Reprinted from

Tenth International Symposium

Machine Processing of Remotely Sensed Data

with special emphasis on

Thematic Mapper Data and Geographic Information Systems

June 12 - 14, 1984

Proceedings

Purdue University
The Laboratory for Applications of Remote Sensing
West Lafayette, Indiana 47907 USA

INTERCEPTION OF LIGHT BY A PLANT CANOPY

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ABSTRACT

Vertical reflectance factor measurements were obtained from cotton plant (Gossypium hirsutum L.) canopies by removing successive leaf layers acropetally to calculate canopy light interception. Light interception in the RED (630-690 nm) and NIR (760-900 nm) wavebands were compared between maturing and senescing cotton plants. A plant canopy reflectance model was used to compute reflected (R), transmitted (T), and absorbed (A) light layer-by-layer through the cotton canopies. Maturing plant canopies intercepted more RED light (absorption by leaf chlorophyll), computed as R + A = 1 - T, than senescing plant canopies. Conversely, maturing plant canopies intercepted less NIR light than senescing plant canopies. Thus, remote measurement of intercepted RED light may be useful for early warning of crop condition and stress.

I. INTRODUCTION

Interception of the photosynthetically active radiative (PAR) part of the solar spectrum has been defined as that part of the downward flux which is not transmitted through the canopy (Anderson, 1966; Wilson, 1981). It corresponds to the light reflected back upwards plus that absorbed by the canopy. Since the light reflected (R), transmitted (T), and absorbed (A) by a diffusing medium such as a plant canopy must be conserved:

$$R + T + A = 1, \qquad (1)$$

then light interception in a plant canopy may be expressed according to Wilson's definition, as:

$$R + A = 1 - T. \qquad (2)$$

Since R is approximately zero in the PAR then absorbed light closely approximates intercepted light (that is; $A \sim 1 - T$).

In terms of downward light flux density (Wilson, 1981), recorded above (Io) and below (Ig) a plant canopy with cosine corrected light sensors, the intercepted light flux in a plant canopy may be written as Io-Ig where units are commonly quoted in units of W/cm^2. The fractional light transmitted and intercepted are given, respectively, as Ig/Io and (Io-Ig)/Io. Notice that (Io-Ig)/Io=1-T.

Interception of light primarily by leaves of plant canopies is important to agricultural remote sensing because photosynthesis depends on leaf chlorophyll absorption of the incident light. Stress affects canopy development by decreasing light interception. Thus, development of the relation of vegetation spectral responses (reflectance, transmittance, absorption, and interception) to important agronomic parameters (biomass, leaf area index (LAI), and leaf layer nodes) may be useful for early warning of crop condition and stress. The objective of this paper was to compare the light intercepted by maturing and senescing leaves of irrigated cotton canopies, respectively, under favorable growing conditions.

II. PLANT CANOPY REFLECTANCE THEORY

In agricultural remote sensing studies, light reflectance (R) rather than transmittance (T) is the quantity most generally measured. Operationally, it will be necessary to measure light interception as R+A rather than as 1-T; as shown by equation (2). A traditional two-parameter one-dimensional model for diffuse reflectance and transmission of light through a scattering and absorbing medium, as applied to plant canopies by Allen and Richardson (1968), was used to study light interception. Starting with equations (8) and (9) from Allen and Richardson (1968) and using the following transformation equations; $b^n=e^{kn}$, $a=1-B^2$, $a^2=(1+B)^2$, $1=(1-B)^2$, and n=0 for reflectance at the top of the canopy and n=N for transmittance at the bottom of the canopy; the model results in the following equations for estimating R and T:

$$R = \frac{b^n Rv(1-RvRg)-b^{-n}(Rv-Rg)}{b^n(1-RvRg)-b^{-n}Rv(Rv-Rg)}, \qquad (3)$$

$$T = \frac{1-Rv^2}{b^n(1-RvRg)-b^{-n}Rv(Rv-Rg)}, \qquad (4)$$

and

$$A = 1 - R - T. \qquad (5)$$

The asymptotic vegetation reflectance (Rv), bare soil reflectance (Rg), plant reflectance (R) and growth measurement (n) are observed in the field. The optical constant b is found from:

$$b = \frac{(1-RRv)(Rv-Rg)^{1/2n}}{(1-RgRv)(Rv-R)}, \qquad (6)$$

at each plant canopy layer for which R and n are measured. The average value of b over all plant canopy layers is used to estimate R and T from equations (3) and (4) for all n. Scattering (s) and absorption (k) coefficients, as given by Allen and Richardson (1968), may be calculated by:

$$s = (2a/(a^2-1))\log b, \qquad (7)$$

and $$k = ((a-1)/(a+1))\log b, \qquad (8)$$

where $a = 1/Rv$.

Equation (3) describes how reflectance increases exponentially, starting from Rg, and approaches the asymptotic reflectance (Rv) as n varies from zero to infinity. That is:

$$Rg < R < Rv \text{ as } 0 < n < \text{infinity}. \qquad (9)$$

Equation (4) describes how transmission changes exponentially from unity and asymptotically approaches zero as n varies from zero to infinity. That is:

$$1 > T > 0 \text{ as } 0 < n < \text{infinity}. \qquad (10)$$

The units of measure for k and s are the reciprocal of the units for n. If the units for n are dimensionless, as for leaf area index (LAI) measurements, then k and s are dimensionless. If n is a measure of biomass and is measured in kg/ha, then k and s are in ha/kg.

Park and Deering (1982) simplified Allen and Richardson's (1968) reflectance model, using equation (6), when they found that for most practical applications in the PAR the ratio of (1-RRv)/(1-RgRv) was approximately unity. Since $b^{-2n} = \text{EXP}(-2Kn)$ Park and Deering (1982) obtained:

$$R = Rv - (Rv - Rg)\,\text{Exp}(-2Kn). \qquad (11)$$

Their simplified derivation of this reflectance model led to a different formulation of the absorption coefficient (K):

$$K = (1 + Rv)/(1 - Rv)k. \qquad (12)$$

III. EXPERIMENTAL PROCEDURES

A 1-ha field of irrigated cotton growing on Hidalgo sandy clay loam (typic Calcustolls), located on the USDA Weslaco Research Farm, was selected for this study. Cotton seed (Gossypium hirsutum L. cv 'McNair 220') was planted on 8 March 1982 in rows 102-cm apart with a population density of about 114,000 plants/ha. Rows were aligned in an east/west direction. The cotton emerged on 14 March 1982.

Hand-held vertical CSFC MARK-II canopy radiometric measurements (mw/cm^2) were obtained from irrigated cotton plots, under good growing conditions, on June 3 and June 29, 1982 (Tucker et al., 1980). Both RED (630-690 nm) and NIR (760-900 nm) waveband radiometric measurements were obtained while leaf biomass was successively removed at two leaf layer nodal intervals acropetally. The RED waveband was used to simulate readings in the PAR for this study. The sensor field-of-view (FOV) was 24 degrees at a sensor height (SH) above ground of 1.00 m on June 3, 1982, and 1.25 m on June 29, 1982. On June 3, 1982, 12 cotton plants with an average plant height (PH) of 0.90 m that covered a 0.94 x 0.94 m area were used. On June 29, 1982, 13 cotton plants with an average PH of 1.10 m that covered a 1.1 x 1.1 m area were used.

Solar irradiance conditions in the field ranged from full shade to direct sunlight. Therefore, procedures were used to correct radiometric measurements to reflectance at a common solar irradiance reference condition (Richardson, 1981). These procedures used a Dodge Products Model 776 solar meter (M776) to account for intermittent irradiance variations due to solar zenith angle and clouds and to convert the radiometric measurements to RED and NIR reflectance.

Dry biomass plant growth measurements were obtained at two leaf layer nodal intervals through the cotton plant canopy acropetally. Leaf biomass measurements minus stem biomass measurements were correlated to the corresponding reflectance measurements layer-by-layer using Allen and Richardson's (1968) plant canopy reflectance models. Scattering and absorption coefficients describing light attenuation in the cotton plant canopies were computed for the two models and compared between June 3, 1982, and June 29, 1982, for maturing and senescing cotton canopies, respectively. Light interception was computed for each leaf layer through the plant canopy on each date.

IV. RESULTS AND DISCUSSION

Table 1 gives the field-measured MARK-II reflectance factors of cotton canopies in the RED and NIR, and the field agronomic data obtained on June 3 and June 29, 1982. Biomass and canopy layer node position varied directly with NIR reflectance and inversely with RED reflectance. Reflectance in the RED was lower and in the NIR it was higher for all canopy layers on June 29, even though there were 2.6 times as much total biomass on June 29 as on June 3. Therefore, light was attenuated more by the maturing cotton on June 3 than by the senescing cotton on June 29.

Figure 1 shows the agreement for Allen and Richardson's (1968) reflectance model on June 3 between measured reflectance factors and biomass (kg/ha) (r^2 = 0.99 and 0.96; for RED and NIR wavebands, respectively). Optical constants, bare soil and asymptotic reflectance, and scattering and absorption coefficients resulting from application of the model are given in Table 2. The absorption coefficient (k) was much higher in the RED (k=1.36E10-3 ha/kg) than in the NIR (K=0.10E10-3 ha/kg) because chlorophyll absorbs more RED than NIR light (Gausman et al., 1970). There was more scattering in the NIR (s=0.710E10-3 ha/kg) than in the RED (s=0.059E10-3 ha/kg) because leaf mesophyll structure increases reflectance in the NIR more than in the RED (Allen et al., 1970).

Figure 2 shows the agreement of Allen and Richardson's (1968) reflectance model on June 29 between measured reflectance factors and biomass (kg/ha) (r^2 = 0.94 and 0.88; RED and NIR wavebands, respectively). Model parameters resulting from application of the model are given in Table 2. In general, the absorption and scattering coefficients had the same relative RED and NIR amplitudes as on June 3. However, the RED absorption coefficient was less on June 29 than on June 3, indicating that senescence had decreased the chlorophyll concentration by June 29. Also, the NIR scattering coefficient was smaller on June 29 than on June 3 because the leaf mesophyll structure was probably less finely divided because of leaf senescence by June 29.

Table 3 gives the fractional light reflected, transmitted, absorbed, and intercepted in the RED and NIR wavebands by the complete cotton plant canopies (maximum n=N) on June 3 and June 29. Even though there was 2.6 times more total biomass on June 29 than on June 3, the RED light that was intercepted was lower on June 29 than on June 3. Conversely, the amount of NIR light intercepted was higher on June 29 than on June 3. Similar results were obtained for absorbed light as for intercepted light.

Chance and Le Master (1978) obtained fractional light intercepted in the RED and NIR of 0.93 and 0.65, respectively, for Penjamo wheat. Their values closely correspond with the light interception values of 0.96 and 0.69, respectively, for the June 3 maturing cotton (Table 3).

The absorption coefficients (K) and (k) computed by Park and Deering (1982) and Allen and Richardson (1968), respectively, compared closely in the RED but not in the NIR (Table 2). Thus Park and Deering (1982) simplifying assumptions are useful for light interception studies in the PAR. Table 4 compares the K's for RED light, ranked in descending order, for maturing cotton, alfalfa (Medicago sativa L.), senescing cotton, and short grass prairie (Bouteloua gracilis). The values of K for alfalfa and short grass prairie were published by Park and Deering (1982). The amount of light intercepted in the RED for this vegetation would be in the same ranked order. These results provide a comparison of the relative photosynthetic activity implied by the absorption coefficients of vegetation over a wide range of biomass amounts.

IV. CONCLUSION

The amount of RED light intercepted was found to be greater for maturing cotton canopies than for senescing cotton canopies. The inverse relation was found for NIR light. Thus, remote measurement of intercepted RED light may be useful for early warning of crop condition and stress.

V. ACKNOWLEDGEMENTS

I thank Wayne Swanson for his invaluable management of the experimental cotton plots, collection of plant canopy reflectance and agronomic plant measurements, and computer data processing and graphic work.

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Table 1 Mark-II reflectance of cotton canopies in the RED (630-690 nm) and NIR (760-900 nm) wavebands and field agronomic data collected on June 3 and June 29, 1982.

June 3, 1982				June 29, 1982			
RED %	NIR %	Biomass kg/ha $x10^3$	Canopy Layer by Node	RED %	NIR %	Biomass kg/ha $x10^3$	Canopy Layer by Node
-	-	-	-	3.3	39.5	8.20	17-20
2.2	57.1	3.09	15-16	3.5	37.9	7.63	15-16
2.1	51.3	3.08	13-14	3.3	38.5	6.94	13-14
2.1	51.1	2.87	11-12	3.6	38.2	5.77	11-12
2.3	50.2	2.34	9-10	3.7	42.6	4.38	9-10
2.4	45.9	1.85	7-8	4.3	37.5	3.29	7-8
3.0	26.5	1.42	5-6	4.1	16.9	2.53	5-6
3.8	25.9	1.11	3-4	4.7	13.9	2.06	3-4
5.6	12.9	0.95	1-2	5.1	12.0	1.81	1-2
6.2	13.8	0.89	main stems	5.2	11.1	1.72	main stems

Table 2 Optical constants (a and b), bare soil (Rg) and asymptotic (Rv) reflectance, and scattering (s), and absorption (k) parameters resulting from applying Allen and Richardson's (1968) plant canopy model to cotton plant biomass at two leaf nodal layer intervals (0-20 nodes) on two dates.

		n = total Dry Biomass by leaf layer - main Stem Biomass							
Date	Waveband	a	b	Rg	Rv	s	k	K	r^2
						(ha/kg x 10^{-3})			
6/3/82	RED	47.8	4.13	0.063	0.021	0.059	1.36	1.42	0.99
	NIR	1.7	1.48	0.126	0.588	0.710	0.10	0.39	0.96
6/29/82	RED	31.3	1.32	0.052	0.032	0.018	0.26	0.28	0.94
	NIR	2.3	1.26	0.111	0.436	0.252	0.09	0.23	0.88

Table 3 Fractional light reflected (R), transmitted (T), absorbed (A) and intercepted (1-T) by complete cotton canopies (maximum n = N = biomass) in the RED and NIR on two sampling dates.

Spectral Measurement	3 June 82		29 June 82	
	RED	NIR	RED	NIR
R	0.021	0.527	0.033	0.422
T	0.044	0.313	0.168	0.187
A	0.935	0.160	0.800	0.390
1-T	0.956	0.687	0.832	0.813
	N = 3,086 kg/ha		N = 8,195 kg/ha	

Table 4 Absorption coefficients (K) computed by Park and Deering (1982) reflection model for alfalfa, short grass prairie, maturing cotton, and senescing cotton in the RED (630-690 nm) waveband.

Maturing Cotton	K = 1.42	E10-3	ha/kg
Alfalfa	K = 0.582	E10-3	ha/kg
Senescing Cotton	K = 0.28	E10-3	ha/kg
Short grass Prairie	K = 0.166	E10-3	ha/kg

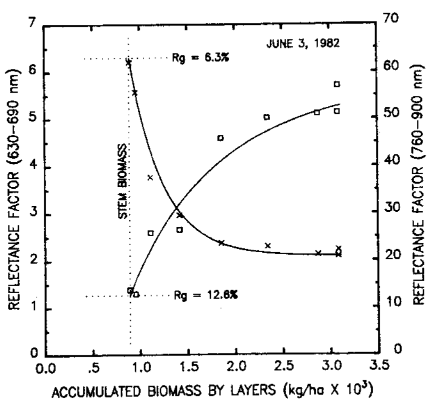

Figure 1. Agreement of cotton canopy reflectance factor measurements, in the RED (630-690 nm, x) and the NIR (760-900 nm, □), with Allen and Richardson's (1968) reflectance model (solid curved lines) for June 3, 1982.

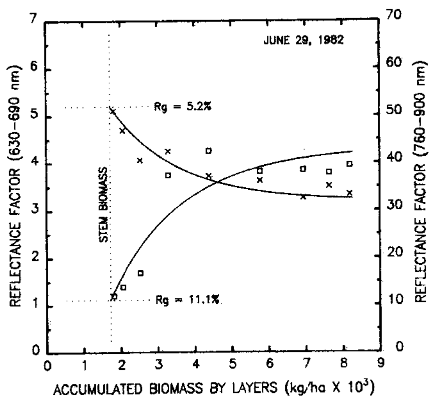

Figure 2. Same as Figure 1 except for June 29, 1982.

AUTHOR BIOGRAPHICAL DATA

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