
1.5	0.6	52	5.4	4.8	32.2	45.8
1.9	1.0	26	5.0	4.5	31.5	44.4
2.2	1.3	26	5.2	4.8	31.7	45.6
2.6	1.7	26	4.9	4.5	31.0	44.2
3.0	2.1	26	5.1	4.6	31.2	44.8
4.2	3.3	26	5.1	4.9	28.0	40.3
5.7	4.8	26	5.0	4.8	28.1	40.6
8.8	7.9	26	4.8	4.6	27.1	39.4
10.2	9.3	26	4.6	4.4	27.5	40.1
			Soybean full canopy			
1.3	0.2	51	5.1	4.3	33.0	44.6
1.7	0.6	51	5.4	5.1	34.8	50.3
2.0	0.9	26	5.0	4.6	32.7	45.5
2.4	1.3	26	5.6	5.1	34.8	48.6
2.8	1.7	26	5.1	4.5	31.4	44.3
3.1	2.0	26	5.5	4.9	34.0	47.2
4.3	3.2	26	5.5	5.1	32.5	46.2
5.8	4.7	26	5.4	4.9	32.0	45.8
8.9	7.8	26	5.2	4.8	31.0	44.1
10.4	9.3	26	5.3	4.8	31.0	43.8

vation of the characteristics of the lift truck and measurement apparatus indicated that errors in horizontally positioning the transect at each altitude over the same location of the canopy were 2 to 3 cm across the rows (along the transect) and fractions of a meter along the rows.

The reflectance data were plotted as a function of sensor altitude and horizontal distance across the rows (Fig. 1 to 3). The variation of the reflectance factor measurements at low altitudes is attributed to row effects which diminished at higher altitudes where the sensor integrated over several rows.

The principal components of the corn canopy were sunlit leaves, shaded leaves, and shaded soil. Sunlit soil was a minor component of the sensor FOV as very little direct sunlight penetrated to the soil surface. At the lowest sensor altitude, less than 0.2 m above the canopy, the reflectance factor in the visible wavelength region (Fig. 1) varied from less than half to more than double the mean reflectance factor as the sensor moved across the rows and viewed different proportions of shadows and sunlit leaves. At the same altitude, the reflectance factor in the infrared changed from 0.5 to 1.5 times the mean as the sensor moved across the rows. Both visible and infrared canopy reflectance factors have meaxima when the sensor viewed sunlit leaves and minima when the sensor viewed shadows. The amplitude of the variation in reflectance factor in both bands decreased rapidly as the sensor was elevated.

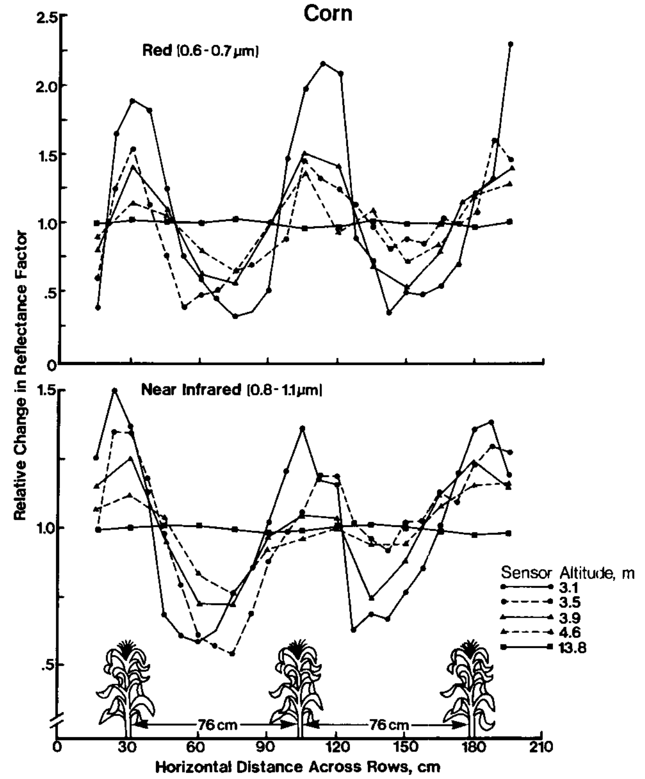

Fig. 1. Relative changes in reflectance factor as a function of sensor altitude and horizontal distance across 76 cm rows of corn.

The soybean row canopy contained sunlit soil, sunlit vegetation, shaded soil, and shaded vegetation. In the visible wavelengths (Fig. 2), the canopy reflectance factor was greatest (more than twice the mean canopy reflectance factor) when the sensor was positioned over sunlit soil, indicating that sunlit soil was the brightest component of the canopy. When the sensor was positioned over foliage—presumably sunlit leaves, the canopy reflectance factor corresponded with the mean canopy reflectance factor. When the sensor was positioned over shaded soil and vegetation which the ancillary photographs indicated was shaded, the canopy reflectance factor was less than the mean. This contrasts with the corn canopy where leaves were the brightest components. The near infrared canopy reflectance factor was greatest for sunlit leaves and lowest for bare soil and shadows between the rows. Shadows in the infrared are not as dark as in the visible due to the multiple scattering of near infrared energy by leaves.

The canopy reflectance factors in the visible and near infrared wavelength bands even varied with sensor position across the canopy with the completely covered soil (Fig. 3). A few senescing (yellow) leaves at the top of the canopy and some isolated lodging which created relief in the canopy surface contributed to variations in reflectance factor measured with position across the canopy. However, at the lowest altitudes, the ranges in canopy reflectance factors of this full soybean canopy (Fig. 3) were less than either

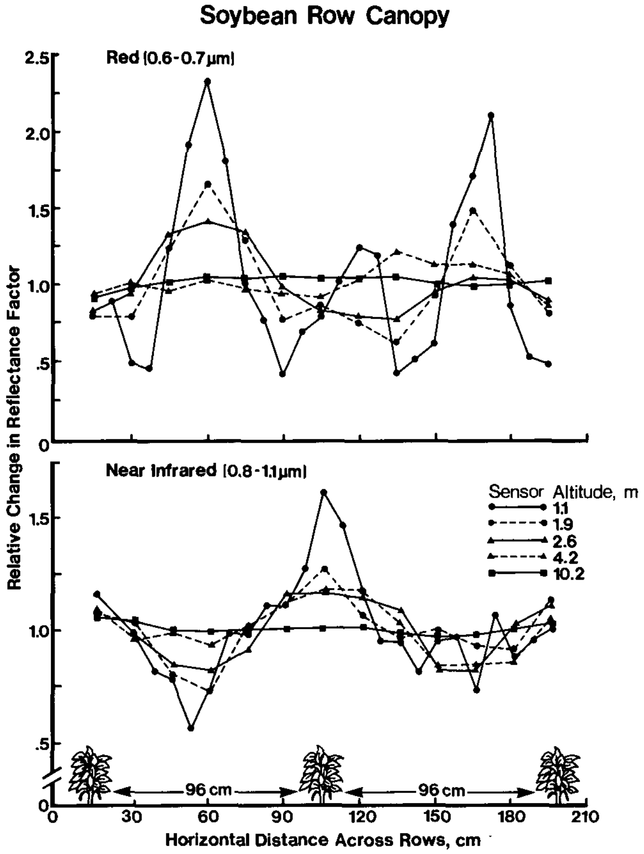

Fig. 2. Relative changes in reflectance factor as a function of sensor altitude and horizontal distance across 96 cm rows of soybeans with incomplete soil cover.

the corn (Fig. 1) or the soybean canopy with rows (Fig. 2). The variation in reflectance factor measured across this full canopy of soybeans was more random and less a function of rows than for the previous two canopies.

Coefficient of Variation Versus Altitude

Coefficient of variation (CV) normalizes standard deviations by the mean and is useful for comparing relative variations of both the visible and near infrared bands. The CV at each altitude was calculated using four sampling schemes. First, all measurements across two complete row spacing intervals (e.g., 1.5 m of the 2.0 m transect for the corn and full soybean canopies and 1.9 m of the 2.0 m transect for the two canopy soybeans) were used to calculate the CV at each altitude. This analysis approach assumes simple random sampling of the canopy.

A second sampling scheme used means for all possible pairs of measurements (25 pairs) acquired at 15-cm intervals across each canopy to calculate CV's for each altitude. This scheme provided a check of any gains made in reducing CV simply by using means instead of individual measurements.

The next two sampling schemes considered the means of pairs of samples acquired at one half of the row spacing intervals across the canopy. For example, if one measurement was acquired directly over the row, then the second measurement of the pair would be acquired halfway between the two adjacent rows. The third sampling scheme included all possible pairs of measurements (20 pairs) acquired at 45-cm intervals across the canopy, while the fourth scheme considered only the means of those measurements (8 pairs) acquired directly over the rows and directly over the middle or furrow of the two adjacent rows. In practice, these half row spacing sampling schemes were not perfect, but were within 7.0 cm of the desired sample spacing for the 76 cm rows and within 3.0 cm for the 96 cm rows.

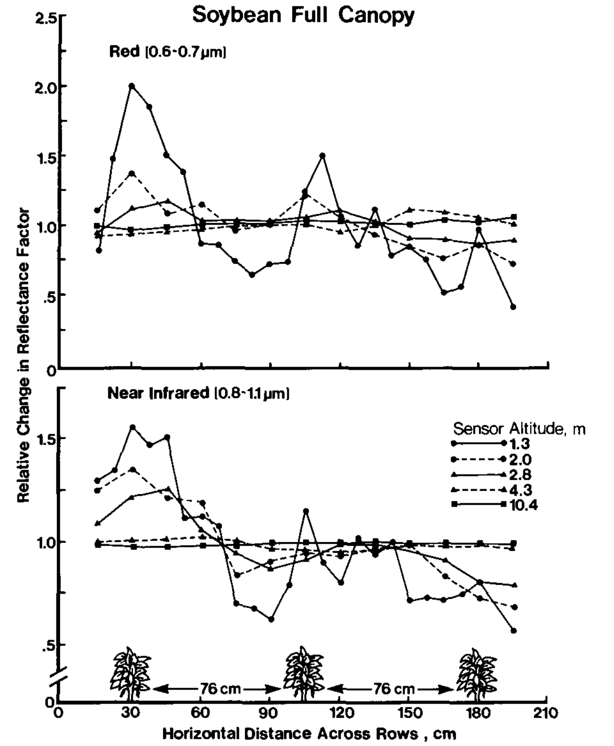

Fig. 3. Relative changes in reflectance factor as a function of sensor altitude and horizontal distance across 76 cm rows of soybeans with complete soil cover.

The CV of the canopy reflectance factor in both visible and near infrared bands decreased significantly with increasing sensor altitude when the diameter of the sensor's field of view at the top of the canopy exceeded the row spacing (Fig. 4, 5, 6). The CV decreased more rapidly for the soybean canopy with 100% soil cover (Fig. 6) than for the soybean canopy with rows and 71% soil cover (Fig. 5).

For all three canopies, the CV for the red band was greater than the CV for the near infrared band. In the visible wavelength bands, the greater contrast between sunlit soil/sunlit vegetation and shadows probably contributed to the greater CV for the red band compared with the infrared band.

The three systematic sampling schemes employing means of two measurements consistently had lower CV's than the simple random sampling using individual measurements. This is expected since the variance of a sample of means drawn from a population is less than the variance of individuals drawn from the same population (Cochran and Cox, 1957).

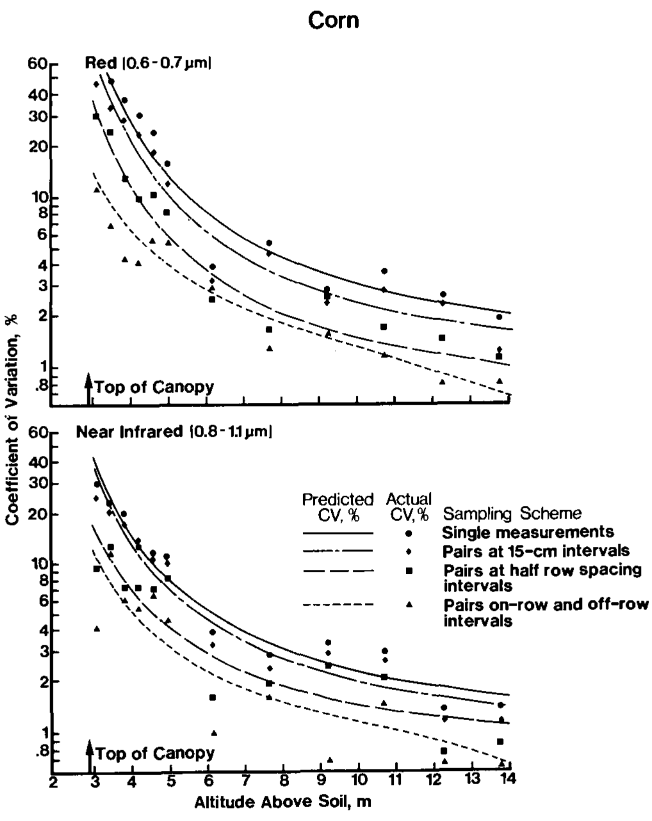

Fig. 4. Changes in predicted and actual coefficients of variation (CV) for reflectance factors of a corn canopy.

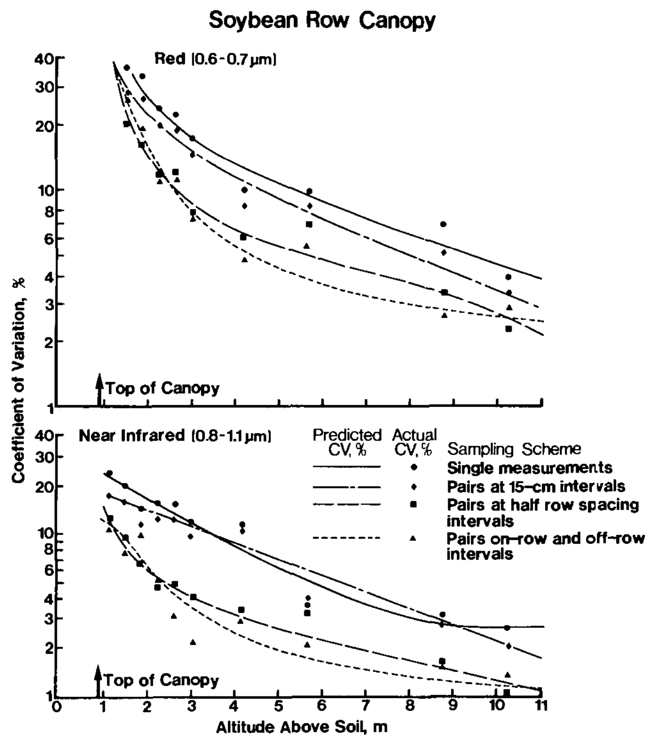

Fig. 5. Changes in predicted and actual coefficients of variation (CV) for reflectance factors of a soybean canopy with incomplete soil cover.

Sampling at half row spacing intervals (schemes 3 and 4) reduced the CV for both visible and near infrared reflectance by nearly 50% (Fig. 4, 5, and 6). Reductions in CV are possible for canopies with distinct rows if knowledge of the canopies is employed and samples are acquired at intervals which are odd multiples of 0.5 times the row spacing. However, the asymmetry across the rows shown in Figs. 1, 2, and 3 indicate that taking one measurement over a row and another over the soil and then averaging the two may not yield a sufficiently accurate value of the composite scene. Taking a number of measurements as the sensor is moved across the rows may be a more appropriate sampling scheme, especially at low altitudes if the diameter of the field of view is less than the row spacing. Care must be exercised in making measurements and in interpreting data acquired at low altitudes.

Practical Applications

In practice, a researcher wants to know how many observations or measurements must be acquired to be reasonably confident of detecting specific differences among crop canopies. He faces questions about how to allocate the finite number of measurements that can be acquired in a reasonable length of time between the number of measurements per plot and the total number of plots (treatments) in the experiment. If he does not acquire enough samples or measurements per plot, his estimate of the true reflectance of a plot will be too inaccurate to be useful. Con-

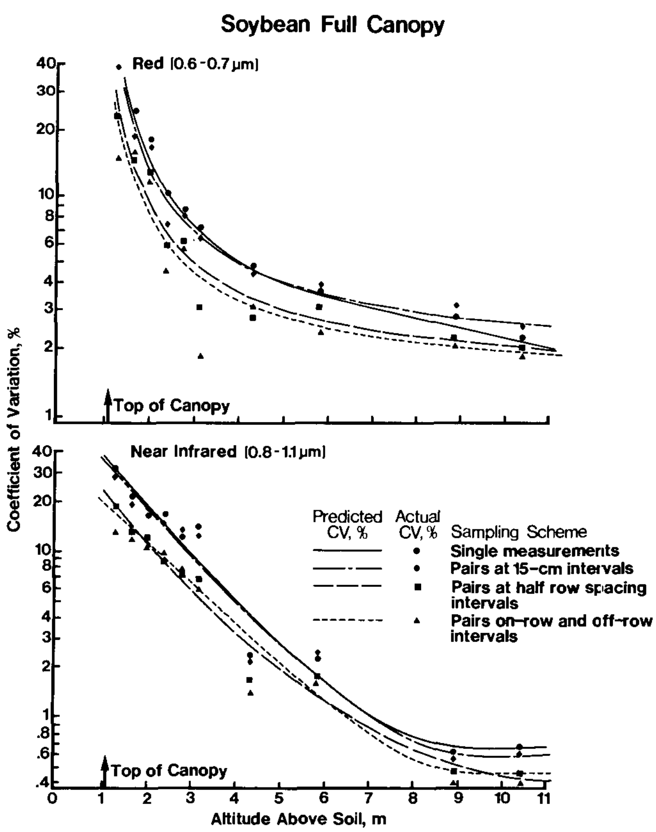

Fig. 6. Changes in predicted and actual coefficients of variation (CV) for reflectance factors of a soybean canopy with complete soil cover.

Table 3. Minimum number of measurements required by four sampling schemes for detecting true differences among treatments using $\alpha = 0.10$ test of significance and a 90% probability of obtaining a significant result.

Canopy type (Spectral band)	Sensor altitude: Above soil	Sensor altitude: Above canopy	Simple random sampling†				Random pairs at 15 cm‡				Random pairs at 0.5 W‡				Pairs "on row and off row"§			
			True differences as percent of the mean															
			2	5	10	20	2	5	10	20	2	5	10	20	2	5	10	20
	m	m	number of individual measurements¶															
Corn (0.6–0.7 μm)	4	1	--	--	--	44	--	--	--	54	--	--	64	20	--	74	22	8
	5	2	--	--	41	12	--	--	50	16	--	64	20	8	--	30	10	6
	7	4	--	31	9	4	--	40	12	6	80	16	8	4	56	12	6	4
	9	6	72	13	5	3	90	18	8	4	36	10	4	4	28	8	4	4
	11	8	41	8	4	2	52	12	6	4	22	6	4	4	16	6	4	2
	15	12	21	5	3	2	28	8	4	4	14	6	4	2	8	4	2	2
Corn (0.8–1.1 μm)	4	1	--	--	49	14	--	--	80	24	--	90	26	10	--	52	16	6
	5	2	--	56	16	5	--	90	26	10	--	34	12	6	--	22	8	4
	7	4	82	15	5	3	--	24	10	4	60	14	6	4	40	10	6	4
	9	6	38	8	3	2	60	14	6	4	32	8	4	4	22	6	4	4
	11	8	24	6	3	2	38	10	6	4	22	6	4	4	14	6	4	2
	15	12	14	4	2	2	22	6	4	4	16	6	4	2	6	4	2	2
Soybean row (0.6–0.7 μm)	2	1	--	--	--	39	--	--	--	56	--	--	92	26	--	--	--	66
	3	2	--	--	68	19	--	--	--	28	--	--	36	12	--	--	40	14
	5	4	--	--	27	8	--	--	40	14	--	56	18	8	--	38	12	6
	7	6	--	50	14	5	--	68	20	8	--	36	12	6	--	24	8	4
	9	8	--	27	8	4	--	34	12	6	--	22	8	4	90	18	8	4
	11	10	88	16	6	3	94	18	8	4	56	12	6	4	74	16	6	4
Soybean row (0.8–1.1 μm)	2	1	--	--	60	17	--	--	88	24	--	66	20	8	--	68	20	8
	3	2	--	--	31	9	--	--	56	18	--	32	12	6	--	24	10	4
	5	4	--	34	10	4	--	88	26	10	76	16	6	4	44	10	6	4
	7	6	72	13	5	3	--	38	12	6	42	10	6	4	26	8	4	4
	9	8	41	8	4	2	86	18	8	4	26	8	4	4	20	6	4	4
	11	10	49	10	4	2	36	10	4	4	16	6	4	2	18	6	4	2
Soybean full (0.6–0.7 μm)	2	1	--	--	46	13	--	--	78	22	--	--	40	14	--	--	32	10
	3	2	--	46	13	5	--	82	24	10	--	46	14	6	--	48	12	6
	5	4	92	16	6	3	--	32	12	6	--	20	8	4	88	18	8	4
	7	6	55	11	4	2	--	22	6	4	68	14	6	4	60	14	6	4
	9	8	36	8	3	2	90	18	8	4	56	12	6	4	48	12	6	4
	11	10	18	5	2	2	76	16	6	4	48	12	6	4	40	10	6	4
Soybean full (0.8–1.1 μm)	2	1	--	--	80	22	--	--	--	40	--	--	60	18	--	--	58	18
	3	2	--	--	22	7	--	--	42	14	--	62	18	8	--	74	22	8
	5	4	36	8	3	2	88	18	8	4	44	10	6	4	52	12	6	4
	7	6	4	2	2	1	16	6	4	2	12	4	2	2	10	4	4	2
	9	8	2	1	1	1	10	4	4	2	4	2	2	2	6	4	2	2
	11	10	1	1	1	1	10	4	4	2	4	2	2	2	6	4	2	2

† simple random sampling scheme assumes that each measurement is acquired independently of any previous measurements.
‡ These two sampling schemes assume that measurements are acquired in pairs which are then averaged. The sensor is randomly positioned over the canopy for the first measurement of the pair and then a second measurement is acquired either at 15 cm away horizontally or at 0.5 times the row spacing (W) away.
§ The "on row and off row" sampling scheme assumes that the first measurement is acquired directly over the plants (on row) and the second measurement is acquired halfway between adjacent rows (off row).
¶ Numbers of measurements greater than 100 are omitted for clarity.

versely, he also wants to avoid taking more measurements per plot than is required to obtain an accurate estimate since such an approach would limit the number of plots that can be measured and possibly the scope of the experiment.

The first step is to decide how small a difference among treatments must be detected—how large an error in reflectance can be tolerated. This demands careful thinking about the use to be made of the estimates of reflectance and about the consequences of a sizeable error. The figure finally reached may be quite arbitrary initially, but does represent a goal which may be refined as experience is gained.

In this paper, we chose four degrees of precision or true differences among treatments—2, 5, 10, and 20% of the mean reflectance. We further specified that we wanted to be 90% confident of detecting significant differences at the alpha = 0.10 level.

Table 3 shows the minimum number of measurements required by the four sampling schemes for detecting true differences in three crop canopies. This represents the smallest number of measurements that satisfied Eq. [2]. Although sampling schemes 2, 3, and 4 used means of pairs of measurements, the data in Table 3 are individual measurements, e.g., 27 pairs of measurements predicted by Eq. [2] for the sampling scheme using random pairs at 15-cm intervals at 4.0 m above the soil for the corn canopy actually represents 54 individual measurements.

The number of measurements required for a given level of precision decreases with increasing sensor altitude and as the sensor's FOV contains a more representative sample of the canopy. Many measurements are required at low altitudes because reflectance measurements tended to be erratic as the sensor is moved across the rows (Figs. 1, 2, and 3). For example, to detect 20% differences in red (0.6 to 0.7 μm) canopy reflectance factor of two soybean canopies with approximately 70% soil cover using the simple random sampling scheme, at least 39 measurements are required when the sensor is 2.0 m above the soil or about as high as a person with an outstretched arm can hold a radiometer. In this example, the number of reflectance measurements decreases rapidly as the sensor is elevated; 19 measurements are required at 3.0 m and only five at 7.0 m above the soil. Altitudes greater than about 2.0 m require that the radiometer be mounted on a boom or in some manner suspended above the crop and away from the operator. Tsuchida (1981) describes and evaluates several booms designed for field research with radiometers.

The number of measurements required for any given level of precision in the red (0.6 to 0.7 μm) band was larger than for the near infrared (0.8 to 1.1 μm) band (Table 3). This is expected from the larger CV shown in Fig. 4, 5, and 6 for the red band compared with the near infrared band. However, because detectors for both bands generally are mounted in the same radiometer, the number of measurements required for an experiment should be based on the larger of the two estimates; i.e., the red band.

Changes in the proportions of soil and crop in the FOV also change the number of measurements required. Fewer measurements are required to characterize the reflectance of a soybean canopy with 100% soil cover than for a soybean canopy with distinct rows and only 71% soil cover. Canopies with foliage in distinct, well-formed rows and equal proportions of sunlit soil/sunlit vegetation and shaded soil/shaded vegetation measured at the lowest sensor altitude would have the greatest variation in reflectance across the rows and should require the largest number of measurements to detect any specified differences in the canopy reflectance factor in the red spectral region. The number of measurements required to estimate with a specified precision the true reflectance of a canopy with rows can be expected to increase from planting until 50% soil cover and then decrease as the proportion of vegetation in the scene increases. The magnitude of this change in number of measurements with crop development should be a function of the relative differences in reflectance factor of sunlit and shaded soil and vegetation. The greater the contrast among these components, the greater the increase in number of reflectance measurements required as the crop grows.

As a researcher continues to plan his experiments, he soon asks which sampling scheme is most efficient, i.e., requires the fewest number of measurements per plot? Of the four sampling schemes evaluated in this paper, the second scheme using the means of pairs of measurements acquired at 15-cm intervals was least efficient. The reductions in CVs associated with averaging pairs of measurements (Fig. 4, 5, and 6) were not sufficient to decrease the total number of measurements to less than required by simple random sampling using individual measurements (Table 3).

The two stratified or systematic sampling schemes based on a knowledge of the row spacing in the crop canopy were more efficient, especially at low altitudes, than the simple random sampling. As sensor altitude increased, efficiencies due to stratified sampling decreased until, in some cases, stratified sampling at half row spacings slightly increased the total number of measurements. Some of the decreased efficiency with stratified sampling schemes was caused by rounding up all fractions of a measurement pair to the next whole number.

SUMMARY AND CONCLUSIONS

This experiment measured variation in reflectance factor of three crop canopies as functions of horizontal distance across rows and vertical distance above the soil. At low altitudes, variations in reflectances as the sensor moved across the canopy were attributable to row effects which disappeared as the sensor altitude above the canopy increased and the sensor integrated across several rows. Coefficients of variation of reflectance decreased exponentially as the sensor altitude increased. Sampling schemes employing a priori knowledge of the canopy row spacing were more efficient (required fewer measurements for a given level of precision) than simple random sampling schemes.

While this experiment cannot provide answers to the number of measurements required for every experiment, it does emphasize that extreme care must be exercised in analyzing and interpreting data acquired at sensor altitudes where the diameter of the sensor's FOV at the top of the canopy is smaller than several multiples of the row spacing. Researchers employing portable ground-based sensors are encouraged to include in the descriptions of their experiments the following information: sensor altitude above soil, crop height, row spacing, diameter of FOV at soil surface, number of measurements per plot, sampling scheme employed, and within plot variances. This information will greatly assist other scientists trying to interpret and use what appears to be conflicting field research data.

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