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DISCRIMINATION OF GROWTH AND WATER STRESS IN WHEAT BY VARIOUS VEGETATION INDICES THROUGH A CLEAR AND A TURBID ATMOSPHERE

R. D. JACKSON, P. M. SLATER, P. J. PINTER

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16. Abstract

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R. D. Jackson,
U. S. Water Conservation Laboratory, Agricultural Research Service,
U. S. Department of Agriculture, Phoenix, AZ 85040

P. N. Slater,
Committee on Remote Sensing and Optical Sciences Center,
University of Arizona, Tucson, AZ 85721

P. J. Pinter, Jr.,
U. S. Water Conservation Laboratory, Agricultural Research Service,
U. S. Department of Agriculture, Phoenix, AZ 85040

ABSTRACT

Reflectance data were obtained over a drought-stressed and a well-watered wheat plot with a hand-held radiometer having bands similar to the MSS bands of the Landsat satellites. Data for 48 clear days were interpolated to yield reflectance values for each day of the growing season, from planting until harvest. With an atmospheric path radiance model and Landsat-2 calibration data, the reflectances were used to simulate Landsat digital counts (not quantized) for the four Landsat bands for each day of the growing season, through a clear (≈100 km meteorological range) and a turbid (≈10 km meteorological range) atmosphere. Several ratios and linear combinations of bands were calculated using the simulated data, then assessed for their relative ability to discriminate vegetative growth and plant stress through the two atmospheres. The results showed that water stress was not detected by any of the indices until after growth was retarded, and the sensitivity of the various indices to vegetation depended on plant growth stage and atmospheric path radiance.

INTRODUCTION

The discrimination of vegetation and the detection of stressed vegetation is a primary purpose for analyzing satellite imagery obtained over agricultural lands. Various ratios and linear combinations of bands have been proposed to aid in the analysis. However, these "vegetation indices" have not been adequately examined because of relatively few acquisition dates during a growing season, the paucity of ground data at the time of acquisition, and the lack of a suitable method to account for atmospheric effects on the radiance received by the satellite. In recent years a considerable amount of ground-based data has accumulated that describe spectral reflectance characteristics of soils and vegetation, without the problem of atmospheric complications. These data, taken repeatedly over numerous small plots that received different agronomic treatments, have been used to obtain relationships between agronomic variables and remotely sensed ratios and linear combinations of bands. The ground-based data, when extended to orbital altitudes using appropriate atmospheric models, can serve as a guide in the interpretation of satellite data. A first step is to examine the various indices as to their ability to discriminate vegetation and to detect stress, in the presence of a scattering atmosphere.

The ratio of the near-IR to visible red radiation has been reported to be a sensitive indicator of green biomass (Tucker, 1979). Much of the data presented in support of this conclusion was obtained using ground-based radiometers. Switzer et al (1981) pointed out that atmospheric path radiance effects contribute to falsely large ratio values (for well illuminated slopes) in Landsat data. Dave (1980) simulated satellite data and showed that atmospheric path radiance had a marked effect on the relation between the ratio of the Thematic Mapper bands 4 and 2 and the leaf water content of blue grama grass.

Slater (1980) described several image ratioing procedures used for the radiometric correction of remotely sensed data. Deering et al (1975) found that the ratio of the difference between the near-IR and red bands and their sum (now called the normalized difference) was a more sensitive indicator of vegetation on sparsely vegetated rangelands than was the simple near-IR/red ratio. Richardson and Wiegand (1977) discussed simple band differences (e.g., near-IR minus the red) and other ratios. They proposed that a plot of MSS5 versus MSS7 for bare soils at various water contents would yield a straight line and that the presence of vegetation would cause a deviation from that line, with the perpendicular distance from the line to the vegetation point being an index of vegetation (called the PVI). Their data base came from satellite sources.

Kauth and Thomas (1976) developed a "tasseled cap" transformation that used linear combinations of the four Landsat MSS bands. Their results included indices for soil brightness, greenness, yellowness, and a fourth, called "nonsuch." The development was also based on the assumption that a unique soil line exists. The analyses were based largely on satellite data with some laboratory measured soil reflectances used as a guide. Atmospheric conditions were not specified. Slater and Jackson (1982) showed that path radiance affected the soil line, especially when soil reflectance was low. Dave's (1981) results indicated that atmospheric effects have considerable influence on the tasseled cap transformation, and on the greenness-brightness relationship for wheat at several stages of growth. The tasselled cap model has gained acceptance and is frequently used for the interpretation of satellite data (Thompson and Wehmanen, 1980).

The purpose of this report is to examine several ratios and linear combinations of MSS bands as to their ability to discriminate vegetation from the soil background and to detect stress, for two different atmospheric conditions. Reflectance data for a stressed and a non-stressed wheat crop over the entire growing season are presented. These data were converted to simulated Landsat digital counts for two atmospheric conditions and then used to calculate the several indices.

MEASUREMENTS AND CALCULATIONS

Agronomic aspects

Wheat (*Triticum durum* Desf. var Produra) was planted in 11 x 13 m plots on 6 February 1980 (Julian day 37) and flood irrigated two days later. Subsequently, one plot was irrigated on days 79, 105, 123, and 134 (called non-stressed), and a second plot was irrigated on day 100 (called stressed). About 10 cm of water was added at each irrigation. Rainfall on days 63 and 71 was 0.9 and 1.5 cm, respectively. The plots were harvested on day 156. Grain yields were 1869 kg/ha for the stressed and 4301 kg/ha for the non-stressed. The terms "stressed" and "non-stressed" are used in a qualitative sense to designate that plant growth was different between the two plots because of different water treatments. In fact, the non-stressed plot underwent some stress shortly after heading.

Six randomly selected plants were removed from each plot twice weekly for the assessment of green and brown leaf area. The green leaf area index (GLAI) was calculated by multiplying the average green leaf area per plant by the plant density. The data are shown for the two plots in Figure 1. Circles and x's represent measured values for the stressed and the non-stressed plots, respectively. The lines represent smoothed data obtained using a sliding polynomial interpolation technique. Leaf area measurements are straightforward but tedious and time-consuming. The scatter evident in the data was largely due to the limited number of plants sampled. Time and labor constraint prohibited more extensive sampling.

Even with the scatter it is apparent that the GLAI for the stressed plot was considerably lower than that for the non-stressed plot by day 90, and remained lower for the remainder of the season. For subsequent discussions we will consider that growth was retarded in the stressed plot, as determined by plant measurements, by Julian day 85.

Another measure of green vegetation is the green cover presented in Figure 2. The fraction of green vegetation was obtained at one to two week intervals from two nadir view color slides of the canopy in each plot. The slides were projected on a white gridded posterboard on which 200 dots were randomly positioned (Jackson et al, 1980). The number of dots that "hit" green vegetation was counted and divided by the total number to obtain the fraction of green cover.

As with the GLAI, there is some scatter in the data (no attempt was made to smooth the values shown in Figure 2). The data clearly show that by day 85 the non-stressed plot had more green vegetation than the stressed plot, and the difference increased as the season progressed. Note that 15% cover was achieved by about day 60, nearly 50% by day 70, and about 80% by day 80. These values will be of interest when compared to spectral data in a later section.

Spectral Measurements

Reflected solar radiation was measured using a 15° full field-of-view hand-held radiometer with bandpass intervals corresponding to 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, respectively). The radiometer was held in such a manner as to obtain a nadir view from about 2 m above the soil. A series of 12 measurements was made over designated areas within each plot beginning at 1340 on each clear day. Irradiance values were obtained from radiance measurements of $BaSO_4$, before and after the plot measurements. Directional reflectances were obtained by ratioing the average of the 12 measurements to the irradiance.

Spectral measurements were started on day 42 and continued throughout the growing season, yielding data for 48 cloud free days. Data for the four bands were plotted as a function of time. Data for missing days were obtained using a sliding polynomial interpolation technique. This procedure yielded a reflectance value for every day between Julian day 40 and day 155, with the interpolated values being the expected value had that day been cloud free.

Data for the stressed plot are given in Figure 3, and for the non-stressed plot in Figure 4. The measured values of reflectance are indicated by symbols and the lines represent the smoothed values. Growth stages (emergence, tillering, jointing, heading, flowering, ripening, and harvest) are shown at the top of the figures. From the time of the post planting irrigation until after emergence (about day 54) the soil surface remained wet. Rain and irrigations are identified by arrows on the day that the event occurred. Reflectances for the two plots are essentially the same until day 80, the day following the irrigation of the non-stressed plot. After this irrigation, near-IR reflectances decreased as a consequence of a wet soil background and remained lower than that of the stressed plot from day 80 to day 95. If only the infrared bands were considered during this period, (without knowledge of the irrigation) it could be concluded that the stressed plot had more green vegetation because of the greater IR return. These data demonstrate the desirability of using band combinations to minimize the effect of soil background. Canopy cover for both plots ranged from 80 to 95% during this time period.

Both plots were irrigated during the late jointing and early heading stages (day 100 for the stressed and day 105 for the non-stressed). This was the period of maximum green vegetation. Reflectance changes before and after irrigation in the visible (bands 4 and 5) were quite different than changes in the near-IR (bands 6 and 7) for this period. A few days prior to irrigation reflectance in the visible bands began to increase, then began to decrease on the first day after irrigation. For the stressed plot (Figure 3), the near-IR began to decrease a few days prior to irrigation and continued to decrease for about five days after irrigation, and then rapidly increased. For the non-stressed plot (Figure 4) the same behavior was evident but on a smaller scale. Plant temperatures measured with a thermal IR radiometer on these plots also showed a 5 to 7 day recovery period following irrigation (Jackson, 1981).

Radiance at the top of the atmosphere

The radiative transfer calculation technique developed by Herman and Browning (1975) was used to obtain radiance values at orbital altitudes through a simulated atmosphere. Details of the calculation and a discussion of scattering was given by Slater and Jackson (1982). Briefly, the output from the radiative transfer calculations gave the radiance emerging from the top of the atmosphere (for an irradiance of unity) at 5° from nadir as a function of five ground reflectances (0, 0.1, 0.25, 0.5, and 0.75) for four wavelengths at the centers of the MSS bands 4, 5, 6, and 7, for sun zenith angle of 45°. Calculations were made for a clear (Ω100 km meterological range) and a turbid (Ω10 km meterological range) atmosphere.

Since the calculation technique yielded radiance values for only five ground reflectance values, it was necessary to interpolate for other reflectances. Polynomial equations of the form

$$L_i = a + b\rho_i + c\rho_i^2 \quad (1)$$

were statistically fit to the five radiance (L) and reflectance (ρ) values for each bandwidth and each atmosphere. The index i refers to the four Landsat MSS bands. Correlation coefficients for the eight regressions were >0.99. Coefficients for the 8 equations are given in Table 1.

We have approximated the atmospheric path radiance for the season by using a fixed irradiance geometry. Errors in scale caused by not accounting for solar zenith angle changes during the season were generally less than 15%. The approximation should not affect the conclusions.

Landsat digital counts

Richardson et al (1980) presented tables of calibration constants for the three Landsat satellites, and of the solar constant, for each of the four MSS bands. Landsat digital counts (DC) were calculated using the relation

$$DC_i = (L_i E_i - B_i)/A_i \quad (2)$$

where L is the radiance calculated from equation (1), E is the solar constant (Table 2), A and B are calibration constants (Table 2). Using equation (1) with coefficients from Table 1, the smoothed reflectances shown in Figures 3 and 4 were converted to radiances at the top of the atmosphere. These radiances and values of E, A, and B from Table 2 were used in equation (2) to calculate Landsat digital values for the four bands for 115 growing season days, and for two atmospheres. The various vegetation indices discussed in the following section were calculated using the digital count data. Since the purpose of the following section is to assess the ability of various band combinations to discriminate vegetation from the soil background, to discriminate stressed vegetation, and to evaluate the influence of the atmosphere on this discriminatory ability, the digital counts were not quantized. If quantized the lines would be step functions, not the smooth lines that more clearly show the discriminatory ability of the band combinations.

VEGETATION INDICES

The ratio MSS7/MSS5

The ratio MSS7/MSS5 was formed using the digital counts calculated as described in the previous section. Data for the stressed plot are given in Figure 5 and in Figure 6 for the non-stressed plot. Both clear and turbid atmospheres are shown, with the clear represented by the smooth line and the turbid by the dotted (but connected) line.

The ratio is influenced only slightly by changes in soil reflectance caused by soil water content changes. This follows from the fact that a change in soil reflectance due to a soil water content change is essentially the same for reflectance in the near-IR and the visible portions of the spectrum. Since the opposite is the case for vegetation (increasing green vegetation decreases red reflectance and increases near-IR reflectance), the ratio is, theoretically, a good discriminator of vegetation. Indeed, during the jointing and heading stages the ratio is a sensitive indicator of vegetation. Note that the irrigation given during the later part of the jointing stage is clearly portrayed in both plots. However, from emergence through tillering, the ratio changed very little. By day 70, with 50% green cover, the ratio is only slightly greater than for bare soil. We conclude that the ratio is not a good discriminator for green vegetation covers less than 50%, but is quite sensitive when the green cover is high.

A comparison of Figures 5 and 6 (for clear atmospheres) shows that the ratio for the two plots was essentially the same until the non-stressed plot was irrigated on day 79. The change in soil reflectance due to wetting affected the ratio slightly (a small increase in the ratio for the non-stressed plot). Even when this small change is accounted for the data show a higher ratio for the non-stressed plot before day 85, and a large difference by day 95. The ratio for the stressed plot reached a maximum by day 95 and decreased rapidly until day 100, when the plot was irrigated. The non-stressed plot reached a maximum about day 97 and subsequently decreased as it entered a short stress period. An increase in green vegetation was indicated after irrigation (day 105).

When the atmosphere is turbid the ratio is considerably less sensitive to vegetation. There is only a small difference between the stressed and non-stressed plots, with the difference being detectable about day 90. This sensitivity to atmospheric scattering results for two reasons; the denominator of the ratio is small for green vegetation (ground-measured reflectances may be as low as 2%), and the atmospheric path radiance is larger for the visible than for the near-IR. These factors make the denominator very sensitive to atmospheric conditions. The effect on the ratio is so great that it is questionable whether interpretable results can be obtained from satellite data unless the atmospheric effect is accurately accounted for on a pixel by pixel basis.

<u>The normalized difference</u>

The normalized difference (MSS7 - MSS5)/(MSS7 + MSS5) was calculated from the simulated digital counts. Data for the stressed plot are given in Figure 7 and for the non-stressed plot in Figure 8. The clear and turbid atmospheres are differentiated by the smooth line and the connected dots, respectively.

Early season rains affected the normalized difference (ND) more than they did the simple ratio MSS7/MSS5. This indicated that the ND is somewhat sensitive to the soil background. However, the ND was quite sensitive to vegetation early in the season. Before 15% green cover was achieved (day 60), the ND increased above the values for bare soil. From about 25% cover (day 64) to about 80% (day 80), the ND increased linearly with time. Above 80% cover the sensitivity to vegetation changes decreased. The ND exhibited only small changes during the 40 day period beginning with day 80. The irrigation late in the jointing stage was evident in both plots but was less dramatic than for the simple ratio.

Differences between the two plots caused by plant stress were proportionately smaller for the ND than for the simple ratio. We conclude that the ND is a poor discriminator of stress when the stress occurs at high values of green cover. This does not rule out the possibility of good stress detection for sparsely vegetated plots.

Increased atmospheric path radiance decreased the ND. The effect was sufficiently great that we conclude, as we did for the simple ratio, that it is questionable whether interpretable results can be obtained from satellite data without accurate atmospheric corrections.

The difference MSS7 - MSS5

The difference between the near-IR and the red bands as calculated using the simulated Landsat data is given in Figures 9 and 10, for the stressed and non-stressed plots, respectively. The clear and the turbid atmospheres are indicated as in previous figures. To minimize negative numbers, MSS7 was multiplied by 2 before the differences were formed.

Early season rains are evident in the difference data. Irrigation of the non-stressed plot on day 79 caused the difference to decrease. This indicates sensitivity to soil background. The index detected vegetation at 15 to 25% cover, and increased rapidly with increasing vegetation up to about 80% green plant cover. Above this level the sensitivity of the index to green plants decreased because of the high values of IR and the low values of the red radiation. The irrigations during the late jointing stage were not evident until several days later, the delay being the same as was noted for the near-IR reflectance in Figures 3 and 4. This is further evidence of the dominance of the near-IR.

The stress effects noted earlier for days 85 to 95 are confused by the wet soil background in the non-stressed plot. With no information other than the difference between the two bands, it could be concluded that the stressed and the non-stressed plots were reversed. We rate this index as a poor indicator of stress.

Data for the turbid atmosphere was from 10 to 15% less than for the clear atmosphere, at the high values of green cover. Whether this amount of uncertainty can be tolerated would depend upo the particular application for the data.

The difference difference

The difference difference (2*MSS7 - MSS6) - (MSS5 - MSS4) as shown in Figures 11 and 12, has not, to the authors knowledge, been reported in the literature. It was developed in an attempt to arrive at a vegetation index that was relatively unaffected by atmospheric scattering. The rationale was that the path radiance would be similar for the infrared bards and also for the visible bands. Taking the differences would, therefore, cancel much of the path radiance. Figures 3 and 4 show that the IR differences were greatest for the period of high green cover, whereas the differences in the visible bands were at a minimum during that period. For soil and senesced vegetation the opposite was true. For brevity we denote this index as DD.

An immediate failing of DD is its sensitivity to soil background. The early season rains caused considerable fluctuation in the index. However, if vegetation were grown on a dark soil that exhibited little change in reflectance with water content changes, these fluctuations may not be discernable. If the soil reflectance did not change, DD may be a sensitive indicator of vegetation quite early in the season.

The large change noted in the simple difference when the non-stressed plot was irrigated on day 79 was only slightly observable with DD. Thus, the stressed, non-stressed reversal observed in the simple difference was not evident. However, we rate this index as a marginal detector of stress. It was nearly day 90 before a marked difference between the two plots was observed.

The difference difference is, however, reasonably independent of atmospheric scattering. Over the entire season the difference between data for the clear and the turbid atmosphere was less than 5%.

The perpendicular vegetation index

The PVI of Richardson and Wiegand (1977) requires an equation for the "soil line" in order to calculate the index. The soil line for Avondale loam (the soil on which the wheat was grown) was given by Slater and Jackson (1982) in terms of Landsat digital counts, and was used here to calculate the PVI. The results for the stressed plot are given in Figure 13 and for the non-stressed plot in Figure 14. The two atmospheres are differentiated as before.

Theoretically the PVI is not influenced by soil reflectance changes. The data in Figures 13 and 14, however, show the influence of early season rains and, for Figure 14, the irrigation on day 79. The rain on day 63 (25% cover) had relatively little effect on the PVI, but the rain on day 71 (50% cover) had a considerable effect. The irrigation on day 79 (75% cover) affected the PVI less than the day 71 rain. A partial explanation for this behavior is that plants transmit a considerable portion of the near-IR radiation and absorb much of the red. Therefore, the near-IR "sees" more soil than the red and is influenced more by soil reflectance changes under partial cover. As the plants grow taller and more dense this effect is reduced, as shown by comparing days 71 and 79 in Figure 14.

In comparison to the previously discussed indices, we consider the PVI to be moderately sensitive to vegetation. Some response was observed early in the tillering stage but the overall change was moderate. The irrigation during the late tillering stage for both plots was not observed until several days later. This indicates that the near-IR is the predominant band for this index, at least when green cover is high.

The soil background effect at day 79 puts the PVI in the same category as the simple MSS7 - SS5 difference. The non-stressed plot had lower values than the stressed plot during the day 85 to 95 period. We conclude that the PVI is not a good detector of stress. The effect of atmospheric path radiance on the PVI is on the order of a 10 to 12% reduction from the clear to the turbid atmosphere.

The tasseled cap

The tasseled cap transformation of Kauth and Thomas (1976) is expressed by four linear equations. The coefficients of the equations are dependent on the calibration factors for the sensor system. Since the calibration constants for Landsat-2 were used to calculate the simulated digital counts, we used the coefficients derived for this satellite (Thompson and Wehmanen, 1980). The equations are,

$$BR = 0.33231X_4 + 0.60316X_5 + 0.67581X_6 + 0.26278X_7 \quad (3)$$

$$GN = -0.28317X_4 - 0.66006X_5 + 0.57735X_6 + 0.38833X_7 \quad (4)$$

$$YE = -0.89952X_4 + 0.42830X_5 + 0.07592X_6 - 0.04080X_7 \quad (5)$$

$$NS = -0.01594X_4 + 0.13068X_5 - 0.45187X_6 + 0.88232X_7 \quad (6)$$

where BR is the soil brightness, GN the greenness, YE the yellowness, and NS the nonsuch. The X's are the digital counts for the MSS bands indicated by the subscript.

Soil brightness values are shown in Figures 15 and 16 for the stressed and the non-stressed plots, respectively. Drying and wetting of the soil early in the season is quite evident. Irrigation on day 79 (Figure 16) caused a sharp drop in brightness. The late jointing irrigation affected brightness on the day of irrigation. However, the delayed IR change is also evident. The brightness factor would not be expected to detect stress. It does show a considerable increase late in the season as the vegetation senesced.

The atmospheric effect on brightness is considerable. Values for the turbid atmosphere are 25 to 30% higher than those for the clear atmosphere.

The greenness factor is given in Figures 17 and 18 for the stressed and the non-stressed plots, respectively. Greenness is, theoretically, not influenced by the soil background. However, the rain on day 71 is strikingly evident in both plots. Also the irrigation on day 79 (Figure 18) is readily observable. Thus, the greenness factor suffers from the same malady as the PVI. During its development it was tacitly assumed that radiation in all bands reacted to plants in the same manner, whereas the near-IR is more readily transmitted through the plants and "sees" more soil background than does the red radiation. If only the greenness factor is considered, then the non-stressed plot would have a lower greenness value than the stressed plot during the period from day 85 to 95, and an erroneous conclusion concerning the health of the crop could result. We consider the greenness factor to be a poor indicator of stress.

If the soil background were not a problem, greenness would be a good indicator of the presence of vegetation. Atmospheric effects cause data for the turbid atmosphere to be 15 to 20% lower that for the clear atmosphere.

Figure 19 shows the yellowness and the nonsuch for both stressed and non-stressed wheat. Since the values of yellowness were negative and nonsuch values were near zero, the yellowness was increased by 20 and the nonsuch by 40, for clarity of presentation. The values for the two plots are essentially indistinguishable, except for a small difference between day 125 and day 145. There was very little response to vegetation by either factor. The yellowness response to senesced vegetation was small. From about day 125 to day 145 the non-stressed plot showed slightly less yellowness than the stressed plot (for both atmospheric conditions). This slight difference is not sufficient for the yellowness factor to be useful as a measure of scenescence. Increased atmospheric scattering reduced yellowness.

The nonsuch factor changed very little throughout the growing season. The non-stressed plot was slightly higher than the stressed (opposite to the yellowness) frmm day 125 to day 145. This factor was essentially independent of atmospheric scattering.

CONCLUDING REMARKS

An ideal vegetation index would be highly sensitive to vegetation, insensitive to soil background changes, and only slightly influenced by atmospheric path radiance. None of the indices examined fully met these criteria. For example, the ratio MSS7/MSS5 was insensitive to vegetation when the green cover was less than 50% but was perhaps the most sensitive index for high values of green cover. Increased atmospheric path radiance severely reduced values of the ratio, making its usefulness with uncorrected satellite data questionable. Other indices were less influenced by the atmosphere but were also less sensitive to vegetation. It appears that no one index can optimally assess vegetation over an entire growing season, and that two or more indices may be required. Consider the time period from about day 65 to day 80 (25 to 80% plant cover, the period during which the soil background had the greatest influence on the indices). During this period the difference-difference (DD) increased with increasing soil wetness, whereas the simple difference, the perpendicular vegetation index, and the greenness factor, decreased with increasing wetness. Using several indices may help to decide whether an index value changed because of vegetation changes, soil background changes or atmospheric changes, from one acquisition date to the next.

A comparison of the various indices during the period from day 85 to 95 shows that they did not detect the onset of stress. The ratio MSS7/MSS5 was probably the most sensitive, but it suffered from atmospheric problems. It is evident that measurements of reflected solar radiation will not detect stress before plant growth has been retarded. However, the degree of reduction can be assessed after the fact. Remote sensing techniques that use emitted thermal radiation to evaluate plant temperatures can detect the onset of stress (Jackson, 1981).

Although atmospheric path radiance affected all of the indices, the degree of influence varied considerably. The difference-difference was nearly the same for both clear and turbid conditions whereas the ratio MSS7/MSS5 was reduced by more that 50% when going from a clear to a turbid atmosphere. Other indices were intermediate. The form of the indices (ratio, difference, etc.) determines the magnitude of the atmospheric influence. The relative magnitude of atmospheric path radiance decreases with increasing wavelength (MSS4 > MSS5 > MSS6 > MSS7). In addition to the greater scattering in the visible compared to the IR bands, the reflectance of vegetation is low because of absorption by chlorophyll, causing the radiance at orbital altitudes to be dominated by path radiance. In contrast, the reflectance of vegetation in the near-IR is high, and the magnitude of path radiance at these wavelengths is low. Thus, the contribution of path radiance to the radiance emerging from the top of the atmosphere in the near-IR is essentially negligible.

The atmospheric model used here (Herman and Browning, 1975) considered only scattering phenomena. Absorption by water vapor can affect MSS7 (Pitts et al, 1974; Pinter and Jackson, 1981). Although absorption was not accounted for in these calculations, the effect can be qualitatively evaluated by considering that increased water vapor in the atmosphere would decrease MSS7. The radiance in MSS7 at the top of a saturated atmosphere would be about 77% of that for a dry atmosphere.

The magnitude of the soil background effect noted on most of the indices will be different for other conditions, especially for other soils. For many soils the reflectance when wet will be approximately 1/2 of that when dry. Highly reflecting, light colored soils would influence the indices much more than low reflecting dark soils. Also if measurements are made at low sun elevation angles the soil would probably be more shaded for the visible, and the near-IR would encounter more plant material before striking the soil. Under these conditions the soil background would have less of an effect on the indices than if the sun was at a higher elevation. Other factors that may modify these results are plant geometry (e.g., different plant heights can cause different amounts of soil background to be viewed), and row orientation (causes the sunlit soil background to be sun azimuth as well as sun elevation dependent).

Although the magnitude of the results may be different for other surface conditions, the results presented here should prove useful for determining the amount of information that can be expected from a particular index at a particular growth stage, and for a given atmospheric condition.

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Table 1. Coefficients for the regression equation ($L = a + b_{\rho} + c\rho^2 \mu$) relating radiance at the top of the atmosphere to ground reflectance.

Atmosphere	band	a	b	b
clear	MSS4	0.00957	0.1984	0.02008
clear	MSS5	0.00487	0.2109	0.01154
clear	MSS6	0.00249	0.2245	-0.01015
clear	MSS7	0.00150	0.2202	0.090467
turbid	MSS4	0.01895	0.1702	0.04091
turbid	MSS5	0.01251	0.1850	0.03343
turbid	MSS6	0.00924	0.1934	0.02805
turbid	MSS7	0.00688	0.1999	0.02397

Table 2. The solar constant (E) and the calibration constants for the four Landsat-2 MSS bands for the period 22 Jan 75 to 15 Jul 75.

Band	E	A	B
	$mW\ cm^{-2}$	$mW\ cm^{-2}\ sr^{-1}\ count^{-1}$	$mW\ cm^{-2}\ sr^{-1}$
MSS4	17.3	0.0157	0.10
MSS5	15.1	0.0027	0.07
MSS6	12.4	0.0105	0.07
MSS7	25.1	0.0637	0.14

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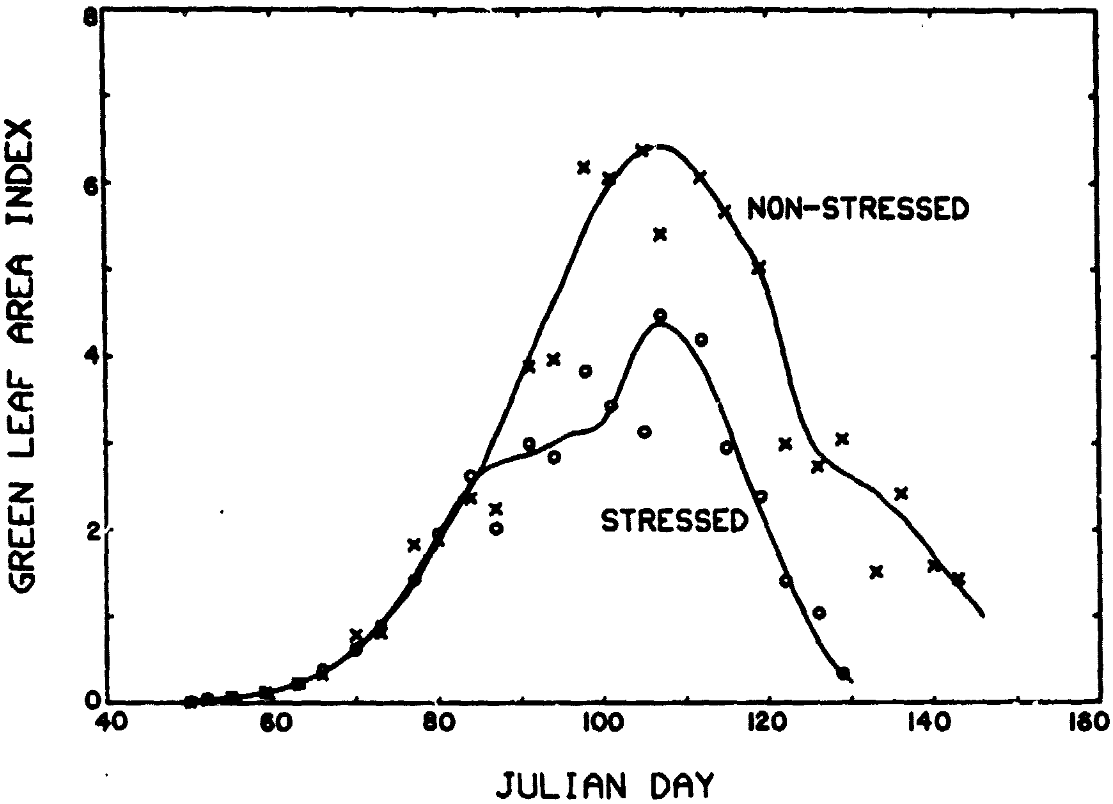

Figure 1. The green leaf area index over a growing season for stressed (o) and non-stressed (x) wheat.

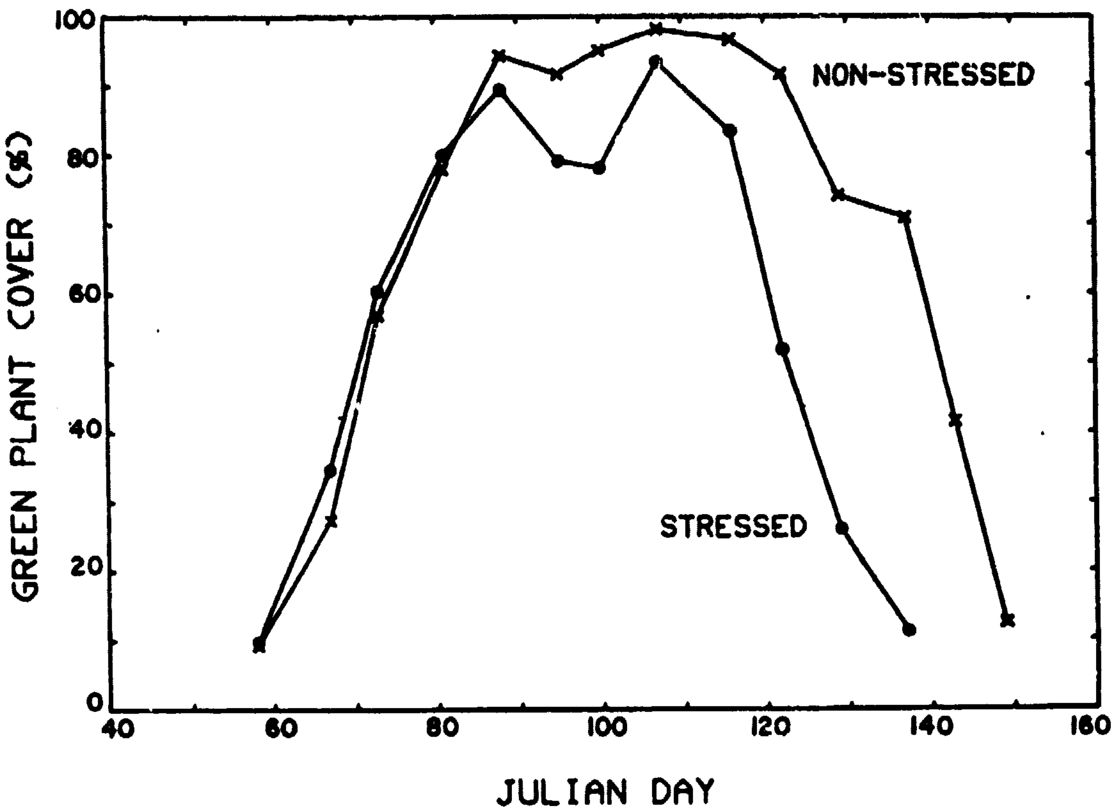

Figure 2. The percent green plant cover over a growing season for stressed (o) and non-stressed (x) wheat.

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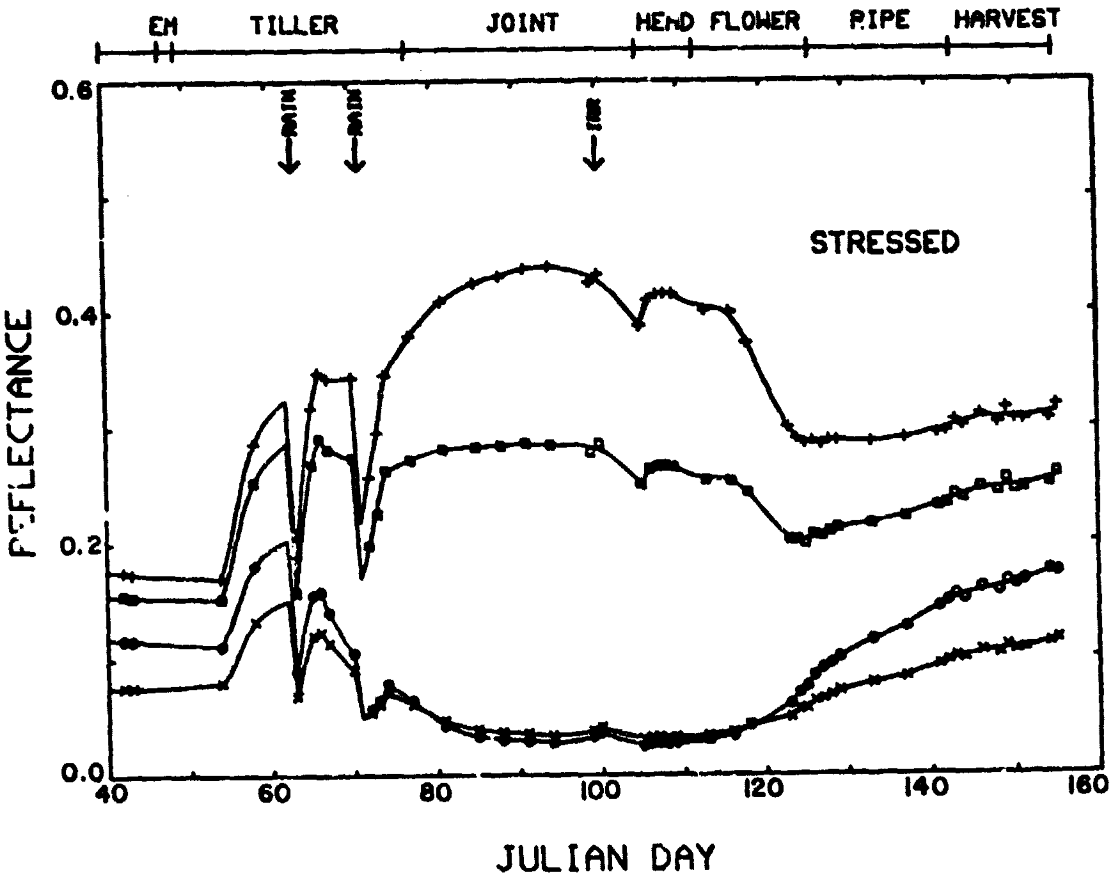

Figure 3. Reflectance in the four Landsat bands over a growing season for stressed wheat. The band identifications are: x, MSS4; circle, MSS5; square, MSS6; and plus, MSS7.

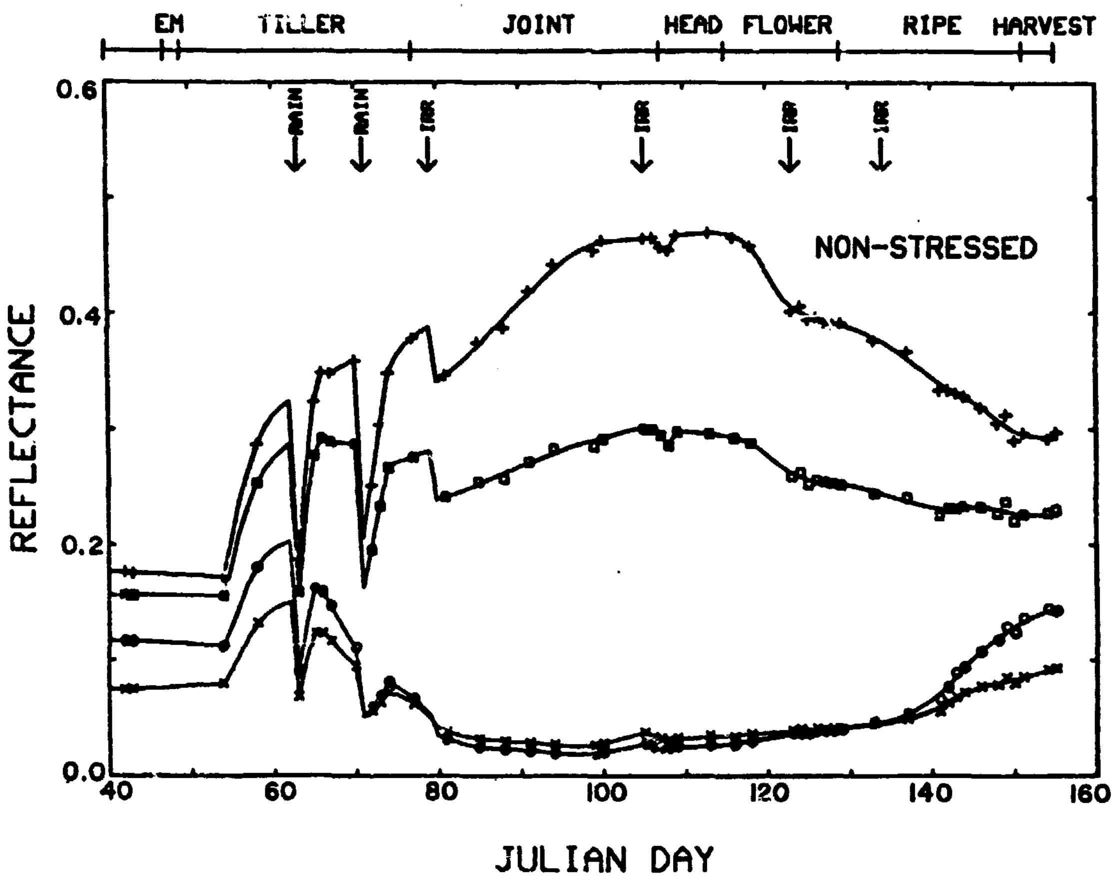

Figure 4. Reflectance in the four Landsat bands over a growing season for non-stressed wheat. The band identifications are: x, MSS4; circle, MSS5; square, MSS6; and plus MSS7.

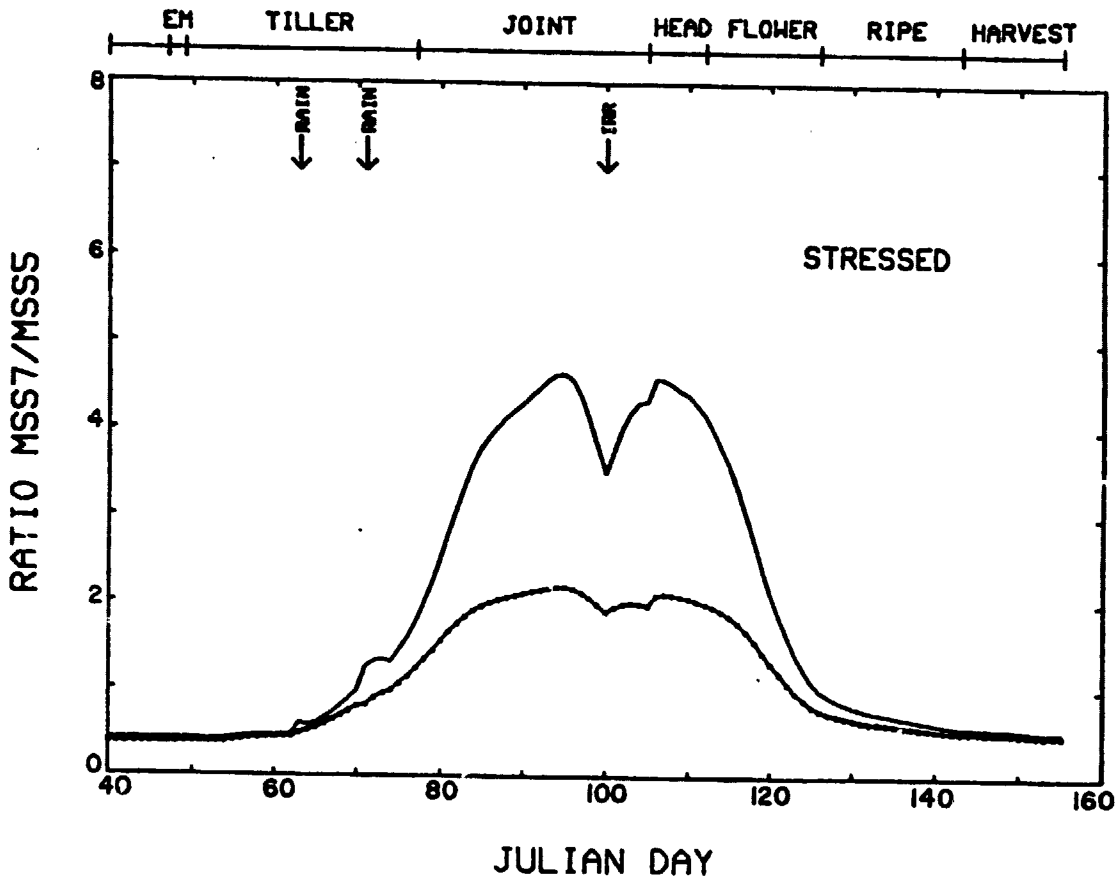

Figure 5. The ratio MSS7/MSS5, calculated using simulated Landsat digital counts, over a growing season for stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

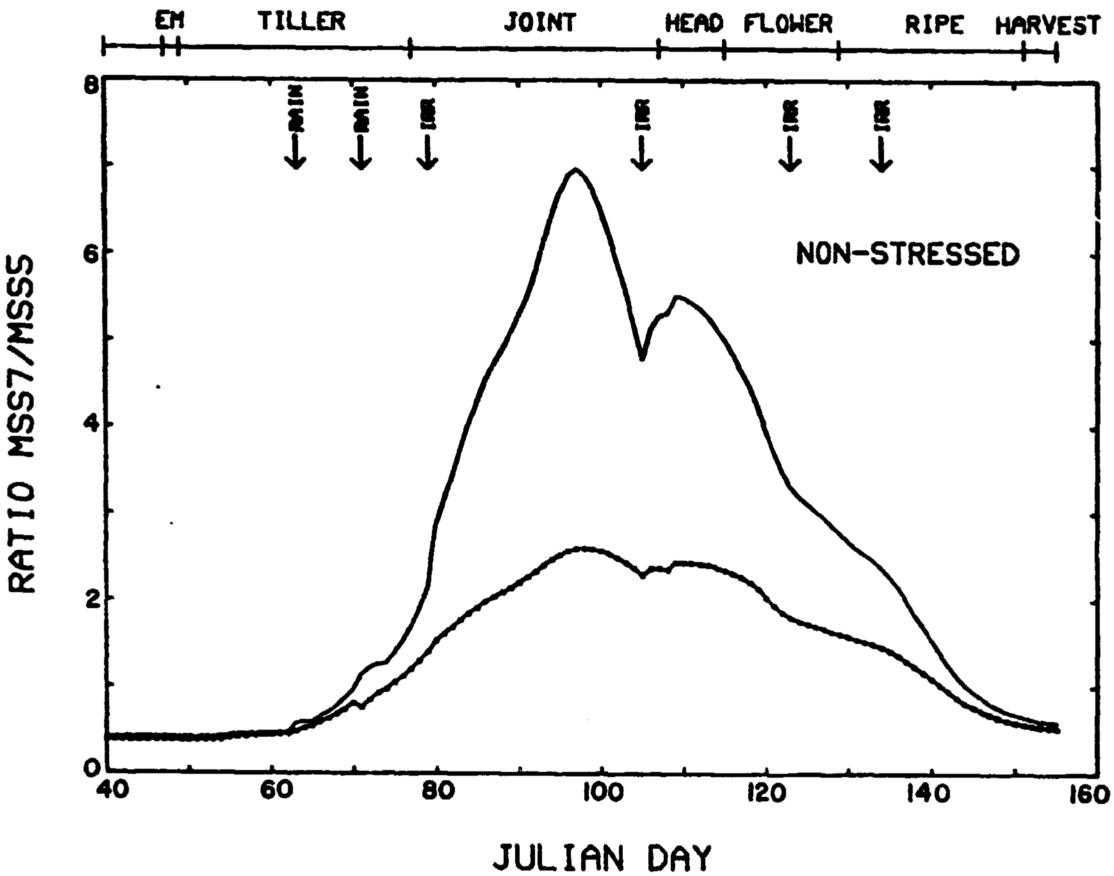

Figure 6. The ratio MSS7/MSS5, calculated using simulated Landsat digital counts, over a growing season for non-stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

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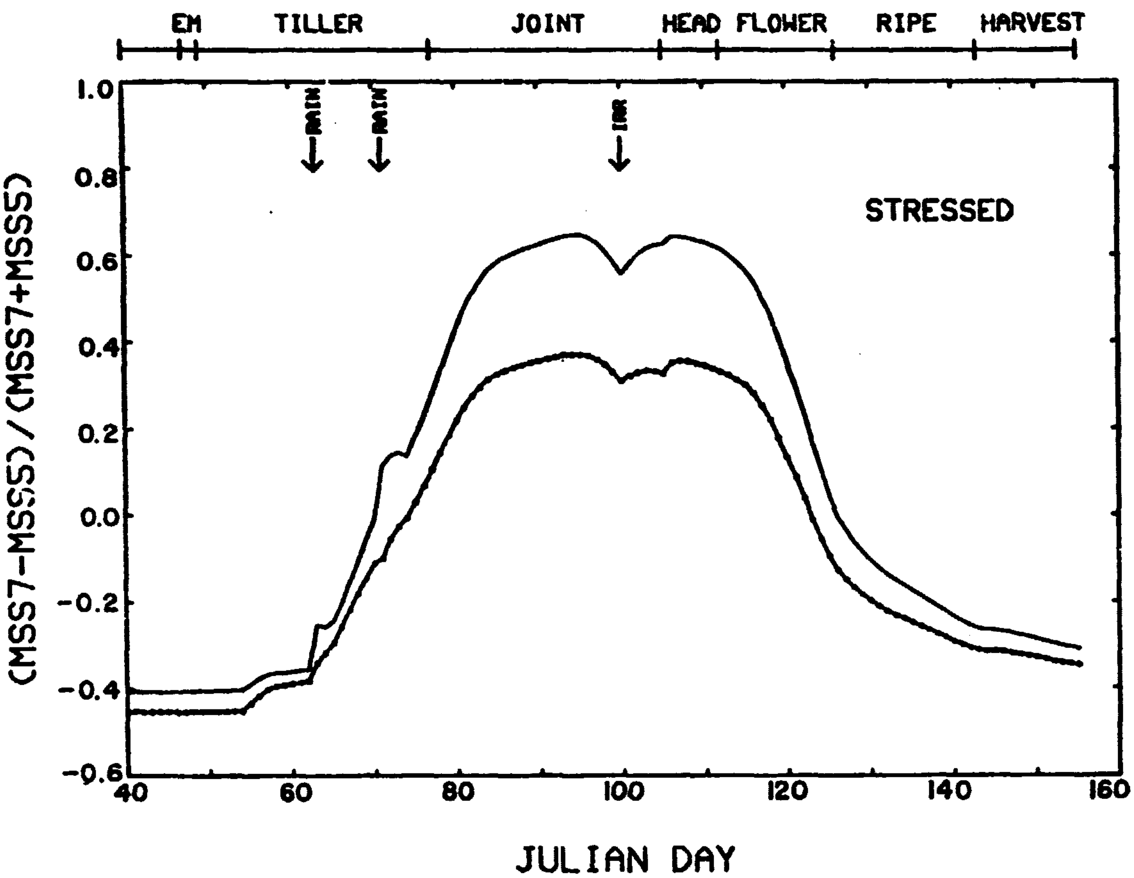

Figure 7. The normalized difference, (MSS7 - MSS5)/(MSS7 + MSS5), calculated using simulated Landsat digital counts over a growing season for stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

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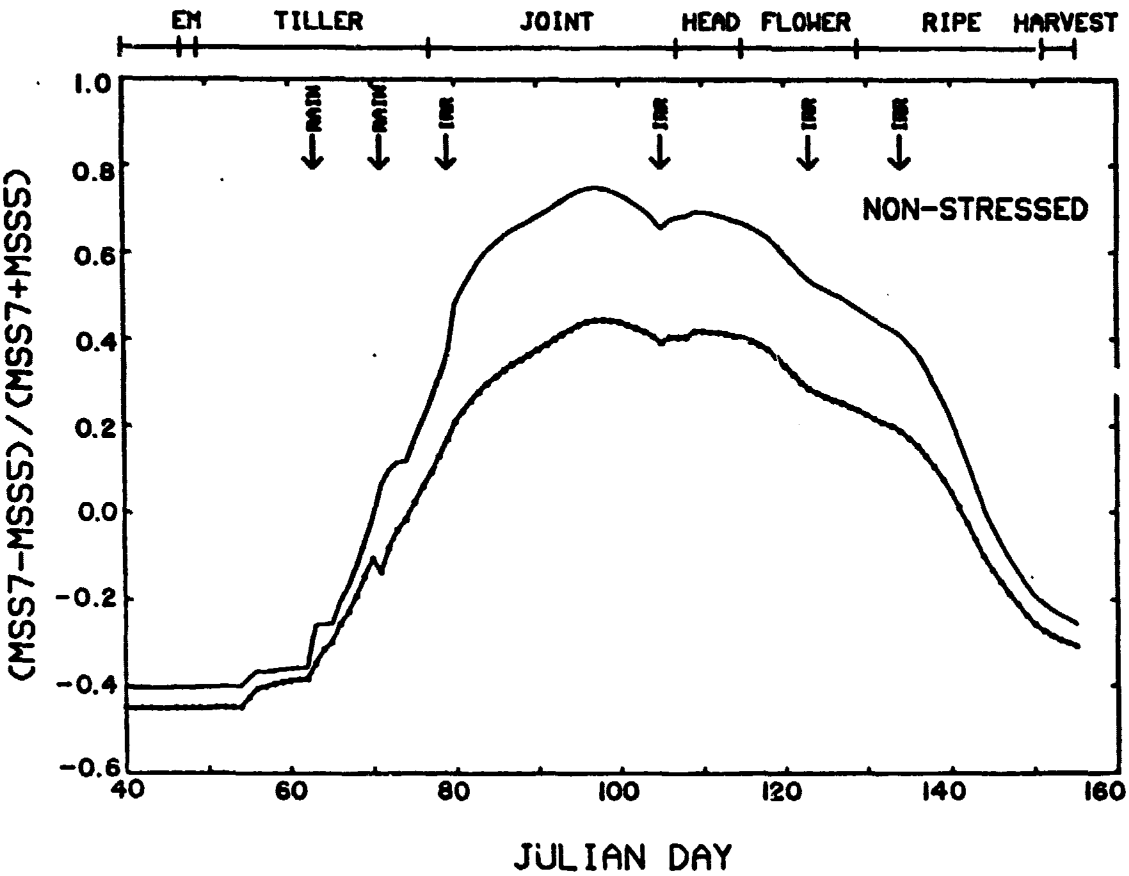

Figure 8. The normalized difference, (MSS7 - MSS5)/(MSS7 + MSS5), calculated using simulated Landsat digital counts over a growing season for non-stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

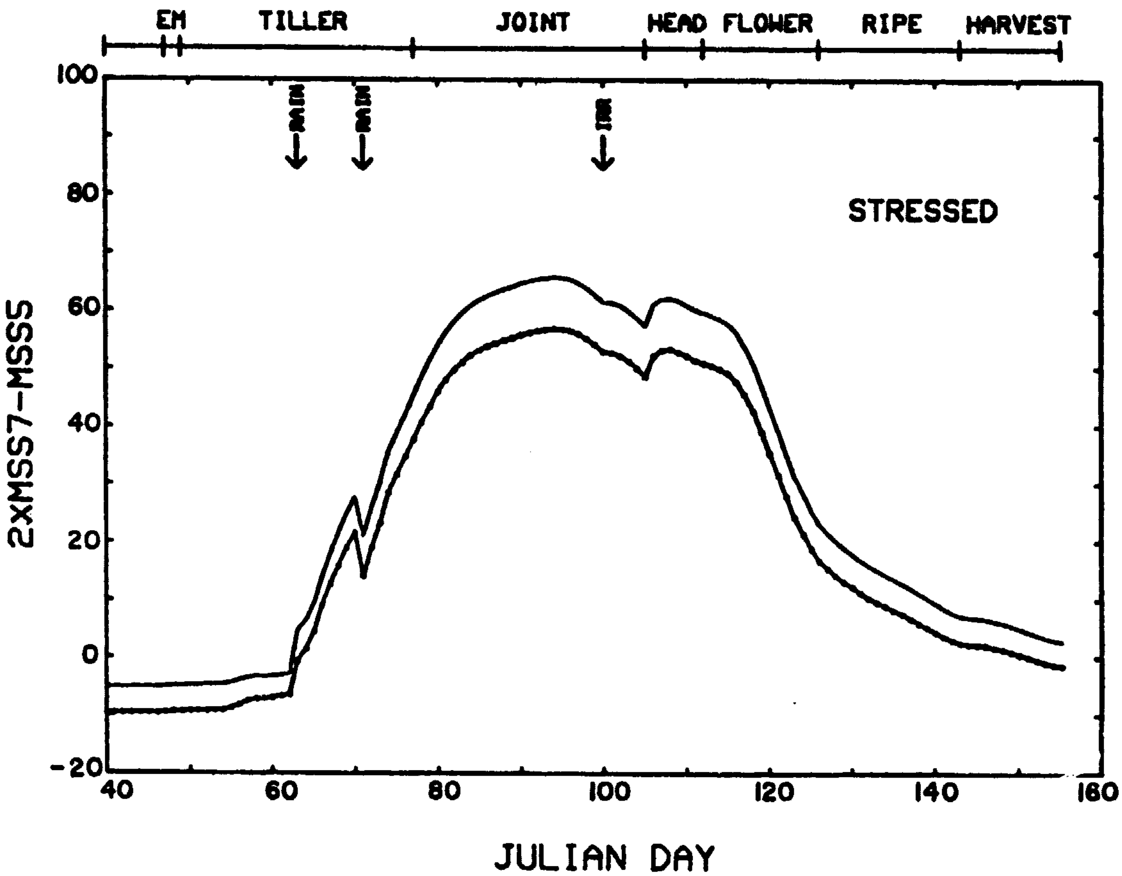

Figure 9. The near-IR, red difference (2*MSS7 - MSS5), calculated using simulated Landsat digital counts over a growing season for stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

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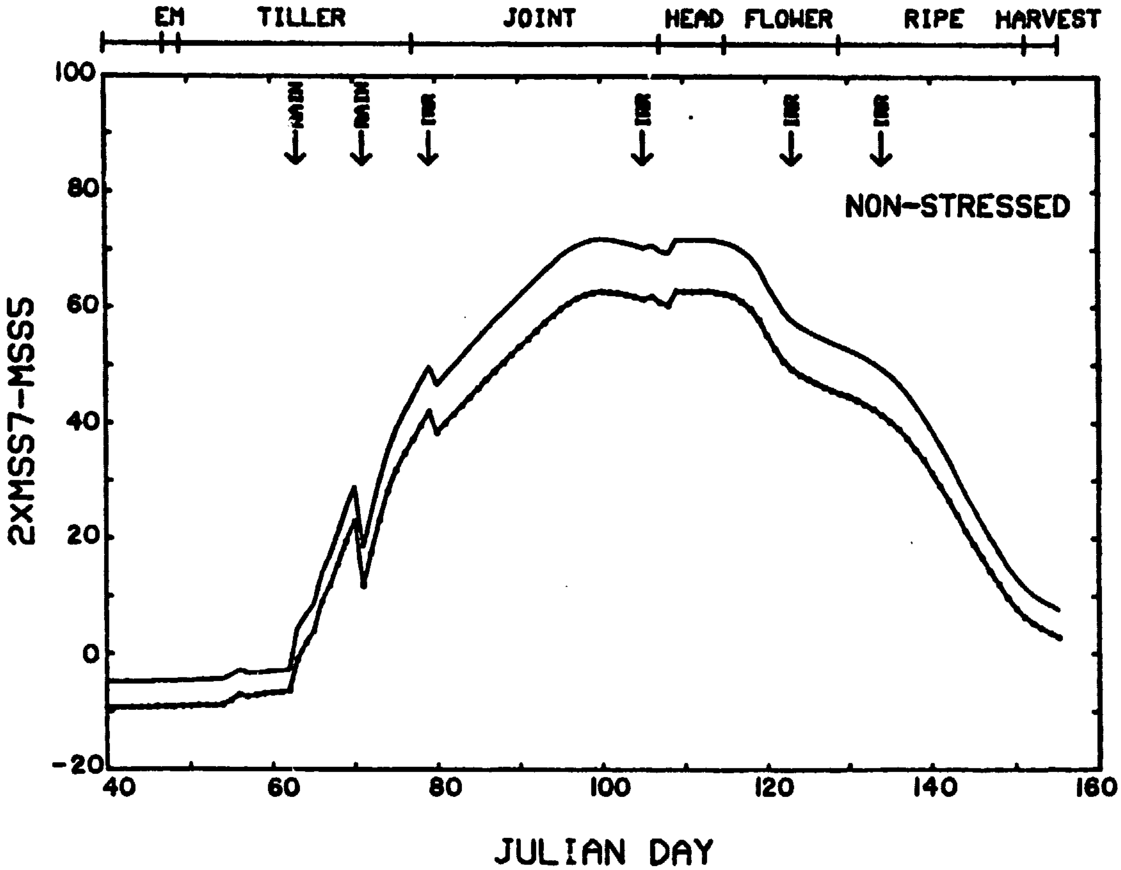

Figure 10. The near-IR, red difference (2*MSS7 - MSS5), calculated using simulated Landsat digital counts over a growing season for non-stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

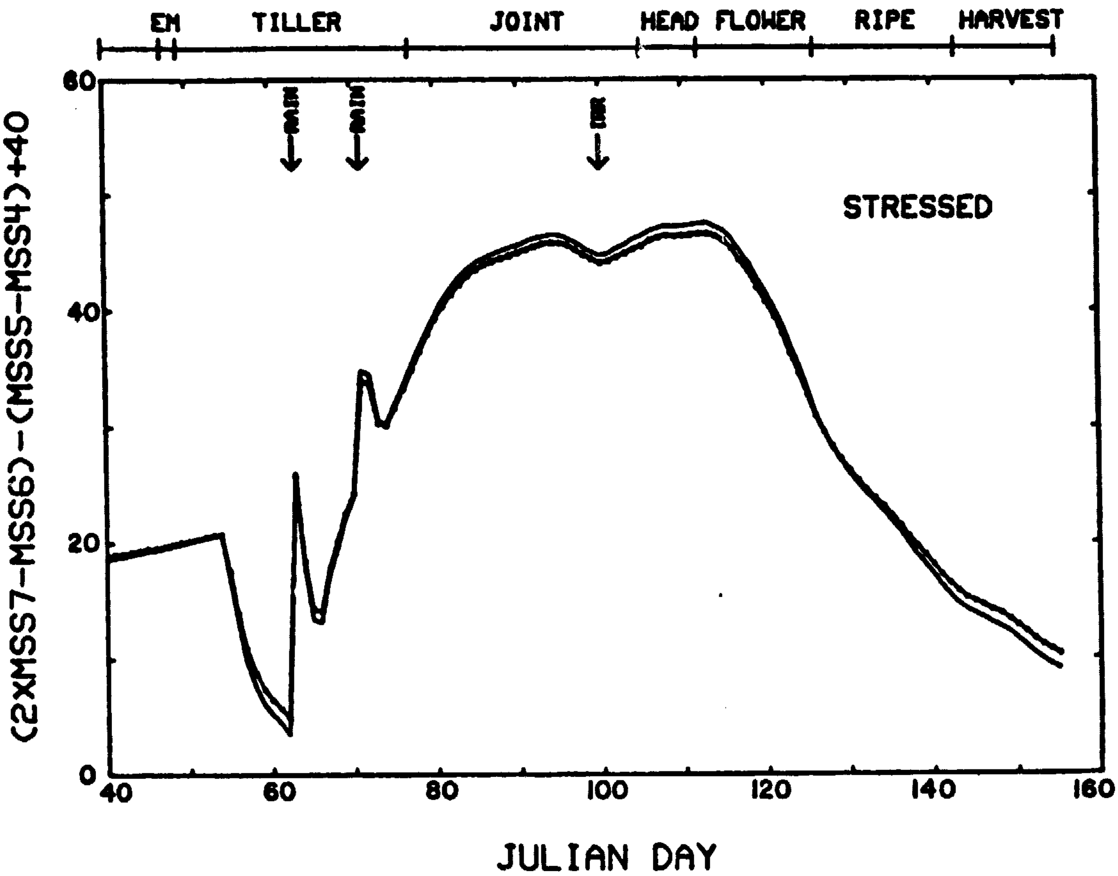

Figure 11. The difference-difference (2*MSS7 - MSS6) - (MSS5 - MSS4), calculated using simulated Lndsat digital counts over a growing season for stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

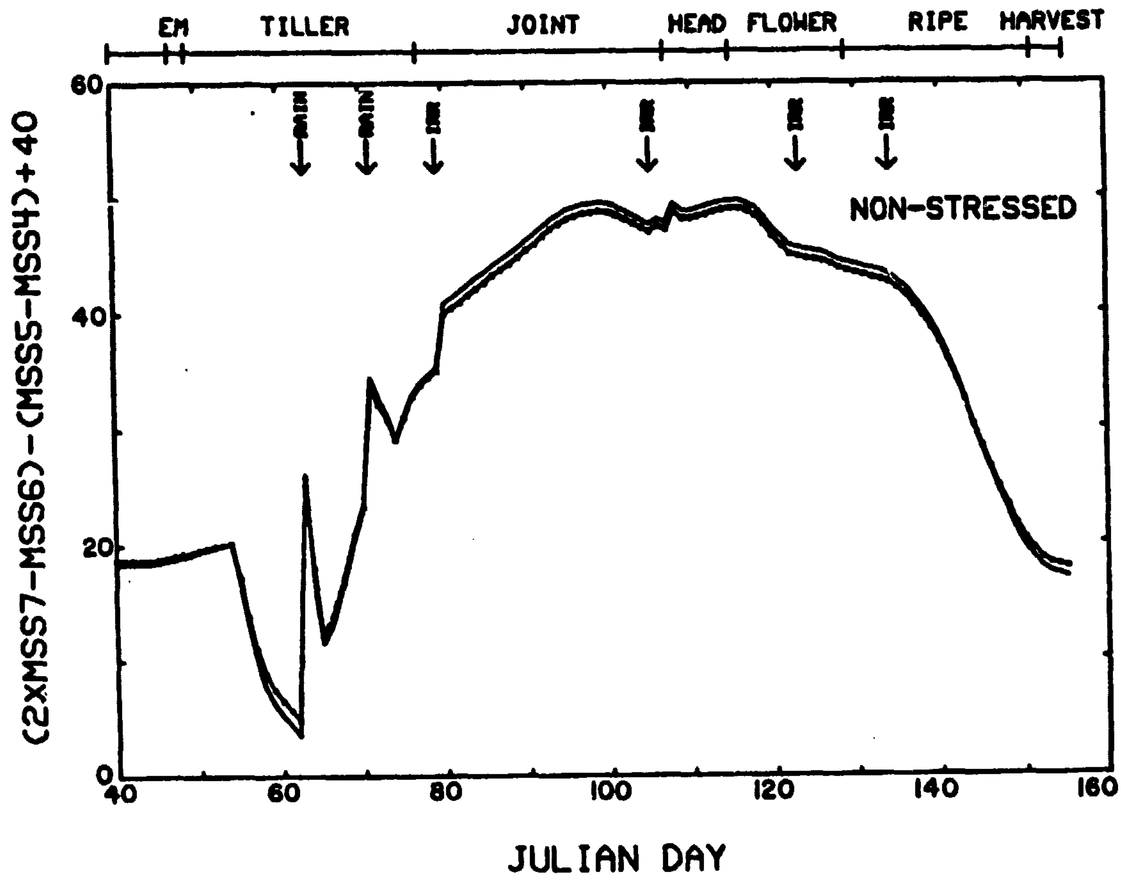

Figure 12. The difference-difference (2*MSS7 - MSS6) - (MSS5 - MSS4), calculated using simulated Landsat digital counts over a growing season for non-stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

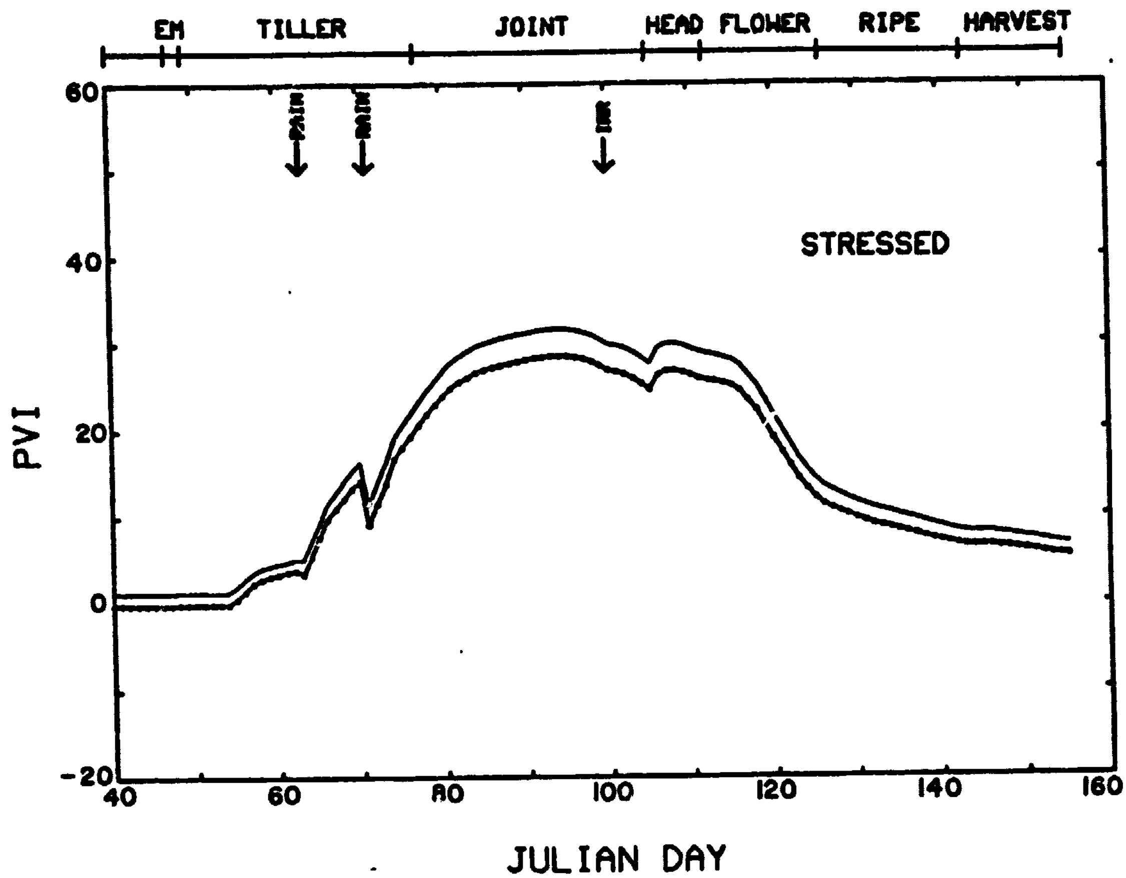

Figure 13. The perpendicular vegetation index (PVI), calculated using simulated Landsat digital counts over a growing season for stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

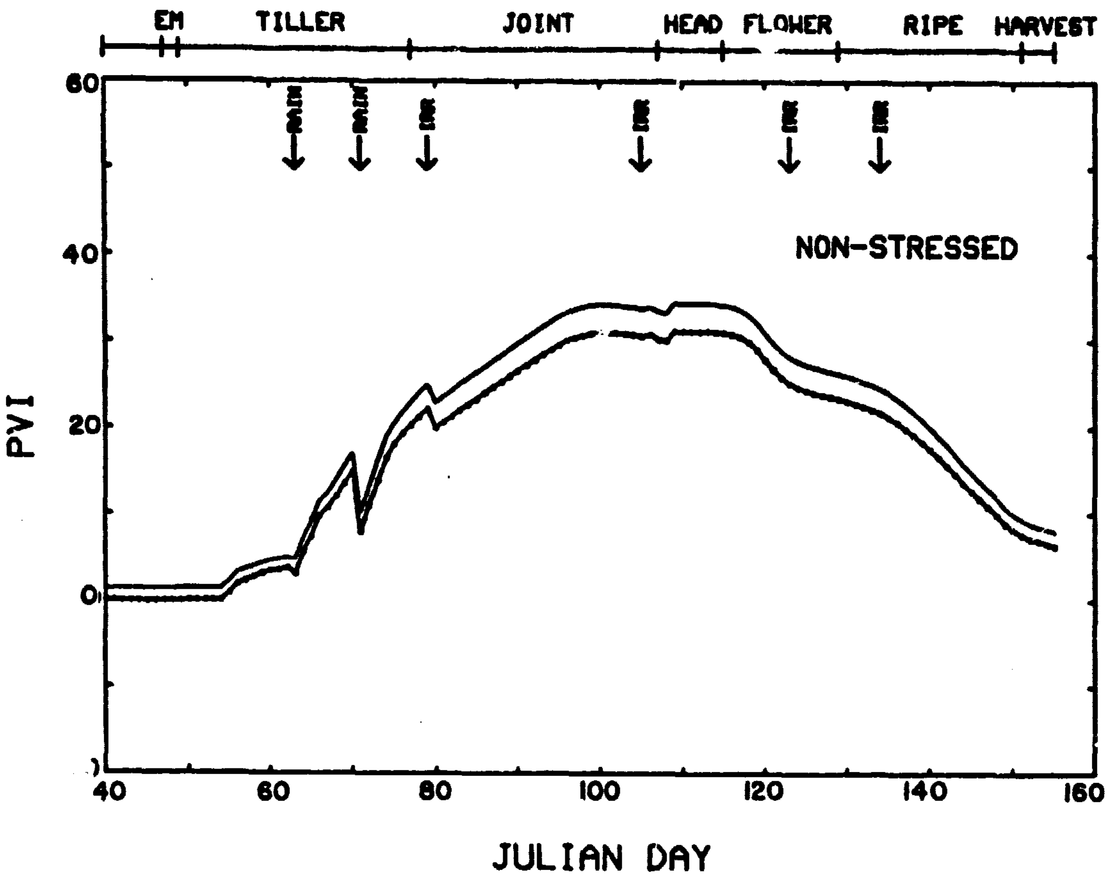

Figure 14. The perpendicular vegetation index ($PV\perp$), calcuuated using simulated Landsat digital counts over a growing season for non-stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

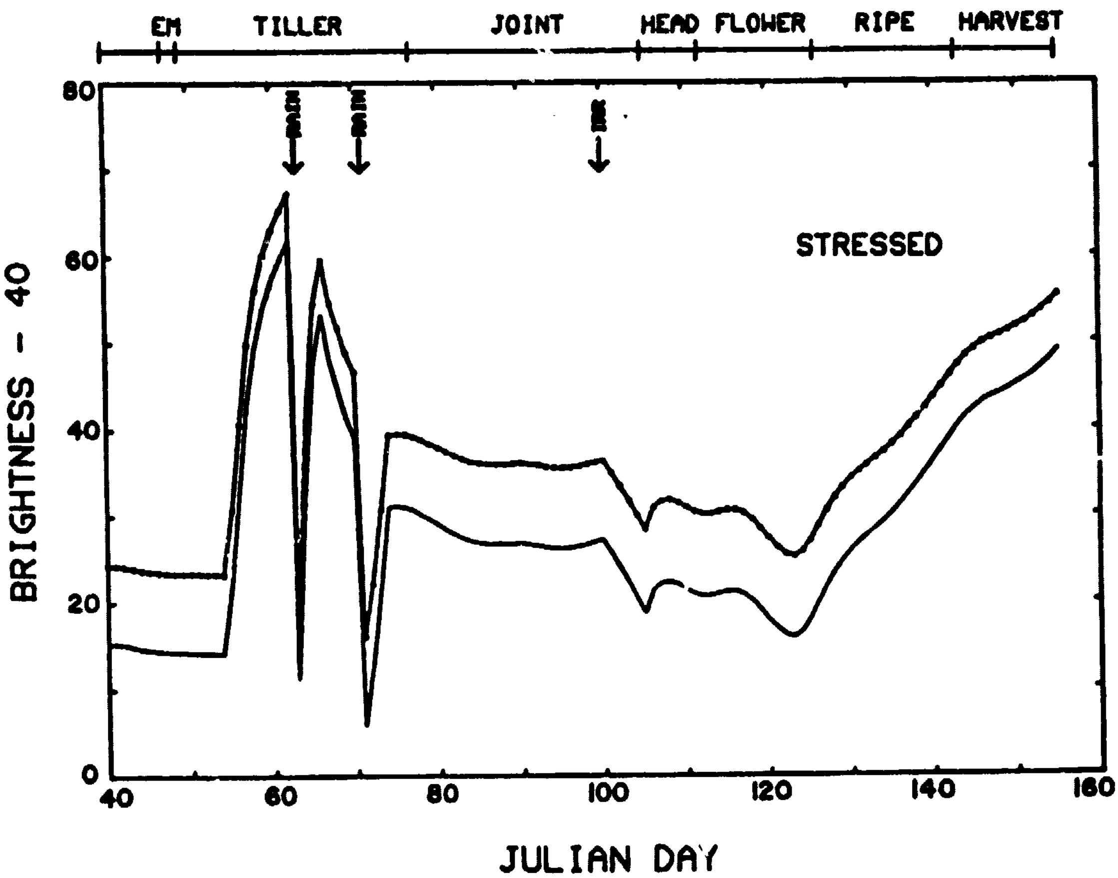

Figure 15. The soil brightness factor calculated using simulated Landsat digital counts over a growing season for stressed wheat. The smoot'. line represents clear and the connected dots represent turbid atmospheres.

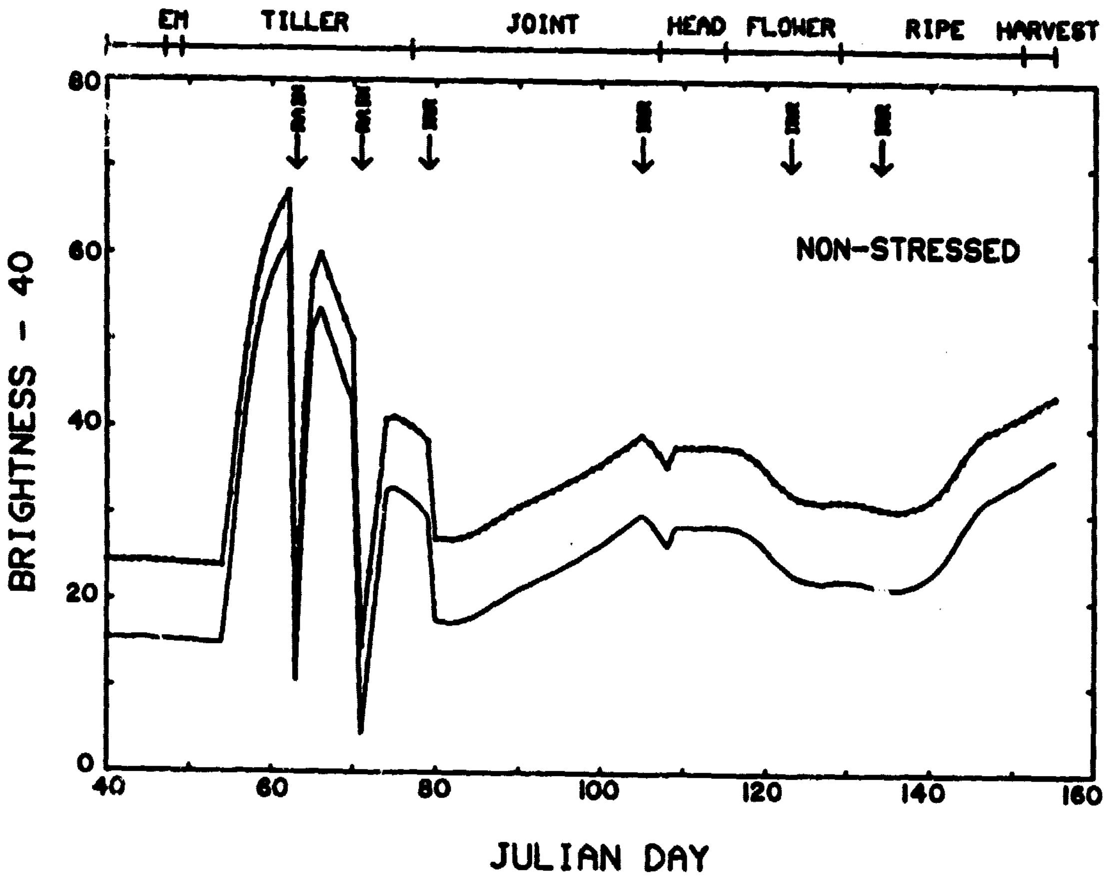

Figure 16. The soil brightness factor calculated using simulated Landsat digital counts over a growing season for non-stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

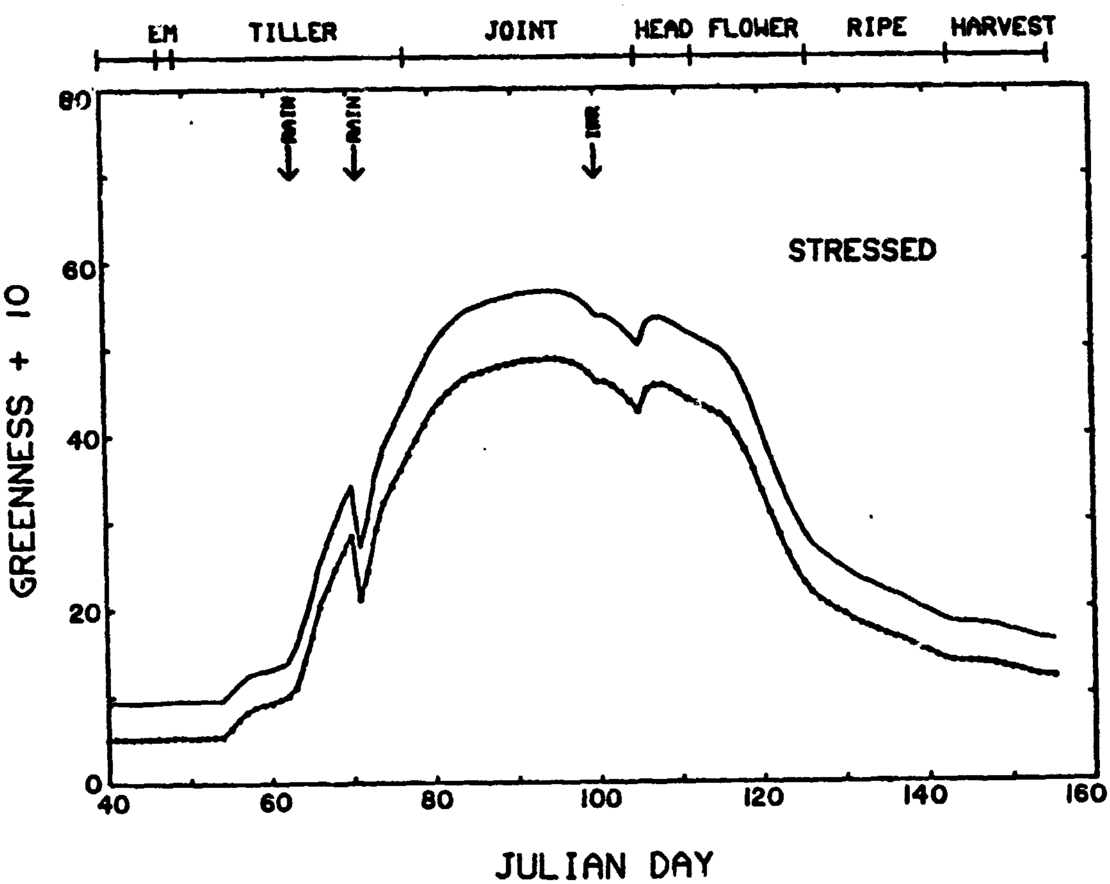

Figure 17. The greenness factor calculated using simulated Landsat digital counts over a growing season for stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

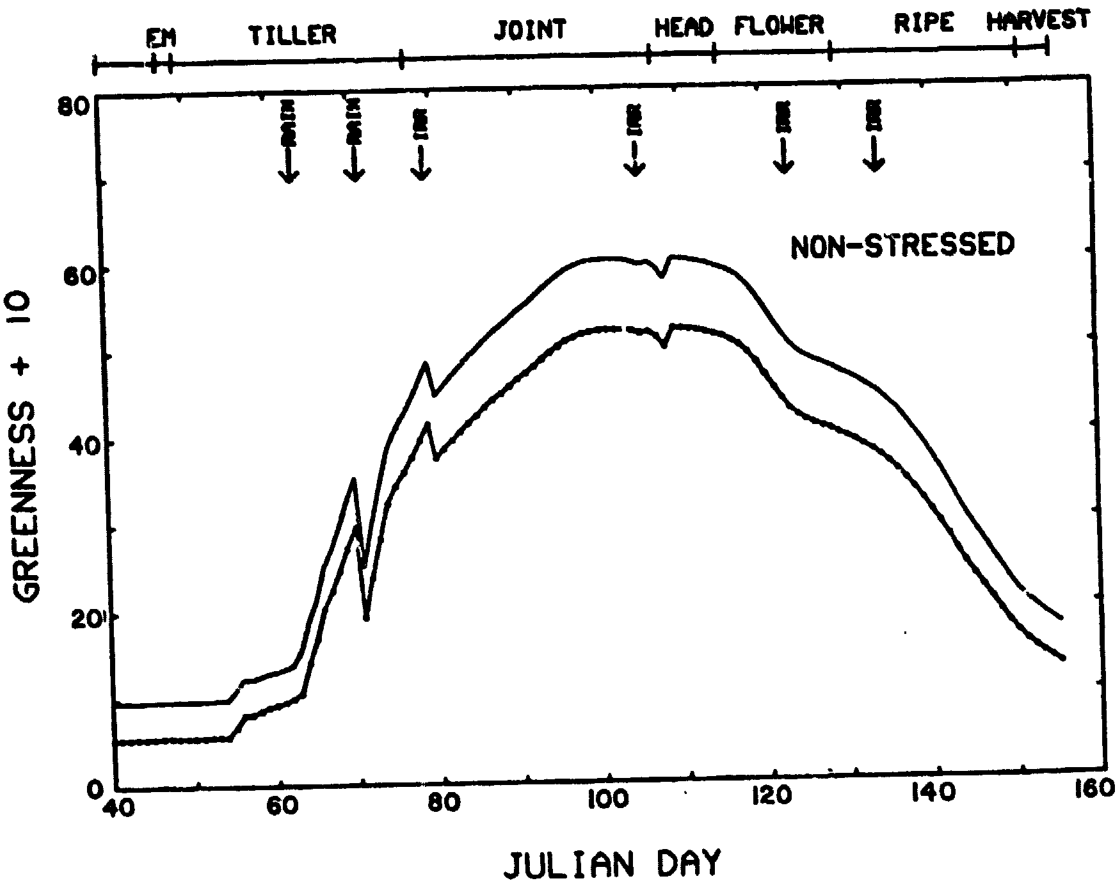

Figure 18. The greenness factor calculated using simulated Landsat digital counts over a growing season for non-stressed wheat. The smooth line represents clear and the connected dots represent turbid atmospheres.

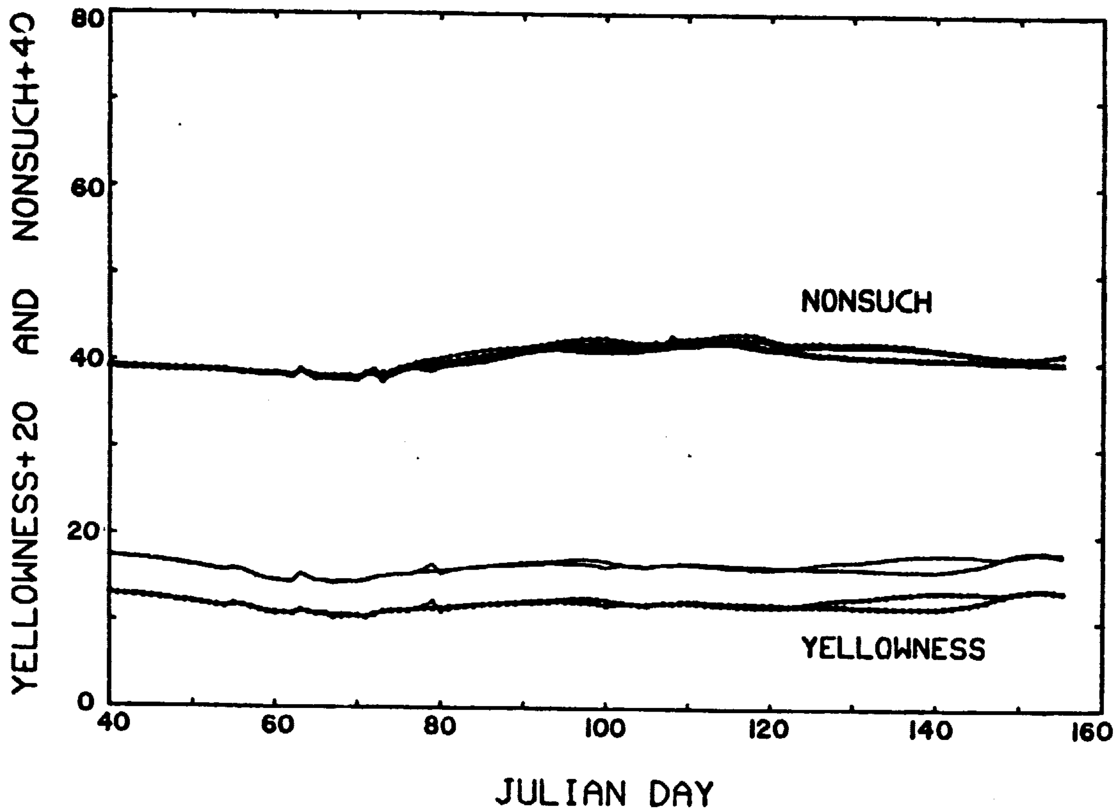

Figure 19. The yellowness and nonsuch factors for stressed and non-stressed wheat over a growing season. The smooth line represents clear and the connected dots represent turbid atmospheres.