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E83-10053

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7. { EW-U2-04334
JSC-18260 CR-16 9569

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A Joint Program for
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Early Warning and Crop Condition Assessment

6. JULY 1982

ADJUSTING THE TASSELED CAP BRIGHTNESS AND GREENNESS FACTORS FOR
ATMOSPHERIC PATH RADIANCE AND ABSORPTION ON A PIXEL BY PIXEL BASIS

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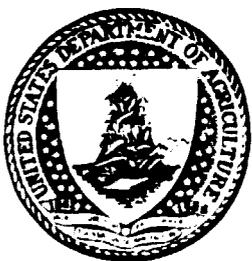
(E83-10053) ADJUSTING THE TASSELED CAP
BRIGHTNESS AND GREENNESS FACTORS FOR
ATMOSPHERIC PATH RADIANCE AND ABSORPTION ON
A PIXEL BY PIXEL BASIS (Agricultural
Research Service) 24 p HC A02/MF A01

N83-14562

4. U.S.D.A.

Unclas
G3/43 00053

U.S. DEPARTMENT OF AGRICULTURE
1050 BAY AREA BOULEVARD
HOUSTON, TEXAS 77058



1. Report No. EW-U2-04334, JSC-18260		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Adjusting the Tasseled Cap Brightness and Greenness Factors for Atmospheric Path Radiance and Absorption on a Pixel by Pixel Basis				5. Report Date July 1982	
				6. Performing Organization Code USDA-ARS	
7. Author(s) R. D. Jackson, P.N. Slater, P. J. Pinter				8. Performing Organization Report No.	
9. Performing Organization Name and Address USDA-ARS U.S. Water Conservation Laboratory Phoenix, Az 85040				10. Work Unit No.	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address USDA-ARS EW/CCA AgRISTARS 1050 Bay Area Blvd., Houston, TX 77058				13. Type of Report and Period Covered Technical Report	
				14. Sponsoring Agency Code SK	
15. Supplementary Notes					
16. Abstract A radiative transfer model was used to convert ground measured reflectances into the radiance at the top of the atmosphere, for several levels of atmospheric path radiance. The radiance in MSS7 (0.8 to 1.1 m) was multiplied by the transmission fraction for atmospheres having different levels of precipitable water. The radiance values were converted to simulated Landsat digital counts for four path radiance levels and four levels of precipitable water. These values were used to calculate the Kauth-Thomas brightness, greenness, yellowness, and nonsuch factors. Brightness was affected by surface conditions and path radiance. Greenness was affected by surface conditions, path radiance, and precipitable water. Yellowness was affected by path radiance and nonsuch by precipitable water, and both factors changed only slightly with surface conditions. Yellowness and nonsuch were used to adjust brightness and greenness to produce factors that were affected only by surface conditions such as soils and vegetation, and not by path radiance and precipitable water.					
17. Key Words (Suggested by Author(s)) Path radiance Radiative model Landsat Kauth-Thomas Atmospheric corrections			18. Distribution Statement		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 22	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161

1. Introduction

Scattering of radiation by gaseous molecules and aerosols in the atmosphere adds an unknown amount to the radiance received by satellite sensors. Water vapor in the atmosphere absorbs radiation at certain wavelengths, thereby decreasing the radiance received by a sensor in those wavelengths. Several schemes have been proposed to account for path radiance effects on satellite data (e.g., Potter and Mendlowitz 1975; Lambeck et al. 1978; Switzer et al. 1981). Most use Landsat data to estimate a parameter such as the optical depth, or to locate a reference site such as a water body, from which entire scene corrections are made. Absorption by water vapor is generally considered to be negligible at visible wavelengths. Pitts et al. (1974) demonstrated that radiance in the near-infrared band at 0.8 to 1.1 μm may be reduced more than 20% by absorption. Pinter and Jackson (1981) showed that absorption affected ground based measurements in the near-infrared. Models that account for absorption require information concerning water vapor distribution in the atmosphere. Atmospheric path radiance and absorption vary temporally from one acquisition date to another, and also spatially within a scene. The spatial variability can only be corrected on a pixel by pixel basis.

The tasseled cap transformation of Kauth and Thomas (1976) yields linear combinations of the four Landsat bands from which the brightness, greenness, yellowness, and nonsuch factors are calculated. Kauth and Thomas anticipated that brightness and greenness would contain almost all of the variation within a sample segment, and suggested that shifts in yellowness and nonsuch were diagnostic of a physical state of the atmosphere. The average yellowness for "good" pixels forms the basis of the XSTAR haze correction algorithm of Lambeck et al. (1978). Kauth et al. (1979) stated that nonsuch primarily contains noise

variation. Brightness and greenness factors have proved useful for evaluating soil and vegetation features in Landsat data (Kauth et al. 1979; Thompson and Wehmenen 1980). Jackson et al. (in press) used simulated Landsat data to show that brightness increased and greenness decreased with increasing path radiance. Yellowness was also affected by path radiance but was essentially independent of vegetation changes throughout an entire wheat growing season. Nonsuch was insensitive to vegetation changes and appeared to be independent of path radiance conditions.

In this report we explore the effect of absorption by water vapor on the tasseled cap factors and develop an empirical method of removing much of the atmospheric effects on brightness and greenness by using nonsuch and yellowness as a measure of absorption and path radiance. The simple correction is applied on a pixel by pixel basis. Although the results appear convincing, caution is suggested because the relationships may depend on how well the atmospheric model simulated actual conditions.

2. Experiment and calculations

Spectral reflectance measurements were made over experimental wheat plots using a hand-held radiometer having four bands similar to the Landsat MSS bands 4 through 7 (0.5 to 0.6 μm , 0.6 to 0.7 μm , 0.7 to 0.8 μm , and 0.8 to 1.1 μm). Data were obtained on 48 clear days distributed throughout the growing season. A sliding polynomial interpolation technique was used to infer data for missing days. This procedure yielded data for every day of the growing season, with the interpolated values being the expected value for cloud free conditions. Other experimental details were given by Jackson et al (in press).

The radiative transfer calculation technique developed by Herman and Browning (1975) was used to transform ground-measured reflectance data into

radiance values at orbital altitudes through four simulated atmospheres. The extinction coefficient (optical depth) is the primary quantity that determines the influence of the atmosphere on the total radiance received by an orbital sensor (Slater, 1980). Extinction coefficients for the four simulated atmospheres are given in table 1. The output from the radiative transfer model gave the radiance at the top of the atmosphere (for an irradiance of unity at each of the four wavelengths) at 5° from nadir for sun zenith of 45° . Polynomial equations as described by Slater and Jackson (1982) were used to interpolate for reflectances other than the five (0, 0.1, 0.25, 0.5, and 0.75) considered in the original model. Additional details concerning the path radiance calculations can be found in Slater and Jackson (1982).

Absorption effects were not included in the path radiance calculations but were estimated from Figure 4 of Pitts et al. (1974). Their figure shows the average transmission in MSS7 (0.8 to 1.1 μm) as a function of the total precipitable water in the atmosphere for a sun-target-satellite path. Absorption in bands 4, 5, and 6 were assumed negligible. We chose four transmission values, 100, 90, 82, and 77% to represent 0, 1, 5, and 10 cm of total precipitable water, respectively. The simulated radiance at the top of the atmosphere in MSS7 for the four path radiance cases was reduced by the transmission fractions for each of the four levels of precipitable water.

Simulated Landsat digital counts (not rounded to whole numbers) were calculated for the four path radiance and the four absorption conditions using calibration constants for Landsat-2 for the Jan-July 1975 period (Richardson et al. 1980). Brightness (BR), greenness (GN), yellowness (YE), and nonsuch (NS), were calculated from the simulated Landsat data according to the technique of Kauth and Thomas (1976), but with the coefficients for Landsat-2 as given by Kauth et al. (1979) and Thompson and Wehmanen (1980), i.e.,

$$BR = 0.33231X_4 + 0.60316X_5 + 0.67581X_6 + 0.26278X_7 \quad (1)$$

$$GN = -0.28317X_4 - 0.66006X_5 + 0.57735X_6 + 0.38833X_7 \quad (2)$$

$$YE = -0.89952X_4 + 0.42830X_5 + 0.07592X_6 - 0.04080X_7 \quad (3)$$

$$NS = -0.01594X_4 + 0.13068X_5 - 0.45187X_6 + 0.88232X_7 \quad (4)$$

where X represents the radiance in digital counts for the four Landsat bands.

The subscript identifies the bands.

3. The tasseled cap factors

The brightness, greenness, yellowness and nonsuch factors for four surface conditions calculated for four path radiance and four absorption conditions are given in Tables 2 through 5, respectively. The four surface conditions, drying soil, wet soil, maximum green vegetation and senescent vegetation were selected to give a wide range of brightness and greenness values.

Values of the brightness factor (Table 2) show that brightness changed considerably with changes in soil wetness, as it was expected to do. As path radiance increased brightness increased by about 7 and 19% for drying and wet soil, respectively. Brightness was reduced by about 3% when precipitable water was increased from 0 to 10 cm. Since the decrease was small, brightness was assumed to be independent of water vapor.

The data in Table 3 show that the greenness factor responded well to green vegetation, as it was expected to do. As the path radiance increased the greenness decreased, by as much as 17% for green vegetation. This factor also decreased as the precipitable water in the atmosphere increased, by about 7%. The reduction from a clear, dry, atmosphere to a turbid, humid, atmosphere was nearly 24%. These reductions due to atmospheric effects can cause serious errors in interpretation of greenness information.

The yellowness factor was shown to be relatively independent of surface conditions by Jackson et al. (in press). This point is substantiated by the data in Table 4. This factor was insensitive to precipitable water, increasing only 0.2 units for changes from 0 to 10 cm of water. Yellowness was, however, quite sensitive to path radiance changes. The values decreased by nearly a factor of 2 going from a clear to a turbid atmosphere. This factor may be used to adjust for path radiance changes.

Nonsuch values changed only slightly with surface condition and were independent of path radiance changes (Table 5). Nonsuch decreased with increasing precipitable water, making it a candidate for use in adjusting for changes in water vapor in the atmosphere.

4. Adjusting brightness and greenness

Examination of the values in Tables 2-5 suggested that the brightness and the greenness could be adjusted for path radiance and absorption effects by using the yellowness and nonsuch as additive factors, i.e.,

$$ABR = BR + C_1YE + C_2NS \quad (5)$$

and

$$AGN = GN + C_3YE + C_4NS \quad (6)$$

where ABR and AGN are the adjusted brightness and greenness respectively. The new factors are not orthogonal.

Since the four surface conditions included extreme values for the brightness and greenness, the problem was to determine the values of C_1 , C_2 , C_3 , and C_4 , so that the adjusted factors would be reasonably constant for all path radiance and absorption levels for each surface condition. An iterative procedure was used to arrive at appropriate values of the coefficients. For

example, C_1 was initially taken as 1 and the yellowness was added to the brightness for the four path radiance levels and the four surface conditions (since yellowness was negative, the effect was to reduce brightness). The results indicated that C_1 should be larger. The value of C_1 was increased by increments of 0.2 until essentially constant values of the adjusted brightness resulted for all path radiance levels within each surface condition. At this point $C_1 = 2.0$. In the previous section it was shown that brightness was reasonably independent of absorption, therefore C_2 was taken to be 0. Hence, the adjusted brightness can be expressed as one equation by adding the coefficients of equation (1) and 2 times the coefficients of equation (3) to get

$$ABR = -1.46673X_4 + 1.45976X_5 + 0.82765X_6 + 0.18118X_7 \quad (7)$$

Equation (7) was used to calculate the adjusted brightness for the several conditions given in Table 2. Results are given in Table 6. The maximum difference of the adjusted values was about 2%.

Brightness values for an entire wheat season are shown in Figure 1, and adjusted values are given in Figure 2. The numbers identifying the lines indicate the level of path radiance. The dotted line in both figures (labeled 0) represents the case for no path radiance nor absorption. The values were calculated directly from the reflectance data using equation 9.9 of Slater (1980), with the path radiance terms taken as zero. Radiance values were converted to digital counts. The "no atmosphere" case will serve as a reference. Figure 2 shows that the adjusted brightness values fall nearly on the reference line, indicating that equation (7) adequately compensates for atmospheric effects.

The greenness factor needed to be adjusted for both path radiance and absorption. It was found that if $C_3 = -1$, the low values of greenness were adequately adjusted. However, a value of -1.6 was required during the period of maximum greenness. It was apparent that one value of C_3 would not be sufficient for the entire growing season. Since the greenness curve for the season was approximately bell shaped, it appeared that C_3 could be taken as -1 at the start of the season and be increased as greenness increased. The value of C_4 was found to be $-1/2$. The resulting equation for the adjusted greenness (AGN) was

$$AGN = GN - (1 + 0.018GN)YE - NS/2 \quad (8)$$

The multiplicative factor in the second term on the right hand side prevents the AGN from reducing to a simple equation as did the brightness adjustment (equation 7).

The adjusted greenness was calculated using equation (8). Results for the four surface conditions are shown in Table 7. The adjusted values differ by a maximum of 1.2 units for any particular surface condition. Greenness values for an entire wheat season are shown in Figure 3. The path radiance effects are obvious. Adjusted greenness values (for a dry atmosphere) are presented in Figure 4. The dotted lines (labeled 0) represent the value of greenness that would occur in the absence of an atmosphere. The adjusted values fell quite close to the reference values. The data indicate that equation (8) adequately adjusted the greenness for path radiance and absorption effects.

5. Concluding remarks

Our results support the suggestion of Kauth and Thomas (1976) that shifts in yellowness and nonsuch are diagnostic of a physical state of the atmosphere. Both Kauth and Thomas (1976) and Jackson et al. (in press) noted that yellowness and nonsuch changed only slightly with surface condition changes. If they were, in fact, independent of surface conditions, a stable reference value may exist such that the difference between this reference and measured yellowness and nonsuch values could possibly be used to estimate haze levels and precipitable water. It may be that the present surface condition dependence is due to an imprecision in distinguishing soils from vegetation in the derivation of the tasseled cap factors.

We have considered only path radiance and precipitable water in adjusting the brightness and greenness factors. Clouds, cloud shadows, and sun angle corrections also present problems. Lambeck et al (1978) described a method to exclude garbled data and data from unwanted targets such as clouds from Landsat data over agricultural scenes. Procedures of this type should be used in conjunction with the adjusted brightness and greenness.

The results reported here were based on ground-measured reflectances over wheat that were transformed to radiance values at the top of the atmosphere using a radiative transfer model. The usefulness of these results in the analysis of satellite data will depend on how well the model simulates actual conditions. It is possible that equations (7) and (8) are dependent on model characteristics and may need to be redefined for actual situations. In

any case, the final evaluation of the concept will be achieved only after numerous tests using aircraft and satellite data.

Accounting for atmospheric path radiance and water vapor absorption effects on a pixel by pixel basis appears feasible. If this concept proves valid, it could be used with "smart" sensors to automatically compensate for atmospheric haze and water vapor prior to transmitting the data to ground stations.

6. Acknowledgement

P. N. S. wishes to thank the USDA (Broadform Contract Number 12-14-5001-38) for partial support.

7. References

- Herman, B. M. and Browning, S. R., 1975, The effect of aerosols on the earth-atmosphere albedo. *J. Atmos. Sci.* 32:1430-1445.
- Jackson, R. D., Slater, P. N., and Pinter, P. J. Jr., 1982, Discrimination of growth and water stress in wheat by various vegetation indices through a clear and a turbid atmosphere. *Remote Sens. of Environ.* (submitted).
- Kauth, R. J., and Thomas, G. S., 1976, The tasseled cap - A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. *Proc. Symp. on Machine Processing of Remotely Sensed Data, LARS, Purdue Univ., West Lafayette, IN*, pp. 41-51.
- Kauth, R. J., Lanbeck, P. F., Richardson, W., Thomas, G. S., and Pentland, A. P., 1979, Feature extraction applied to agricultural crops as seen by Landsat. *Proc. LACIE Symp. II:705-721, JSC-16015, NASA, Johnson Space Center, Houston, TX.*
- Lanbeck, P. F., Kauth, R. J., and Thomas, G. S., 1978, Data screening and preprocessing for Landsat MSS data. *Proc. 12th Intern. Symp. on Remote Sensing of Environ., ERIM, Ann Arbor, MI*, pp. 999-1008.
- Pitts, D. E., McAllum, W. E., and Dillinger, A. E., 1974, The effect of atmospheric water vapor on automatic classification of ERTS data. *Proc. 9th Intern. Symp. on Remote Sensing of Environ., ERIM, Ann Arbor, MI*, pp. 483-497.
- Pinter, P. J., Jr., and Jackson, R. D., 1981, Dew and vapor pressure as complicating factors in the interpretation of spectral radiance from crops. *Proc. 15th Intern. Symp. on Remote Sensing of Environ., ERIM, Ann Arbor, MI*, pp. 574-554.

- Potter, J. F., and Mendlowitz, M. A., 1975, On the determination of haze levels from Landsat data. Proc. 10th Intern. Symp. on Remote Sensing of Environ., ERIM, Ann Arbor, MI, pp. 695-703.
- Richardson, A. J., Escobar, D. E., Gausman, H. W., and Everitt, J. H., 1980, Comparison of Landsat-2 and field spectrometer reflectance signatures of south Texas rangeland plant communities. Proc. 6th Symp. Machine Processing of Remotely Sensed Data, LARS, Purdue Univ., West Lafayette, IN., pp. 88-97.
- Slater, P. N., 1980, Remote Sensing: Optics and Optical Systems. Addison-Wesley, Reading, MA, p. 575.
- Slater, P. N., and Jackson, R. D., 1982, Atmospheric effects on radiation reflected from soil and vegetation as measured by orbiting sensors using various scanning directions. Applied Optics (submitted).
- Switzer, P., Kowalik, W. S., and Lyon, R. J. P., 1981, Estimation of atmospheric path-radiance by the covariance matrix method. Photogramm. Eng. and Remote Sens. 47:1469-1476.
- Thompson, D. R., and Wehmanen, O. A., 1980, Using Landsat digital data to detect moisture stress in corn-soybean growing regions. Photogramm. Eng. and Remote Sens. 46:1087-1093.

Table 1. Extinction coefficients (optical depths) at four wavelengths near the centers of the four Landsat bands for four atmospheres ranging from clear (level 1) to turbid (level 4).

Type of scatter	Path radiance level	Wavelength			
		0.55	0.65	0.75	0.90
Rayleigh	(all)	0.098	0.048	0.027	0.013
Mie	1	0.027	0.026	0.023	0.020
	2	0.147	0.126	0.109	0.095
	3	0.267	0.226	0.196	0.163
	4	0.462	0.397	0.344	0.300
Total	1	0.125	0.074	0.050	0.033
	2	0.245	0.174	0.136	0.108
	3	0.365	0.274	0.223	0.176
	4	0.560	0.445	0.371	0.313

Table 2. Values of the brightness factor at four levels of atmospheric water vapor, four levels of atmospheric path radiance, and four surface conditions. The drying soil had about 10% and the wet soil about 15% green vegetation cover.

Surface condition	Path radiance level	Precipitable water ^a in the atmosphere (cm)			
		0	1	5	10
Drying soil	1	89.9	89.3	88.8	88.4
	2	90.8	90.2	89.7	89.4
	3	92.6	92.0	91.5	91.2
	4	96.1	95.4	95.0	95.0
Wet soil	1	51.3	50.9	50.6	50.4
	2	53.2	52.8	52.4	52.2
	3	55.8	55.4	55.0	54.8
	4	60.8	60.4	60.0	59.8
Maximum green vegetation	1	66.4	65.4	64.7	64.2
	2	68.3	67.3	66.5	66.0
	3	70.8	69.9	69.1	68.6
	4	75.7	74.7	73.7	73.5
Senescent vegetation	1	89.0	88.3	87.8	87.5
	2	90.0	89.3	88.8	88.5
	3	91.8	91.1	90.6	90.3
	4	95.4	94.7	94.2	93.8

Table 3. Values of the greenness factor at four levels of atmospheric water vapor, four levels of atmospheric path radiance, and four surface conditions. The drying soil had about 10% and the wet soil about 15% green vegetation cover.

Surface condition	Path radiance level	Precipitable water in the atmosphere (cm)			
		0	1	5	10
Drying soil	1	2.8	1.9	1.1	0.7
	2	1.6	0.7	-0.1	-0.5
	3	0.6	-0.3	-1.0	-1.5
	4	-1.2	-2.1	-2.8	-3.3
Wet soil	1	5.8	5.3	4.8	4.5
	2	4.4	3.8	3.3	3.1
	3	3.2	2.6	2.1	1.8
	4	1.1	0.4	-0.1	-0.4
Maximum green vegetation	1	46.6	45.2	44.0	43.3
	2	44.4	43.0	41.8	41.1
	3	42.4	41.0	39.8	39.1
	4	38.8	37.3	36.2	35.5
Senescent vegetation	1	6.2	5.2	4.4	3.9
	2	5.0	4.0	3.2	2.7
	3	3.9	2.9	2.1	1.6
	4	2.0	1.0	0.2	-0.3

Table 4. Values of the yellowness factor at four levels of atmospheric water vapor, four levels of atmospheric path radiance, and four surface conditions. The drying soil had about 10% and the wet soil about 15% green vegetation cover.

Surface condition	Path radiance level	Precipitable water in the atmosphere (cm)			
		0	1	5	10
Drying soil	1	-4.9	-4.8	-4.8	-4.7
	2	-5.9	-5.8	-5.7	-5.7
	3	-6.9	-6.8	-6.8	-6.7
	4	-8.8	-8.7	-8.6	-8.5
Wet soil	1	-4.6	-4.5	-4.5	-4.5
	2	-5.7	-5.6	-5.6	-5.5
	3	-6.8	-6.8	-6.7	-6.7
	4	-8.8	-8.7	-8.6	-8.6
Maximum green vegetation	1	-3.2	-3.1	-3.0	-2.9
	2	-4.4	-4.3	-4.2	-4.1
	3	-5.7	-5.5	-5.4	-5.3
	4	-7.7	-7.6	-7.5	-7.4
Senescent vegetation	1	-2.2	-2.1	-2.0	-2.0
	2	-3.3	-3.2	-3.1	-3.0
	3	-4.4	-4.3	-4.2	-4.2
	4	-6.4	-6.3	-6.2	-6.1

Table 5. Values of the nonsuch factor at four levels of atmospheric water vapor, four levels of atmospheric path radiance, and four surface conditions. The drying soil had about 10% and the wet soil about 15% green vegetation cover.

Surface condition	Path radiance level	Precipitable water in the atmosphere (cm)			
		0	1	5	10
Drying soil	1	-1.7	-3.7	-5.4	-6.4
	2	-1.4	-3.4	-5.1	-6.1
	3	-1.4	-3.5	-5.1	-6.2
	4	-1.5	-3.6	-5.3	-6.3
Wet soil	1	-1.1	-2.5	-3.5	-4.2
	2	-0.9	-2.2	-3.1	-4.0
	3	-1.0	-2.3	-3.4	-4.1
	4	-1.1	-2.6	-3.6	-4.3
Maximum green vegetation	1	1.3	-2.0	-4.6	-6.2
	2	1.7	-1.6	-4.2	-5.8
	3	1.8	-1.5	-4.1	-5.7
	4	1.8	-1.4	-4.0	-5.6
Senescent vegetation	1	-0.1	-2.4	-4.2	-5.4
	2	0.2	-2.1	-3.9	-5.1
	3	0.1	-2.2	-4.0	-5.2
	4	0.0	-2.3	-4.1	-5.3

Table 6. Values of the adjusted brightness factor at four levels of atmospheric water vapor, four levels of atmospheric path radiance, and four surface conditions. The drying soil had about 10% and the wet soil about 15% green vegetation cover.

Surface condition	Path radiance level	Precipitable water in the atmosphere (cm)			
		0	1	5	10
Drying soil	1	80.0	79.6	79.2	79.0
	2	79.0	78.6	78.2	78.0
	3	78.7	78.3	77.9	77.7
	4	78.6	78.2	77.8	77.6
Wet soil	1	42.2	41.9	41.7	41.6
	2	41.8	41.6	41.3	41.2
	3	42.1	41.8	41.6	41.5
	4	43.2	42.9	42.7	42.6
Maximum green vegetation	1	59.9	59.2	58.7	58.4
	2	59.4	58.7	58.2	57.8
	3	59.5	58.8	58.3	57.9
	4	60.3	59.6	59.1	58.7
Senescent vegetation	1	84.6	84.2	83.8	83.5
	2	83.5	83.0	82.6	82.4
	3	83.0	82.6	82.2	82.0
	4	82.7	82.2	81.9	81.6

Table 7. Values of the adjusted greenness factor at four levels of atmospheric water vapor, four levels of atmospheric path radiance, and four surface conditions. The drying soil had about 10% and the wet soil about 15% green vegetation cover.

Surface condition	Path radiance level	Precipitable water in the atmosphere (cm)			
		0	1	5	10
Drying soil	1	8.8	8.7	8.7	8.6
	2	8.3	8.3	8.2	8.2
	3	8.3	8.2	8.2	8.1
	4	8.2	8.0	8.0	7.9
Wet soil	1	11.5	11.4	11.4	11.4
	2	11.0	10.9	10.9	10.9
	3	10.9	10.8	10.8	10.8
	4	10.5	10.4	10.4	10.3
Maximum green vegetation	1	51.9	51.8	51.7	51.6
	2	51.5	51.4	51.2	51.1
	3	51.5	51.3	51.1	51.0
	4	51.0	50.7	50.5	50.4
Senescent vegetation	1	8.7	8.7	8.7	8.7
	2	8.5	8.4	8.4	8.4
	3	8.6	8.5	8.5	8.5
	4	8.6	8.5	8.4	8.4

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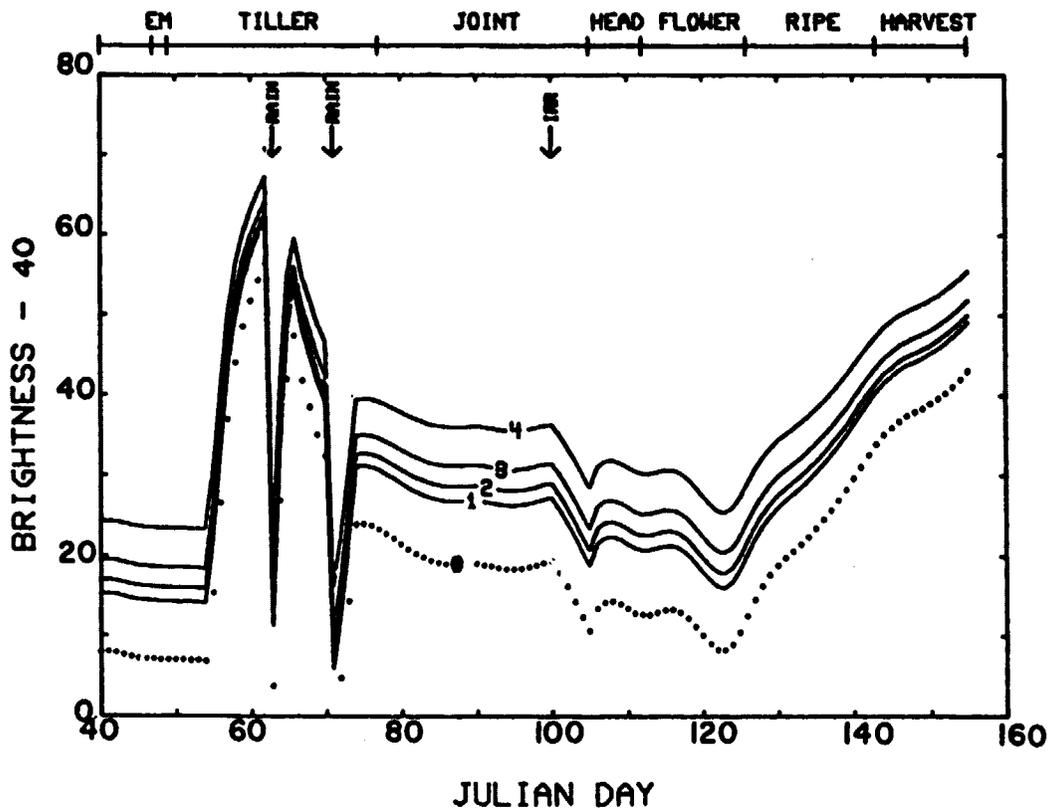


Figure 1. Brightness values over a wheat growing season for five levels of path radiance. Numbers on the lines refer to the path radiance levels given in Table 1 and the "no atmosphere" reference (dotted line, labeled 0).

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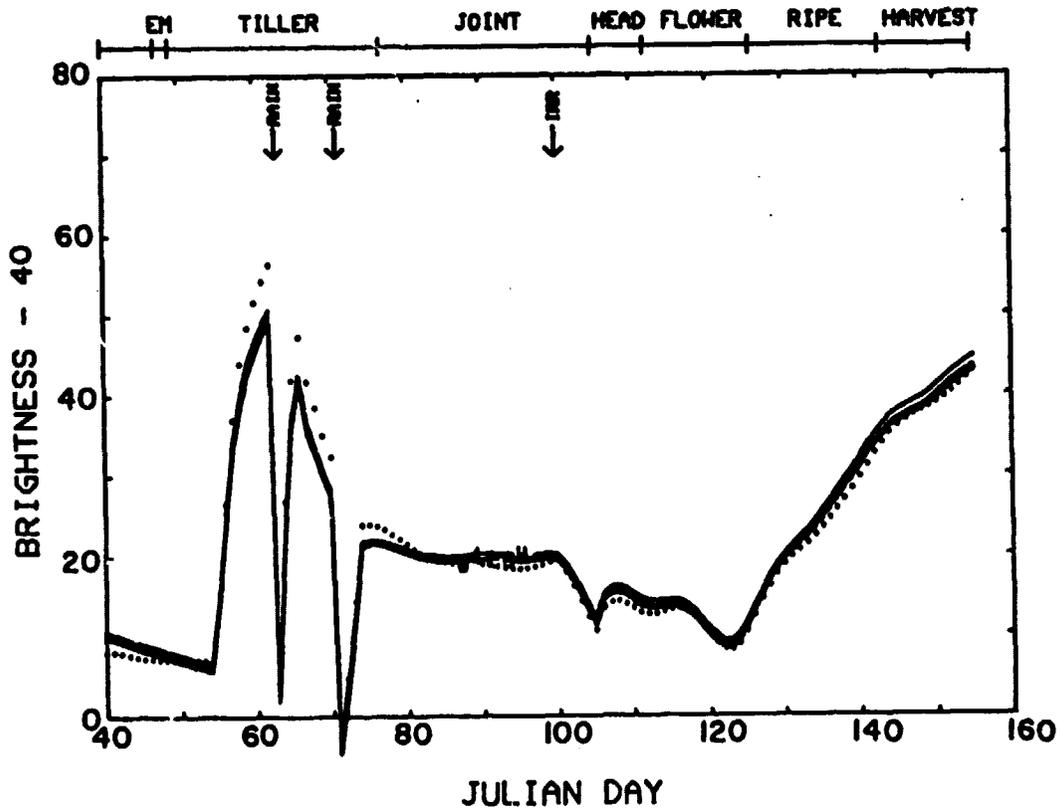


Figure 2. Adjusted brightness values for four levels of path radiance calculated using equation (7) for a dry atmosphere. The "no atmosphere" reference is shown by the dotted line.

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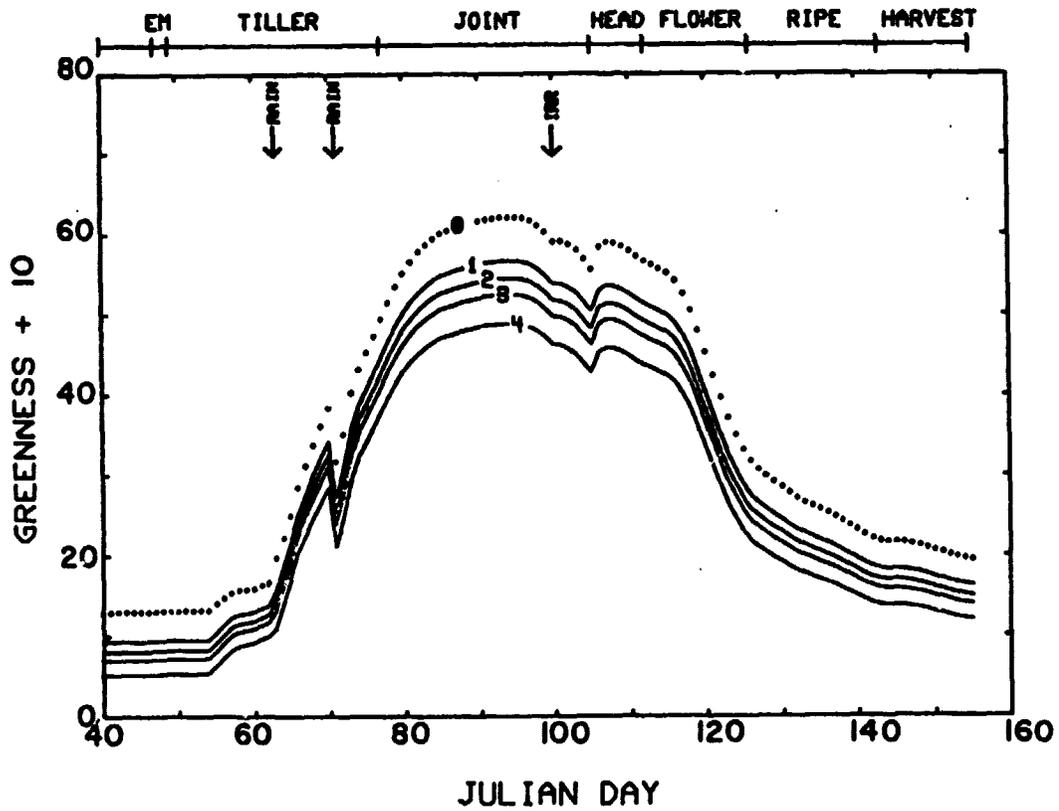


Figure 3. Greenness values over a wheat growing season for five levels of path radiance. Numbers on the lines refer to the path radiance levels given in Table 1, and the "no atmosphere" reference (dotted line, labeled 0).

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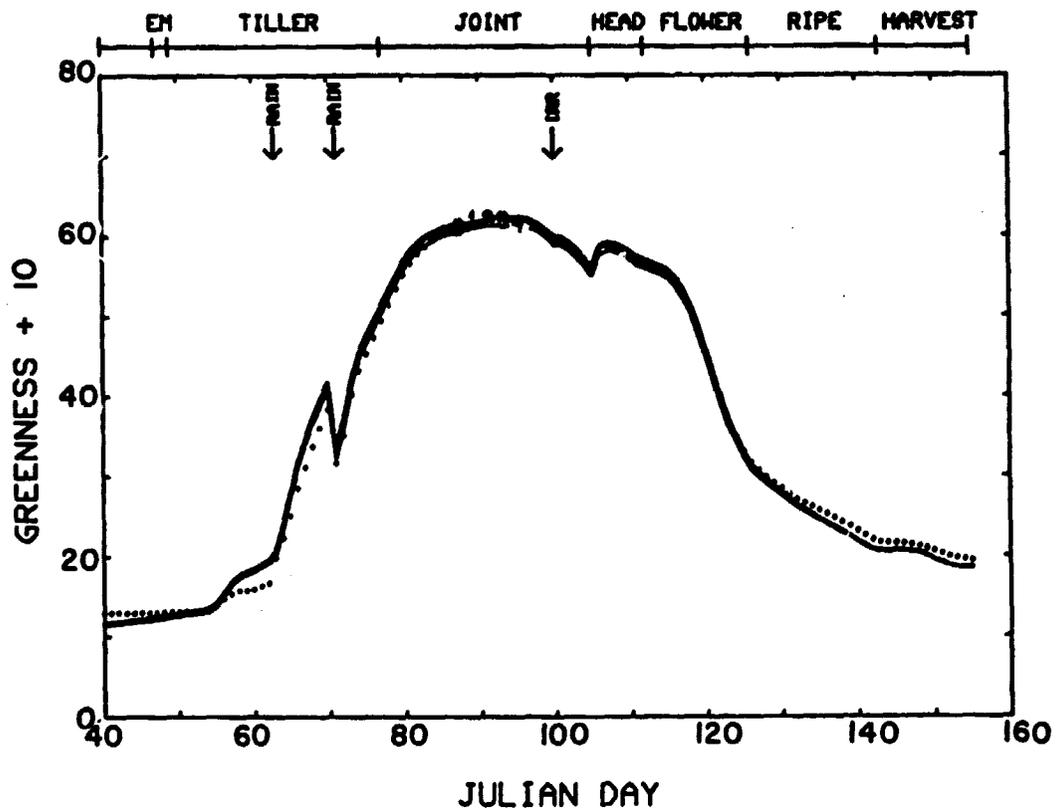


Figure 4. Adjusted greenness values for five levels of path radiance calculated using equation (8) for a dry atmosphere. The "no atmosphere" reference is shown by the dotted line.