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ABSTRACT

Reflectance calculations of soybeans and corn crops at two times during the growing season indicate that the high sensitivity of the thematic mapper mid-infrared band to exposed bare soil between soybean rows is most likely responsible for early season spectral discrimination of corn and soybean crops by this band.

INTRODUCTION AND SUMMARY

Time series plots of "Greenness" and "Brightness" for corn and soybeans derived from the Landsat Multispectral Scanner (MSS) bands for the identification of crops have previously shown that, up to about mid season, the time series plots are not sufficiently different to distinguish soybean fields from corn fields, Roller, et. al (198[illegible]). These plots diverged later (after July) in the growing season.

Corn and soybean crop reflectances for mid and late season conditions are modeled using a row crop reflectance model, Suits (1983), in order to determine the cause for this similarity in early season band spectra and to assess the potential of Thematic Mapper (TM) bands for distinguishing these two crops at mid season.

The reflectance model analysis for mid July shows that the MSS mean vectors for soybeans and corn are nearly collinear. A small variation in the soybean foliage extension into the inter-row region will result in Greenness and Brightness values quite close to the mean values for corn. The mean vectors for corn and soybeans change direction after July. The Greenness of corn remains about the same but soybean Greenness increases significantly. The analysis suggests that the divergence is due to the difference in the maturing and scenesing features of the two crops.

A two-band plot using the 0.79 to 0.90 and the 1.55 to 1.75 μm bands of the Thematic Mapper shows that the mid July TM mean vectors are not collinear but are separated by 16 degrees, offering the potential for early discrimination. The band reflectance for the MSS and TM near-infrared bands are nearly the same. The difference is in the sensitivity of the 1.55 to 1.75 μm band of the TM to exposed soil in soybeans.

The analysis begins with the collection of crop descriptors for corn and soybean fields for mid July and mid August. These descriptors are used as input to the row crop reflectance model and the reflectances are calculated under sun angles appropriate to a midwest-U.S. satellite over-pass time. Two-band plots show the location in spectral space of the crop mean vectors for early soybean, early corn, late soybean and late corn.

A reflectance sensitivity calculation yields the expected shift in the soybean mean vector for hypothetical field feature variations. The feature variation which causes the largest shift towards or away from the corn mean vector is used to identify the feature which is primarily responsible for the spectral separation of the two crops.

FIELD DESCRIPTORS

Two categories of field descriptors are required for the row crop reflectance model input -- spectral properties and geometric properties.

The hemispherical spectral reflectance and transmittance of the plant components -- green leaves, chlorotic leaves, necrotic leaves, and stems -- were obtained by laboratory measurements on samples supplied by G. Safir at Michigan State University. Soil reflectance was obtained similarly. The soil reflectance was a Type 1 spectrum by Condit (1970) classification.

The geometric data -- the mean component projected areas (horizontal and vertical), and the number of such components per unit volume of crop canopy (number density) -- was obtained from a combination of field observations and reported information.

Leaf orientation for corn was obtained from field observations at Michigan State University. Soybean leaf orientation was derived by G. Safir from Blad (1970). The canopy height, row spacing, green leaf area index (LAI), and canopy layer thicknesses were derived from interpretation of LARS (1980) field photographs and field reports for the two times of interest during the growing season, mid July and mid August.

Along with these descriptors, an addititonal description of the row structure of the crop is needed. The number of components per unit canopy volume is specified to be the field average. Across rows, the number density of components changes from maximum on the row to some reduced value between rows. A simple linear variation of number density was chosen for corn where the number density of components are reduced linearly with distance towards the adjacent row. The variable, foliage extension (FE), is the fraction of row spacing at which the number density of components extending from one row to the next becomes zero. Each row is assumed to behave symmetrically so that at FE = 0.5, the foliage from one row progressively becomes more sparse and is zero at the point where the foliage from the opposite row begins to increase from zero density towards its row center. A foliage extension of 1.0 requires that the number density of one row becomes zero at the opposite row center. The sum of the number densities between rows due to extension from adjacent rows is constant and the field is uniform.

The soybean foliage is distributed differently. The LARS field photographs indicate that the distribution of components across rows is more nearly in the fashion of a rectangular distribution where foliage extending into the inter-row regions appears to be uniform up to the point where number density falls to zero abruptly. For a soybean field at FE = 0.5, the field is uniform with foliage from opposite rows meeting in the middle. At FE < 0.5, a clear strip of bare soil can be seen between soybean rows.

The basic parameters for the early corn and soybeans which were used in the analysis are shown in the Appendix. Changes only in geometric parameters were made in order to model late corn and soybeans. The LARS field photographs indicated that the late corn canopy differs from the early corn canopy primarily in the lower canopy layer where after mid July leaf senescence begins progressively upward towards the top of the canopy. The top layer green leaf area index appears to be constant. Consequently, the July layer thicknesses of 0.25 m (lower) and 1.75 m (upper) were changed to 1.0 m (lower) and 1.0 m (upper). The lower layer contains the mixture of green, chlorotic, and necrotic leaves in the leaf slough-off region.

The LARS data shows that the late soybean canopy shows no evidence of senescence during that time but instead soybeans have increased their green leaf area index from 3.5 to 5 and have increased the foliage extension to FE = 0.5 to form a uniform canopy. Thus, the late soybean field parameters are: green leaf projected areas are increased by 5/3.5 and FE = 0.5.

ANALYSIS OF BAND SPECTRA

The calculation of the reflectance spectra, $\rho(\lambda)$ was accomplished using the row crop reflectance model, Suits (1983), from 0.4 to 0.8 μm in steps of 0.01 μm, and from 0.8 to 1.1 μm, from 1.5 to 1.75 μm, from 2.0 to 2.35 in steps of 0.05 μm. Band reflectances were calculated from these spectra using the relation,

$$\rho(\text{band}) = (1/(\lambda_2 - \lambda_1)) \int_{\lambda_1}^{\lambda_2} \rho(\lambda)\, d\lambda$$

where λ_1 and λ_2 are the nominal band limits.

The four MSS bands and the six daylight reflectance bands of TM were used. For convenience, these bands are renumbered and assigned nominal band limits as shown in Table 1.

The resulting band spectra for the four cases -- early corn (C1), early soybeans (S1), late corn (C2), and late soybeans (S2) -- are shown in Table 2. If the field parameters describing the fields were the average values for a hypothetical population of similar fields, then these band spectra could be the mean vectors for the respective populations. A two-band spectral subspace was selected in order to show the relationships graphically between these hypothetical crop mean vectors. The subspace, Band 2 and Band 4, was chosen for the MSS and the subspace, Band 8 and Band 9, was chosen for the TM. Figure 1 shows the MSS two-band mean vectors for the four fields. The scale for Band 2, the red band, was greatly expanded for clarity. Notice that the mean vectors for C1 and S1 are nearly collinear. Using the dot product between C1 and S1 vectors, one can determine the angle between to be about 0.3 degrees. Each mean vector points to the center of its respective hypothetical scatter plot representing the results for the respective hypothetical populations.

Although the actual shape of the cluster of points which would be made by a scatter plot is not obtained from the calculation, experience with both Landsat and airborne scanner scatter plot data has shown that the best fitting ellipse around the clusters (assuming a Gaussian

TABLE 1. BAND NUMBERS AND BAND LIMITS FOR THIS ANALYSIS

Band Number	Band Name	Alias	λ_1 μm	λ_2 μm
1	MSS 4	green band	0.50	0.60
2	MSS 5	red band	0.60	0.70
3	MSS 6	IR 1	0.70	0.80
4	MSS 7	IR 2	0.80	1.00
5	TM 1	blue-green	0.45	0.52
6	TM 2	green band	0.53	0.61
7	TM 3	red band	0.63	0.69
8	TM 4	near IR	0.79	0.90
9	TM 5	mid IR	1.55	1.75
10	TM 7		2.10	2.35

TABLE 2. CORN AND SOYBEAN MEAN VECTORS (%)

BAND	1	2	3	4	5	6	7	8	9	10
Early Soybean	4.3	4.3	23.8	33.1	2.8	4.6	4.3	32.4	28.2	17.7
Early Corn	4.5	4.9	28.5	39.3	3.1	4.7	3.7	40.5	18.8	8.2
Late Soybean	4.1	2.5	38.3	53.2	2.3	4.3	2.2	53.8	34.4	16.3
Late Corn	5.0	4.1	33.8	40.8	3.1	5.1	3.7	41.8	21.5	9.5

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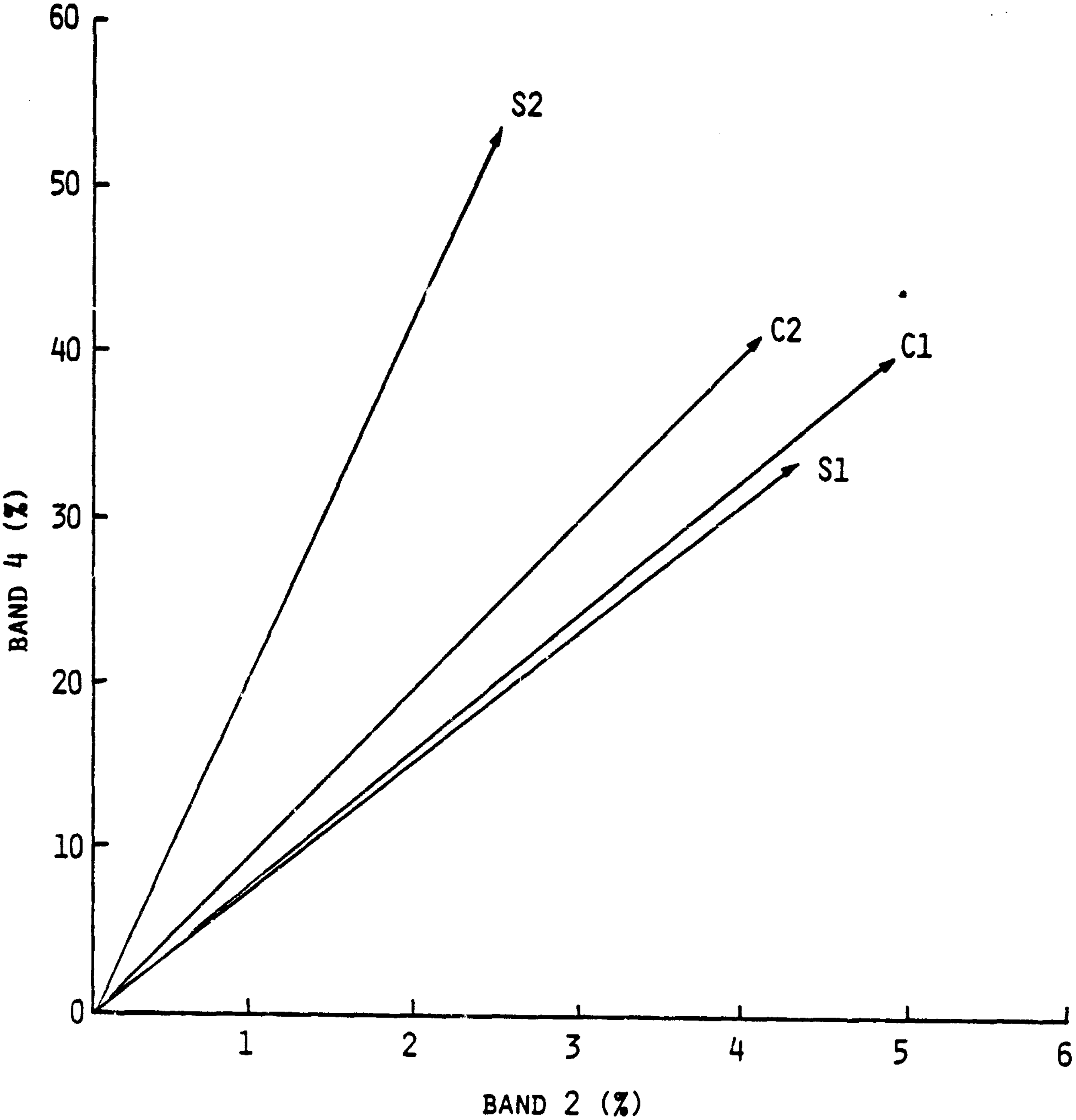

FIGURE 1. CORN AND SOYBEAN MEAN VECTORS IN THE MSS (2, 4) SPECTRAL SUBSPACE. C1 = early corn; C2 = late corn; S1 = early soybeans, S2 = late soybeans. The angle between S1 and C1 is 0.3° with Euclidian reflectance distance of 6.2%. The angle between S2 and C2 is 3° with Euclidian reflectance distance of 12.5%. (Notice the expanded scale for Band 2.)

distributions) is almost always oriented in such a way that the major axis of the ellipse is near the direction of the mean vector. The overlap of the scatter plots will result in errors in classification when multispectral discrimination algorithms are applied. The case of C1 and S1 would probably produce greatly overlapping scatter plots in the major axis direction.

The late season case, C2 and S2, shows that the mean vectors have separated both in distance and in direction. Although the angle between has increased to only 3 degrees, yet, because of the probable shape of the scatter plots, the change in angle may be the most influential in making spectral discrimination algorithms more accurate for late corn and soybeans.

Figure 2 shows the same four fields using the TM two-band subspace. The band spectra scales are the same in this case. Notice the wide separation for the early fields, C1 and S1. The angle between mean vectors is about 16 degrees.

Such a large difference in direction cannot, by itself, lead to the conclusion that early season discrimination would be improved because the minor axes of the scatter plots may also be larger. However, it is certainly a change in the right direction. The results of experiments by Unger and Goward (1982) showed that, using Band 9 instead of the MSS bands, early spectral separation of corn and soybeans was possible in their sample. The question remains as to the physical cause for the early separation.

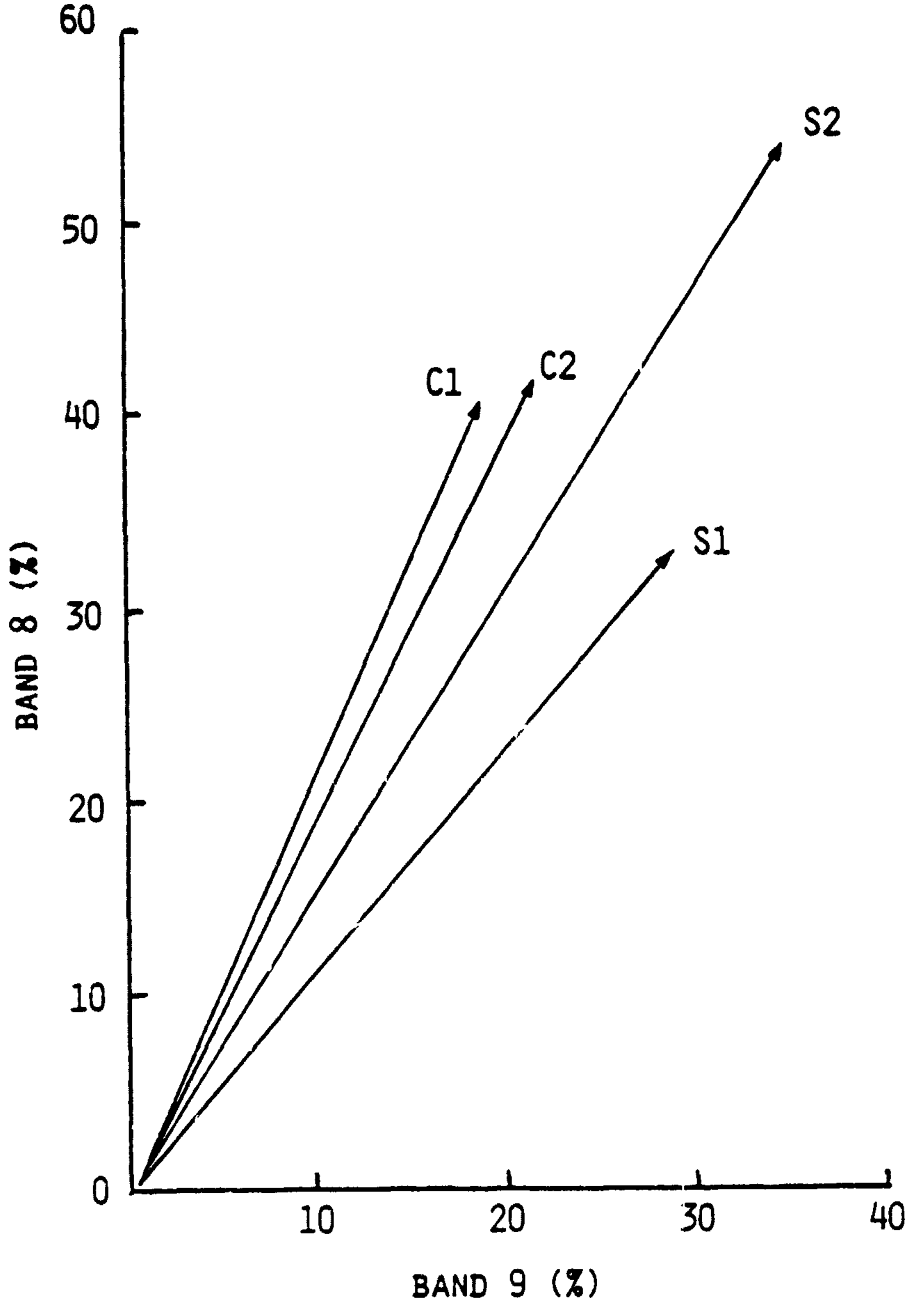

FIGURE 2. CORN AND SOYBEAN MEAN VECTORS IN THE TM (8, 9) SPECTRAL SUBSPACE. C1 = early corn, C2 = late corn; S1 = early soybeans, S2 = late soybeans. The angle between S1 and C1 is 16.1° with Euclidian reflectance distance of 12.4%. The angle between S2 and C2 is 5.4° with Euclidian reflectance distance of 17.6%.

Could the cause be accidental or coincidental to the particular circumstances of the Unger and Goward field measurements or to the particular choices of field parameters in this calculation?

SENSITIVITY ANALYSIS

If one could identify the physical feature of these fields which is primarily responsible for the separation using the TM sub-bands, then one could assess the possibility that the cause may or may not be purely circumstantial for particular choices of test area or choices of modeling parameters. A sensitivity analysis was done in order to identify this feature.

The mean vectors were recalculated with certain field features changed one at a time. The new mean vectors, $\bar{\rho}'$, are related to the previous mean vectors, $\bar{\rho}$, by

$$\bar{\rho}' = \bar{\rho} + S(J)$$

where $\bar{S}(J)$ = shift vector caused by a change in feature J.

Changing some field features required only a change in one of the model parameters; others required a combined change.

Ten field features were chosen for variation:

1. Percent change in plant density (%PD).
2. Percent change in green LAI (%LAI).
3. Degrees change in leaf slope (LS).
4. Percent change in soil reflectance (%RHO).
5. Change in foliage extension (ΔFE).
6. Percent change to chlorosis (%CHL).
7. Percent change to necrosis (%NEC).
8. Percent change in row spacing ($\%\Delta^{p}$).
9. Degrees change in row azimuth (ΔAZ).
10. Percent change in canopy height (%HCAN).

With the exception of changes in chlorotic and necrotic leaf areas, individual features were made to change with all other features held fixed. For example, a change in row spacing will not alter the foliage extension. The foliage would be more thinly distributed than before but would reach the same fractional distance across rows. The percent change to chlorosis and necrosis requires that green leaf area be turned into chlorotic or necrotic leaf area. Green LAI is reduced and is transferred as increments to the chlorotic or necrotic leaf area without any other change.

The changes in field features which were used and the shift vectors for each change are shown in Table 3 for early soybeans.

One may observe that Band 9 in Table 3 appears to respond to a soil reflectance increment, Feature 4, more than to any other field feature change. Also Band 9 responds to soil reflectance with greater sensitivity to that feature than does any other band. The response of Band 10 is a close second. Further, one may observe that a change in row azimuth from east-west to north-south causes a response in the opposite direction in both Bands 9 and 10 with Band 9 being second to Band 10. The sun azimuth of 104° and polar angle of 41° causes some inter-row soil illumination. A change to north-south rows places the sun at approximately the cross-row direction and should shadow much of the inter-row soil. The shift due to a change of row direction from east-west to north-south will tend to shift the early soybeans mean vector in the direction of the early corn mean vector.

One may conclude that the primary cause for the separation of early corn and soybean mean vectors using the TM subspace bands is the high sensitivity of Band 9 to the exposed and illuminated soil in the soybean field. The MSS subspace Bands 2 and 4 also respond to the same feature and in the same sense but the red band is less sensitive than the TM Band 9.

The sensitivity of the two TM long wavelength bands to soil variations has been previously noted by Crist (1983). He reports that, where Kauth and Thomas (1976) described a "plane of soils" in the MSS Tasseled Cap space, in MSS data virtually all the variation normally encountered in soils was confined to the Brightness direction so as to define a "soil

TABLE 3. EARLY SOYBEAN SHIFT VECTORS (%)

	BAND									
Parameter	1	2	3	4	5	6	7	8	9	10
1. %PD (50)	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1	-0.1	0.0
2. %LAI (50)	0.1	0.0	1.1	1.1	0.0	0.1	-0.1	1.3	0.2	0.4
3. LS (10)	-0.2	-0.1	-1.5	-1.9	-0.1	-0.2	-0.1	-1.9	-1.2	-0.6
4. %RHO (50)	0.9	1.4	2.4	3.7	0.7	1.0	1.4	3.2	5.6	4.8
5. ΔFE (1/8)	-0.7	-1.9	7.1	10.3	-0.6	-0.9	-2.1	11.1	1.2	-4.1
6. %CHL (10)	0.6	0.9	0.0	-0.4	0.1	0.8	0.9	-0.5	0.0	0.0
7. % NEC (10)	0.0	0.2	-2.2	-2.3	0.0	0.0	0.2	-2.9	-0.5	0.2
8. % ΔP (20)	0.0	0.1	-0.1	-0.1	0.0	0.0	0.1	-0.1	0.0	0.1
9. ΔAZ (90)	-1.5	-2.5	0.2	1.0	-1.1	-1.7	-2.6	1.6	-4.4	-6.8
10. %HCAN (10)	-0.1	-0.2	0.1	0.1	-0.1	-0.1	-0.2	0.2	-0.5	-0.5

line" instead of a plane. In the analogous TM Tasseled Cap space, a true "plane of soils" can be seen which is due to the contribution of the two TM long wavelength bands.

This sensitivity to exposed soils is reduced when illumination fails to reach the soil so that the separation of early soybeans and corn can be reduced in cases where solar elevation is both low and the sun is near the across-row direction at overpass time. The separation will then be less pronounced.

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APPENDIX

FIELD PARAMETERS

The parameters used for the early mean fields are shown in Table 4. The sun is at polar angle, 41°, and azimuth from north, 104°, to represent a 10 AM EST satellite overpass in the midwest in mid July. The view direction is the nadir.

TABLE 4. FIELD PARAMETERS FOR EARLY CORN AND SOYBEANS (MID JULY)

Parameter		CORN	SOYBEANS
Planting Date		Mid May	Mid May
Plant Density		5.0 m^{-2}	27.4 m^{-2}
Row Direction		East-West	East-West
Row spacing		0.75 m	0.75 m
FE		0.6 (triangular)	0.3125 (rectangular)
Canopy Height		2.0 m	0.45 m
Top Layer		1.75 m	0.30 m
Bottom Layer		0.25 m	0.15 m
Green LAI		3.5	3.5
Layer 1 Slope		60°	52°
Layer 2 Slope		75°	47.4°
Extinction Coefficients			
Top Layer			
Green Leaf	H	0.874 m^{-1}	4.80 m^{-1}
	V	1.514 m^{-1}	6.13 m^{-1}
Chlorotic	H	0.0875 m^{-1}	0.001 m^{-1}
	V	0.154 m^{-1}	0.001 m^{-1}
Necrotic	H	0.0875 m^{-1}	0.001 m^{-1}
	V	0.154 m^{-1}	0.001 m^{-1}
Stem	H	0.0	0.049 m^{-1}
	V	0.303 m^{-1}	0.135 m^{-1}
Bottom Layer			
Green Leaf	H	0.456 m^{-1}	5.27 m^{-1}
	V	1.700 m^{-1}	5.73 m^{-1}
Chlorotic	H	0.080 m^{-1}	0.02 m^{-1}
	V	0.348 m^{-1}	0.02 m^{-1}
Necrotic	H	0.080 m^{-1}	0.02 m^{-1}
	V	0.748 m^{-1}	0.02 m^{-1}
Stem	H	0.0	0.025 m^{-1}
	V	0.280 m^{-1}	0.068 m^{-1}
Soil		Condit Type 1	Condit Type 1

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