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February 1982

Technical Report

ASSOCIATION OF SPECTRAL DEVELOPMENT PATTERNS WITH DEVELOPMENT STAGES OF CORN

Eric P. Crist

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16. Abstract

Association is made between the development stages of corn as defined by Hanway and the temporal-spectral development pattern of corn in a transformed data space derived from Landsat-MSS band reflectance values, using field-collected reflectance and associated data. Results indicate that the spectral vegetation index used (a reflectance equivalent of Tasseled Cap Greenness) reaches a maximum well before the stage at which corn is expected to achieve its peak green leaf area index. Possible physiological and canopy geometry related causes for this and other results are presented.

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TECHNICAL REPORT

ASSOCIATION OF SPECTRAL DEVELOPMENT PATTERNS WITH DEVELOPMENT STAGES OF CORN

by

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This report describes results of research performed in support of the Inventory Technology Development Project of the AgRISTARS Program.

Environmental Research Institute of Michigan
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February 1982

PREFACE

The Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing program, AgRISTARS, is a six-year program of research, development, evaluation, and application of aerospace remote sensing for agricultural resources, which began in Fiscal Year 1980. This program is a cooperative effort of the National Aeronautics and Space Administration, the U.S. Agency for International Development, and the U.S. Departments of Agriculture, Commerce, and the Interior. AgRISTARS consists of eight individual projects.

The research reported herein was sponsored by the Inventory Technology Development (ITD) Project under the auspices of the National Aeronautics and Space Administration, NASA. Dr. Jon Erickson, is the NASA Manager of the ITD Project and Mr. Lewis Wade was the Technical Coordinator for the reported effort.

The association of the time of occurrence of corn development stages to a Landsat-MSS-related greenness measure was performed under NASA contract NAS9-16538 by the Environmental Research Institute of Michigan's Infrared and Optics Division, headed by Richard R. Legault, Vice-President of ERIM, under the technical direction of Robert Horvath, Program Manager and Richard C. Cicone, Task Leader.

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INTRODUCTION

Successful use of remotely-sensed data in crop inventory and condition assessment systems depends in large part on detailed knowledge of the temporal-spectral development patterns (profiles) of crops, and the relationship of those profiles to the physiological and morphological development of the plants themselves. In particular, association of spectral phenomena with specific stages of plant development can aid both the identification and assessment of condition of crops. Knowledge of the physiological and morphological influences on crop spectral development patterns allows design of crop identification techniques which emphasize the most fundamental, and therefore most reliable, differences between crops, and also facilitates adaptation of such techniques to local environmental conditions or changes in cultural practices. Conversely, knowledge of the spectral expression of key developmental events allows for more accurate development stage estimation from remotely-sensed data, and thus improves the ability to assess crop condition and estimate yield.

In this paper, association is made between the development stages of corn as defined by Hanway [7] and the temporal-spectral development pattern of corn in a transformed data space derived from Landsat-MSS band reflectance values, using field-collected reflectance and associated data. Results indicate that the spectral vegetation index used (a reflectance equivalent to Tasseled Cap Greenness) reaches a maximum well before the stage at which corn is expected to achieve its peak green leaf area index. Possible physiological and canopy geometry-related causes for this and other results are discussed.

2
MATERIALS AND METHODS

Data from experimental plots at the Purdue Agronomy Farm have been collected for several years by personnel from the Laboratory for Applications of Remote Sensing (LARS) for the NASA Johnson Space Center. The primary instrument used to collect spectral data has been an Exotech 100 Landsat band radiometer. In addition to spectral observations, measurements of leaf area, percent cover, stage of development, and other plant or canopy characteristics have been obtained. A more complete description of the LARS data collection program is available in References [1,2].

The data used in this analysis were collected as part of the 1979 and 1980 Corn Cultural Practices Experiments, which included as experimental treatments planting date, plant population, and soil brightness [1,2]. Development stages were recorded in text form. Thirty-seven plots were included in the analysis reported here. These were selected on the basis of quality of spectral and developmental data acquisition (number and spacing of observations) and lack of excessive noise in the spectral data. In addition, some plots (seven) were rejected part-way through the analysis because the spacing of observations resulted in distorted profile shapes, as derived by the profile model described later in this section. Table 1 provides a more complete description of the data set used.

2.1 REFLECTANCE DATA PREPARATION

All Landsat band reflectance values were linearly transformed into a data space resembling that which results from application of the Tasseled Cap Transformation to actual Landsat-MSS data [8]. The Tasseled Cap Transformation captures the vast majority (usually 95% or more) of Landsat-MSS data variation over agricultural regions in two

TABLE 1. DATA SET DESCRIPTION

1979 Data

Plot #	Days Observed	Planting Date	Population (K plants/ha)
44	21	2 May	75
46	19	30 May	50
47	21	2 May	50
50	18	30 May	75
56	20	2 May	50
57	19	16 May	50
60	19	16 May	75
65	20	2 May	75
69	20	2 May	50
71	18	16 May	50
74	19	16 May	75
75	20	2 May	75
82	19	16 May	50
83	20	2 May	75
87	20	2 May	50
88	19	16 May	75

TABLE 1. DATA SET DESCRIPTION (Continued)

1980 Data

Plot #	Days Observed	Planting Date	Population (K plants/ha)
31	17	7 May	75
32	17	16 May	50
33	17	7 May	25
37	17	22 May	75
41	13	11 Jun	25
42	17	7 May	50
45	15	22 May	50
47	12	11 Jun	25
50	15	22 May	25
51	15	7 May	50
53	12	11 Jun	50
55	13	29 May	50
56	15	7 May	75
57	15	16 May	50
60	13	7 May	50
63	13	7 May	75
64	11	11 Jun	50
66	10	18 Jun	50
73	11	11 Jun	50
75	11	11 Jun	25
83	10	11 Jun	75

channels which are related to soil brightness or albedo and amount of green vegetation. The procedure used to derive a similar transformation for these reflectance data is described in Reference [3]. The second channel, Green Reflectance (or Greenness for actual Landsat-MSS data), which is related to the amount of green vegetation present in the scene, was used in the analysis reported here. Multiple spectral measurements for a single plot on a single day were represented by their mean.

Continuous profiles were derived from the transformed data values by means of a profile model specifically intended to capture the features of corn Greenness development. Most prominent among these is a flattened peak or plateau observed both in Green Reflectance data [3] and in associated variables such as leaf area index [4]. Reference [3] presents the evidence for the existence of this flattened peak, based on analysis of a larger set of field reflectance data which included the plots used in the present analysis. One of the key pieces of evidence was the nature of the residual errors resulting from fitting the Green Reflectance data with a curve form which was more or less bell-shaped. The pattern of residual errors clearly indicated a more flattened peak in the data. The model developed to produce such a flattened peak is of the form

$$G(t) = \begin{cases} \dfrac{A}{1 + Q^2(t-t_p)^2} \; ; & t \leq t_p \\[2ex] \dfrac{(A-25)*g(\alpha,\Delta)}{\pi} \left(\cot^{-1}[\alpha(t-t_p - \Delta)]\right) + 25 \; ; & t > t_p \end{cases}$$

where

$G(t)$ = Greenness at time t

$A, t_p, Q, \alpha, \Delta$ = model parameters

A = maximum function value (peak Greenness)

t_p = day of maximum function value

Q = inverse time from first half-peak to peak

α = controlling factor for shape after peak (flatness of peak, steepness of decline)

Δ = time from peak to second half-peak

and

$g(\alpha,\Delta) \equiv \pi/\cot^{-1}(-\alpha*\Delta)$ (provides continuity at $t = t_p$)

Evaluation of the model over a larger set of field reflectance data, and comparison to other possible curve-fitting methods, revealed some deficiencies, largely related to the difficulty of parameter estimation, but when parameters could be estimated the model proved more able to capture the plateau feature than were the other techniques considered [3]. Since the plateau is the key feature involved in the present analysis, the profile model was selected for use. To insure that parameter estimation could be accomplished, only those plots for which data had been collected at frequent intervals through most or all of the growing season were included in the analysis.

After the continuous profiles were estimated using the described model, each plot was characterized by a set of standard features corresponding to spectral events of interest. The features used in this analysis, as described and illustrated in Figure 1, included the time of peak Green Reflectance, times of half that value, and time of plateau end.

2.2 DEVELOPMENT STAGE DATA PREPARATION

The text descriptions of development stages available in the LARS/Purdue data base were converted to numerical values representing the stages on the Hanway Scale (as described in Table 2). For the 1979 data, the conversion was defined previously by Bauer, et al., [2];

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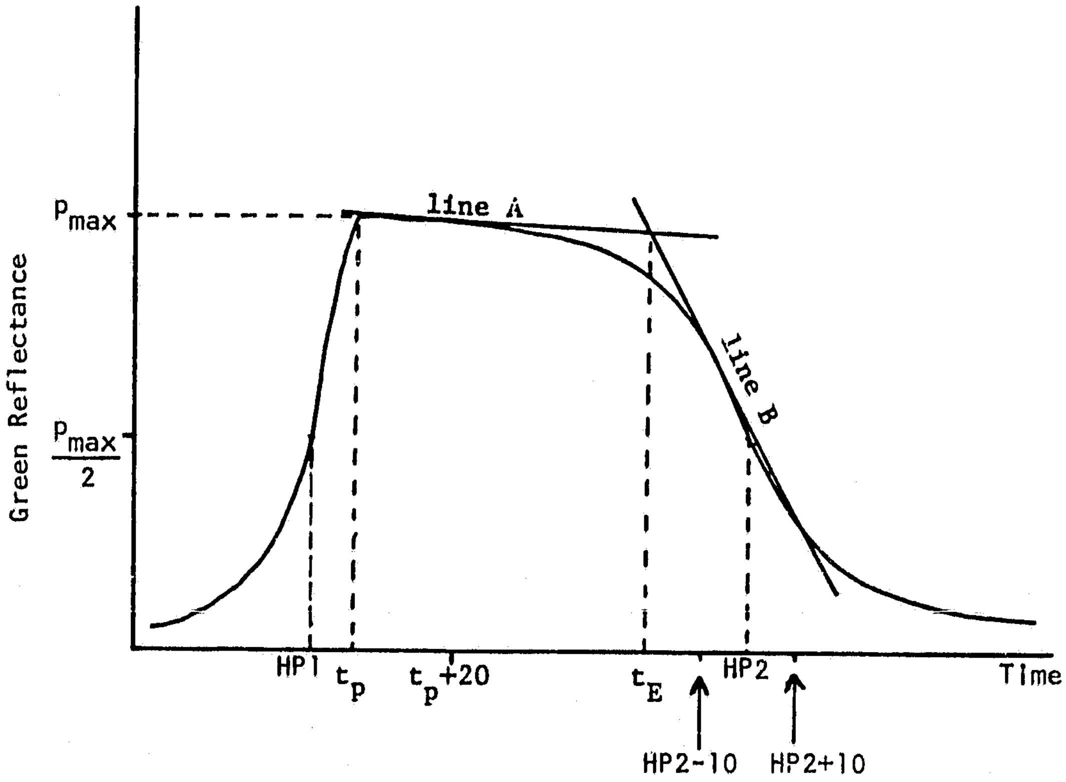

t_p - time of peak profile value

HP1,HP2 - times of peak/2

T_E - time of plateau end - intersection of lines A and B where

line A - drawn through profile values at t_p and t_p + 20

line B - drawn through profile values at HP2-10 and HP2+10

FIGURE 1. PROFILE FEATURES USED IN ANALYSIS

TABLE 2, STAGES OF CORN DEVELOPMENT

Stage	Days Since Planting	Description
0	9	Emergence
1	23	Collar of fourth leaf visible
2	37	Collar of eighth leaf visible; beginning of period of rapid stem elongation
3	51	Collar of twelfth leaf visible; near middle of period of rapid stem elongation
4	65	Collar of sixteenth leaft visible; tips of tassels visible
5	75	75% of plants have silks visible; vegetative growth ceased
6	87	Kernels in "Blister" stage; beginning of period of rapid dry matter accumulation in kernels
7	99	Kernels in very late "Roasting ear" or "Dough" stage
8	111	Kernels in early "Dent" stage
9	123	Kernels in full "Dent" stage
10	135	Grain mature

Based on averages from adapted hybrids in central Iowa from Hanway [7].

a similar conversion was developed for the 1980 data. Third-order polynomials were fit through the converted observations for each plot, and for all plots with the same planting date. The results of the combined curve-fits were compared to published data [7] with regard to the intervals between stages and found to be in reasonable agreement. The analyses carried out used the individual rather than the composite curves, since substantial variations were observed in development curves for plots planted on the same day. Samples of the curves used are shown in Figures 2 and 3.

2.3 ANALYSES CARRIED OUT

Stages of development associated with each of the described spectral features were determined from the polynomial curves for each plot. Mean values were computed for each year separately and for all the plots combined. In addition, the times of occurrence of each of the first nine stages on the Hanway Scale (fourth leaf fully emerged through full dent) were determined for each plot, and merged with graphs of the profile model fits. These were used to qualitatively evaluate both the model fits and the overall interaction between physiological and spectral development.

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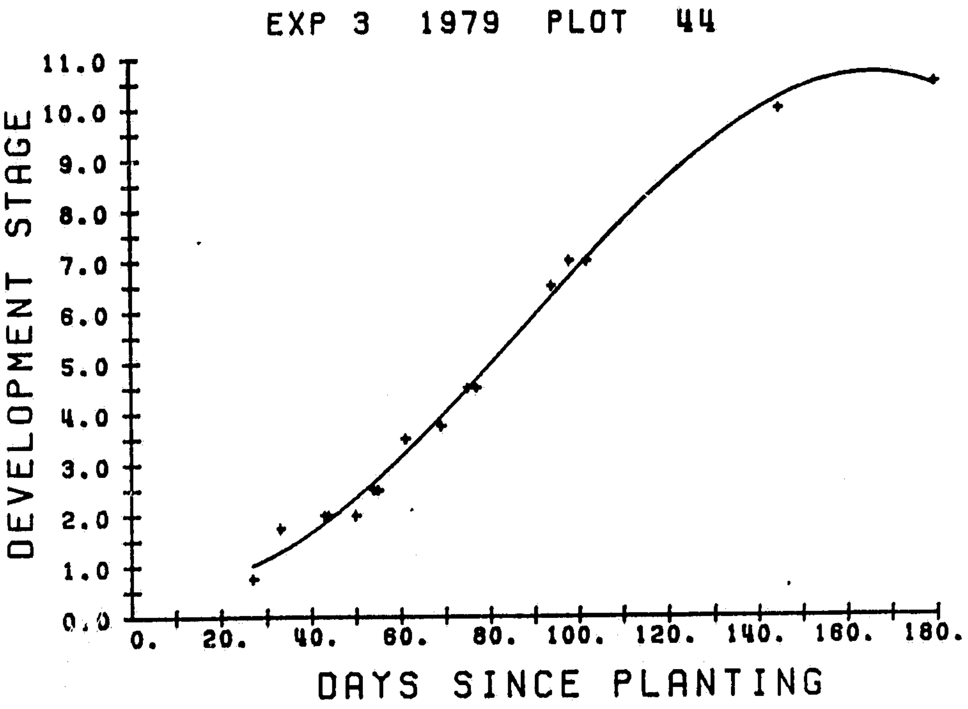

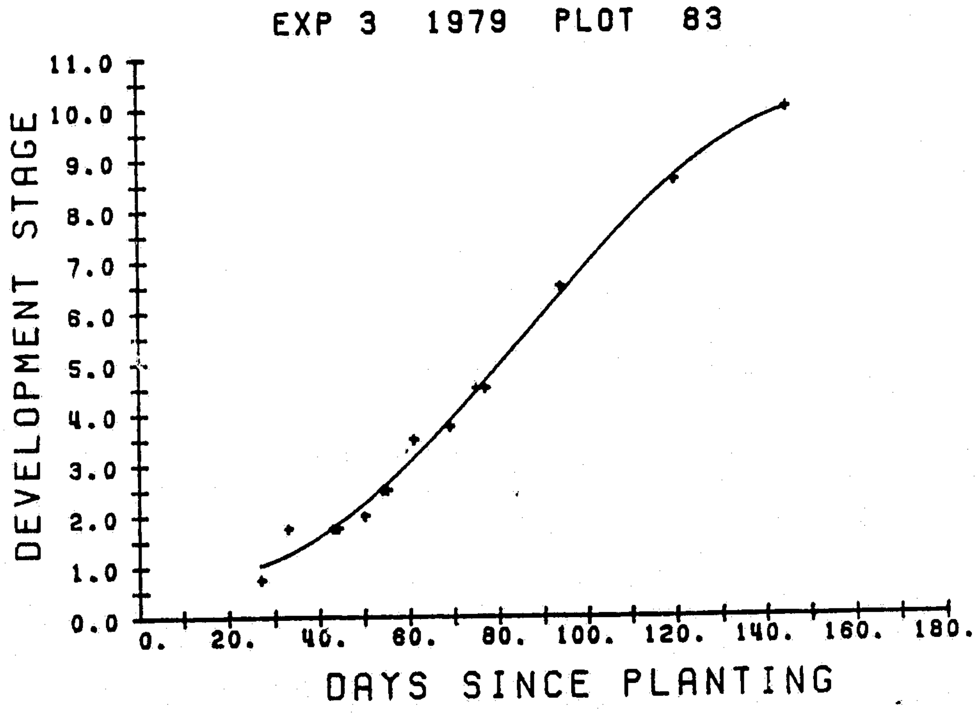

FIGURE 2. EXAMPLE DEVELOPMENT STAGE CURVES

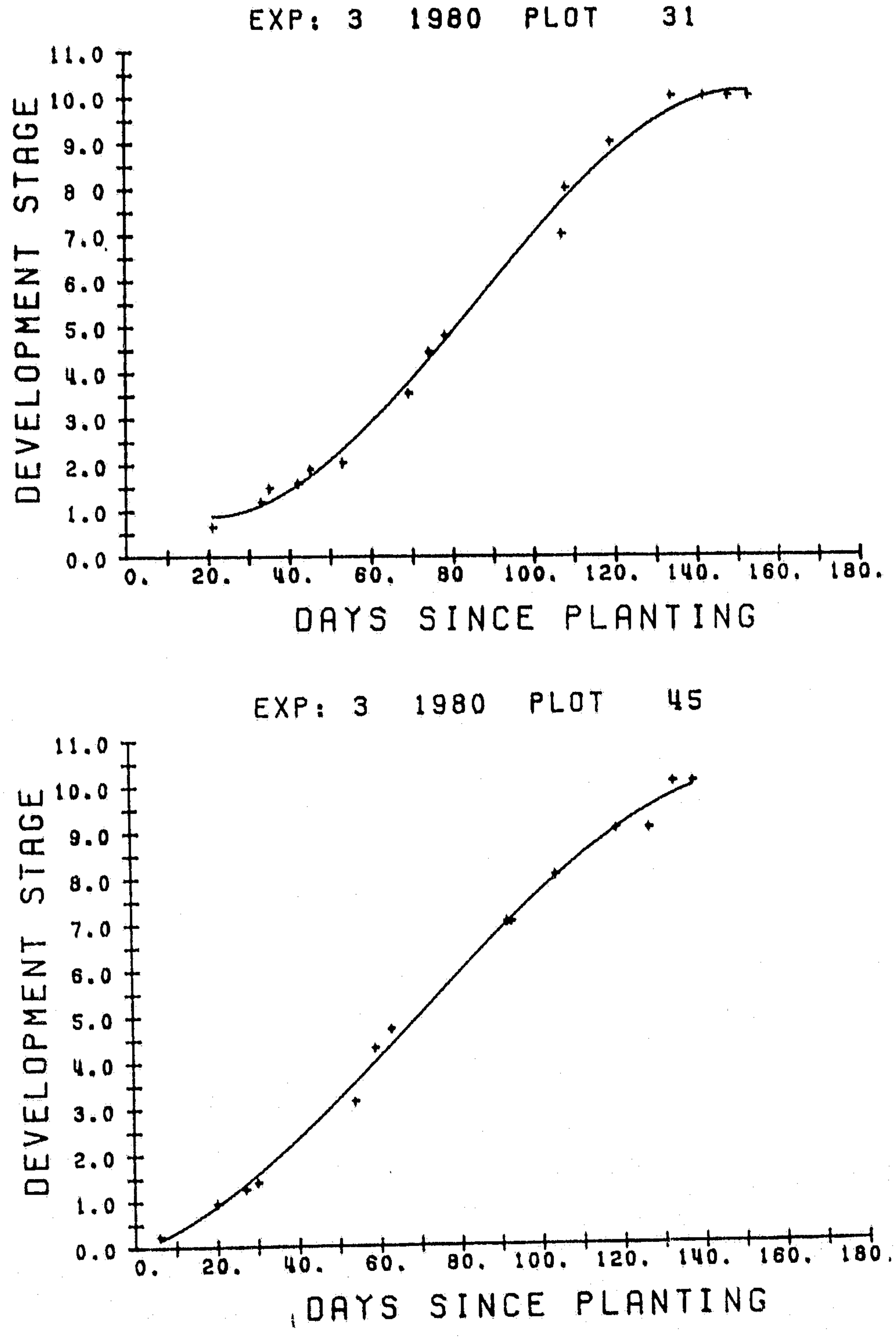

FIGURE 3. EXAMPLE DEVELOPMENT STAGE CURVES

3
RESULTS

Table 3 presents the mean stages associated with each of the spectral events of interest. Figures 4 through 10 show the corn model results and the stages of development for each of the plots. The time of peak Green Reflectance occurred around Stage 2.5 to 3, which corresponds to the tenth or twelfth leaf collar becoming visible (leaf fully emerged). Stage 3 occurs in the middle of the period of rapid growth and elongation of the stem, before all leaves are fully exposed to view [7]. This stage occurred, both in published data [7] and in the smoothed development stage data for the experimental plots, about two weeks prior to tassel emergence.

While a clear difference was apparent in stage of development at peak Green Reflectance between years, other confounding factors were also present. First, only two planting dates were common to both years. Second, planting dates and population densities were not equally represented in the data sets selected from the two years. As a result, no meaningful analysis of year effects could be carried out, and no significance can be attached to the observed differences.

Both planting date and population density had statistically significant (0.9 level) effects on development stage at the profile peak. In 1979, plots planted in early- and mid-May reached peak Green Reflectance at earlier stages than those planted in late May (Stages 2.55 and 2.70 compared to Stage 3.15), while in 1980, mid-May planting resulted in an earlier development stage at peak than that resulting from mid-June planting (Stage 2.8 compared to Stage 3.2). In both years, plots with populations of 50,000 plants per hectare reached peak Green Reflectance at a later stage than plots with 75,000 plants per hectare (1979: 3.0 vs. 2.6, 1980: 2.8 vs. 2.5).

TABLE 3. DEVELOPMENT STAGES AT KEY TIMES

		Mean Stage at:			
Data	# Plots	Peak Green Refl.	End of Plateau	First Half-Peak	Second Half-Peak
1979	16	2.68 ± .33	7.84 ± .65	1.92 ± .19	9.48 ± .52
1980	21	3.05 ± .37	7.90 ± .59	2.23 ± .23	8.96 ± .26
All	37	2.89 ± .40	7.87 ± .61	2.10 ± .26	9.18 ± .47

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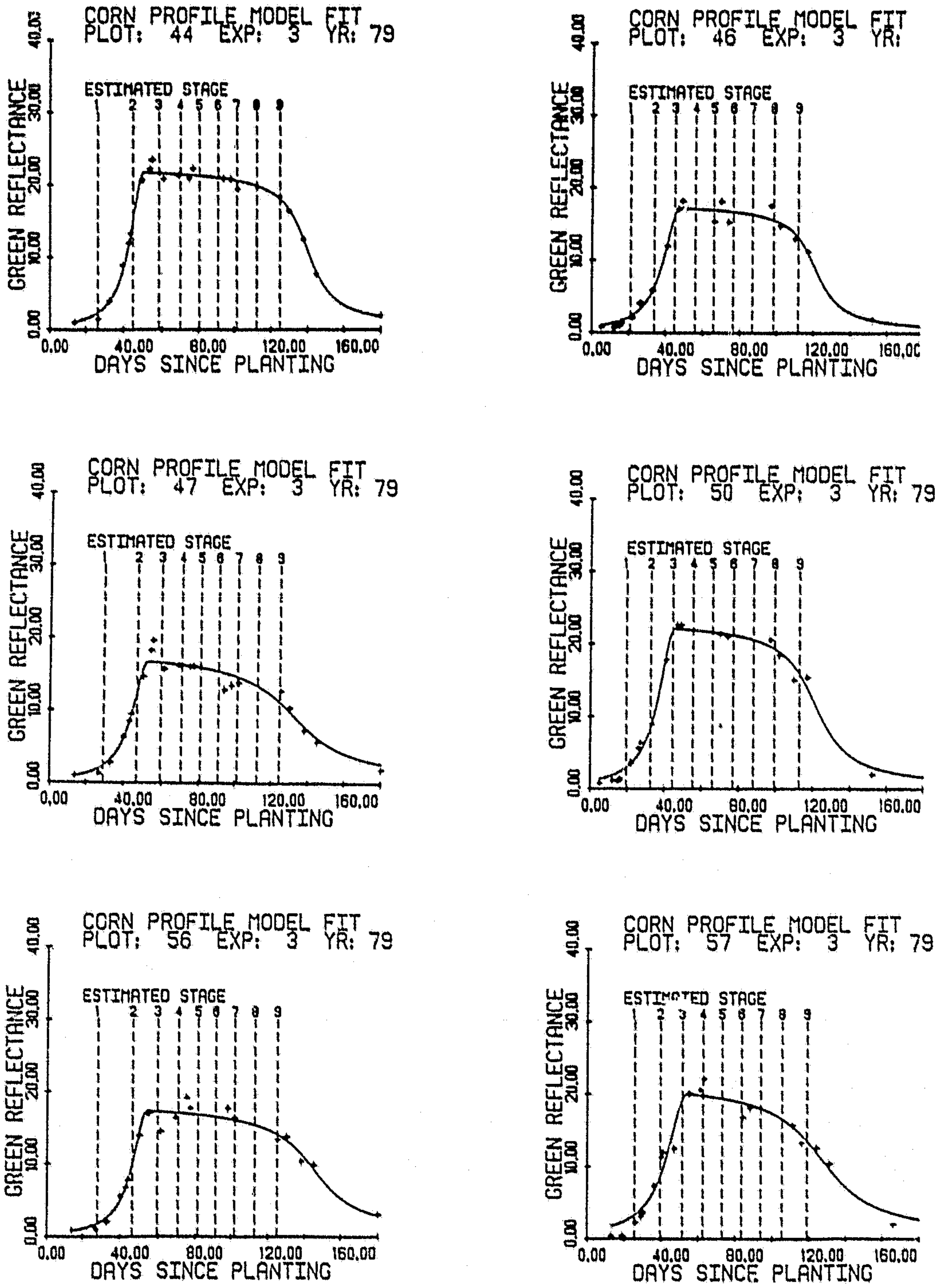

FIGURE 4. 1979 PLOT RESULTS

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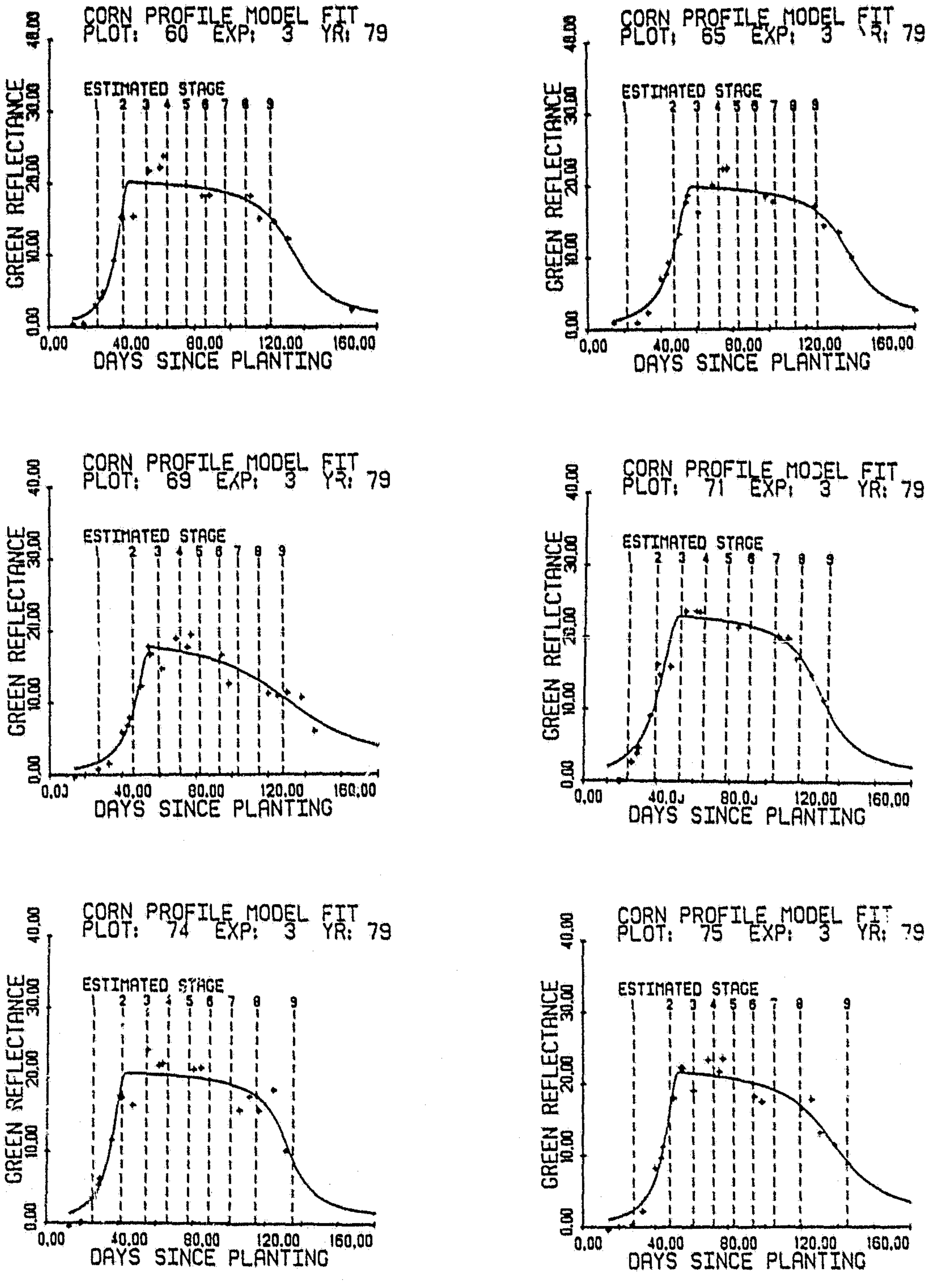

FIGURE 5. 1979 PLOT RESULTS (Continued)

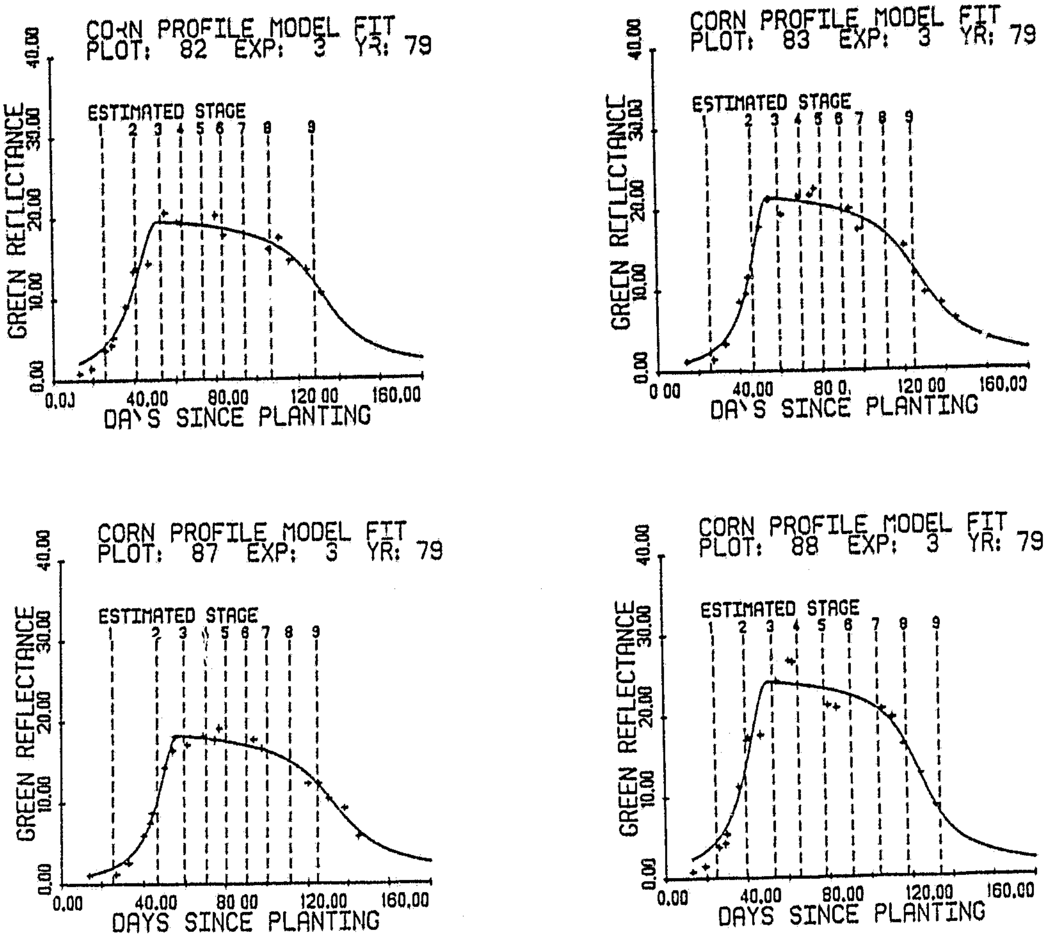

FIGURE 6. 1979 PLOT RESULTS (Continued)

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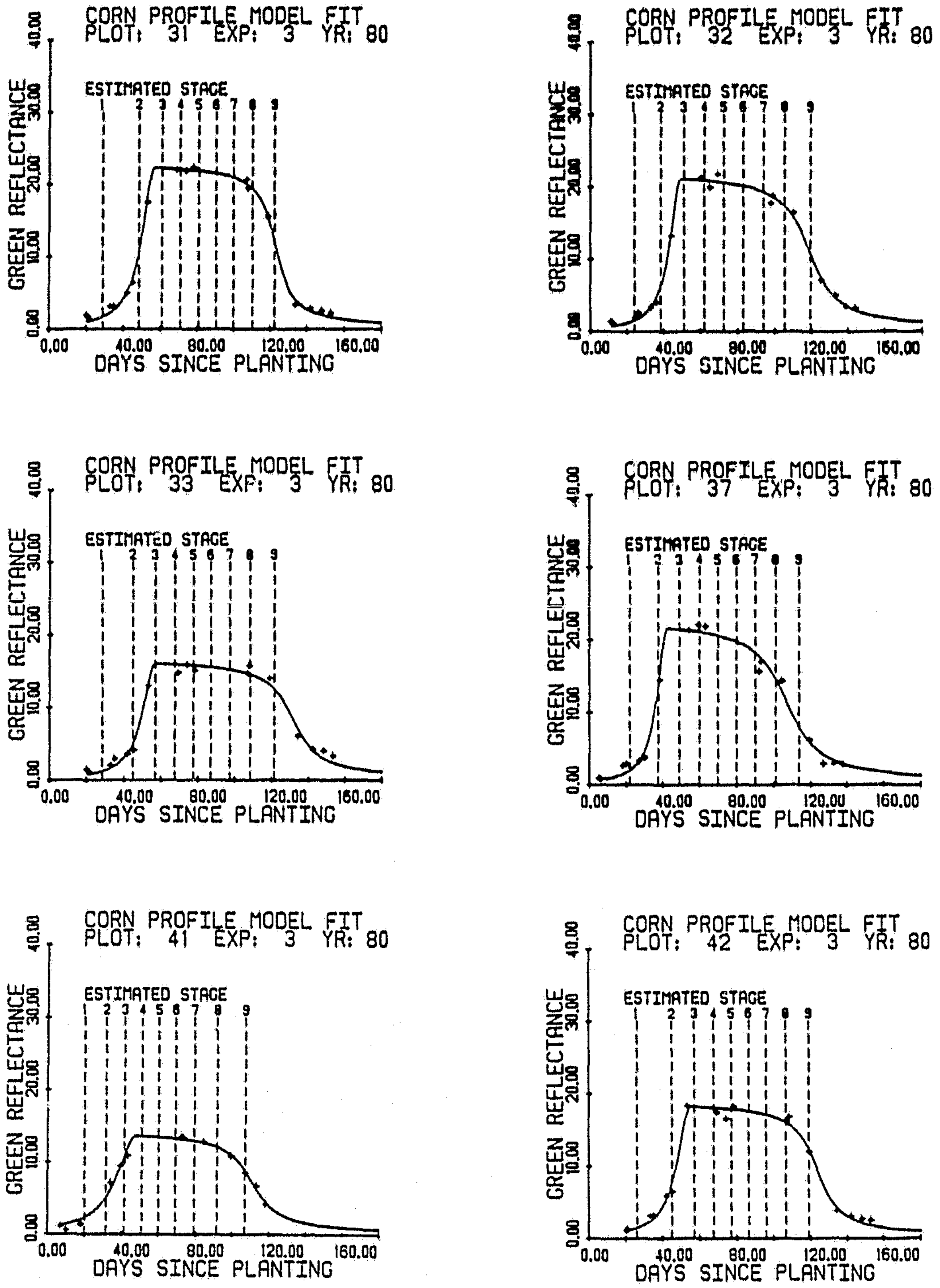

FIGURE 7. 1980 PLOT RESULTS

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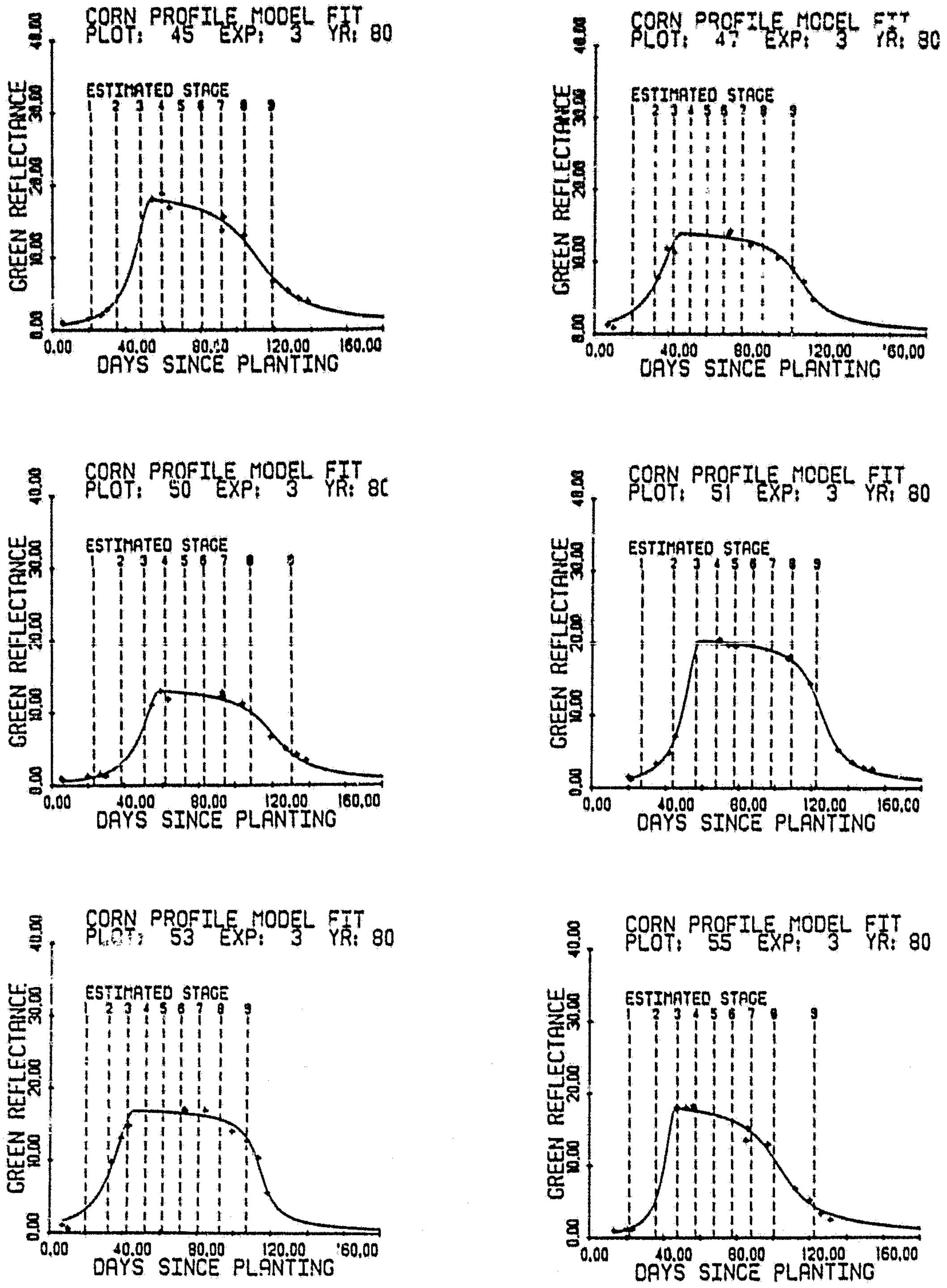


FIGURE 8. 1980 PLOT RESULTS (Continued)

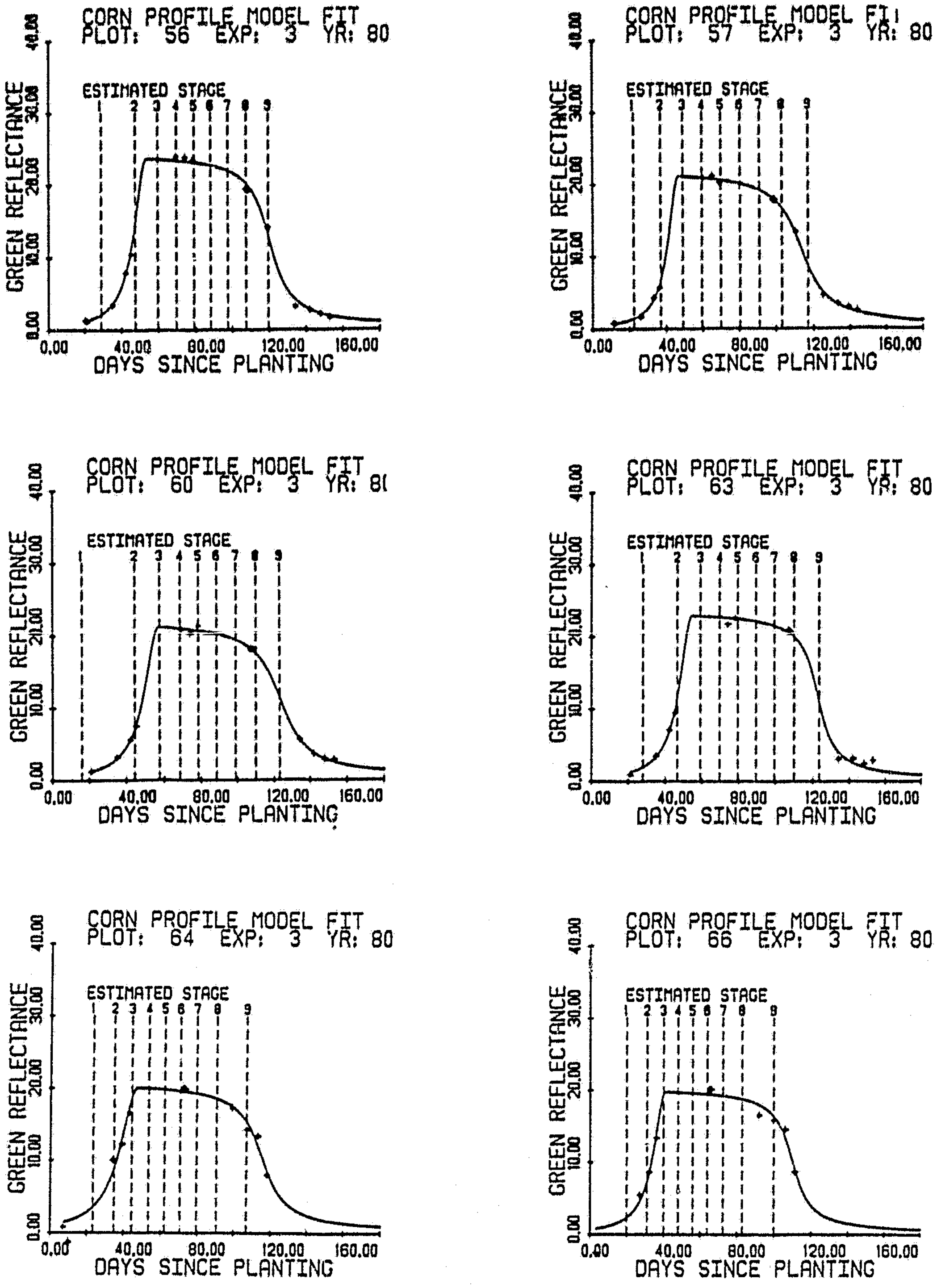
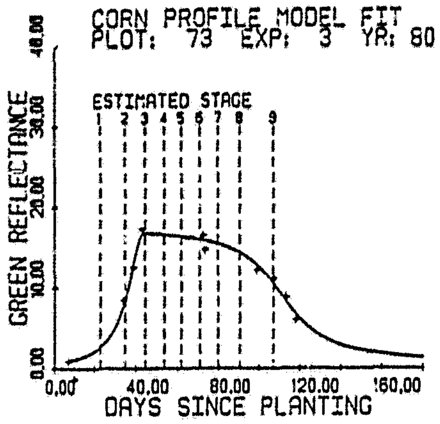
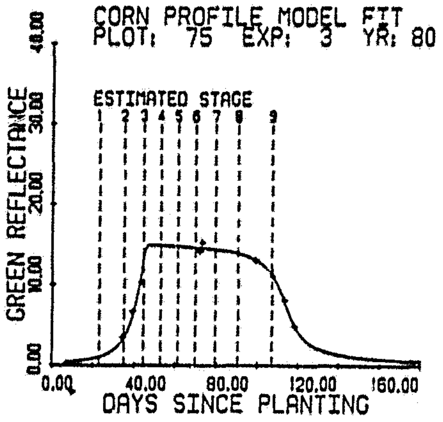


FIGURE 9. 1980 PLOT RESULTS (Continued)





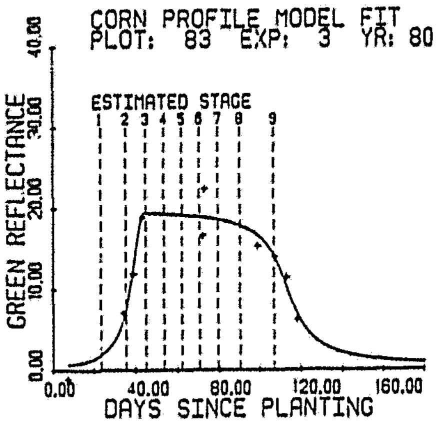


FIGURE 10. 1980 PLOT RESULTS (Continued)

The calculated plateau end, as described in Figure 1, occurred around Hanway Development Stage 8, the early dent stage, which occurs about 36 days after the beginning of rapid dry matter accumulation in the kernels. Development stage at the plateau end was not significantly affected by either planting date or population in 1979, or by plant population in 1980. Some significant effects of planting date were detected in the 1980 data, with mid-June planting resulting in a plateau end at a later development stage than that associated with early- to mid-May planting (8.3 compared to 7.9 and 7.6). An overall trend across the planting dates in 1980 was apparent, though not statistically significant. In general, stage at plateau end decreased from earliest to medium planting dates, and then increased again with later planting. This trend was seen in analysis of other profile features in the same data [3].

The remaining two features, the half-peak points, have a weaker connection to actual physiological or morphological characteristics, but do provide additional reference points in the profile. HP1, the first half-peak point, occurred around Stage 2, which corresponds to eight leaves fully emerged. HP2, the second half-peak point, occurred around Stage 9 to 9.5. Stage 9, the full dent stage, occurs about 12 days prior to physiological maturity.

In three of the 16 1979 plots (plot numbers 44, 56 and 65), and in several others not included in this analysis, Stage 9 occurred at or before the end of the plateau. Since Stage 9 is so near the end of the corn development cycle, one would expect Green Reflectance to have declined substantially from its maximum by this point, as was the case in most of the other plots. The plots in question all exhibited average intervals between estimated stages, apparently reasonable profile fits, and average stages of development at the profile peak, but had plateaus of longer-than-average duration. However, attempts to associate the unusual behavior with data smoothing, planting date, or plant population were unsuccessful, and its cause remains unexplained.

4

DISCUSSION

4.1 STAGE AT PEAK GREEN REFLECTANCE

Reports in the literature suggest that maximum leaf area index (LAI) occurs around the time of silking, or Hanway Stage 5 [4, 13, 15]. This stage occurred about three weeks after Stage 3 in the plots analyzed. Between Stages 2.5 or 3 and Stage 5, an additional eight to ten new leaves become fully emerged. Studies of reflectance properties of spring wheat and soybean canopies have shown very strong correlation between Green Reflectance and LAI [5, 10]. Nevertheless, the consistent result in this analysis is a peak in Green Reflectance well before the expected time of peak LAI.

Leaf area index data, although collected in both years, are too sparse to allow accurate determination of the time of peak in these experimental plots. However, the simple fact that only about half of the leaves are fully emerged by Stage 3 lends ample support to the contention that peak LAI occurs later. Clearly, then, some other factor or factors are causing Green Reflectance to peak at Stage 3 and then decline.

A number of factors may be responsible, at least in part, for the observed spectral behavior. The first has to do with the processes of stem and leaf elongation. Through the first several development stages, the actual stem height of the corn plant is substantially less than the total plant height. At Stage 1.5, when six leaves are fully emerged, the tip of the stem is only at or slightly above the soil surface [7]. At Stage 2, the beginning of the period of rapid stem elongation, the stem may comprise only about 10% of the total plant height, with the percentage increasing to about 50% by Stage 2.5, 75% at Stage 3, and essentially 100% by Stage 4 [9]. That portion of plant height above the stem is made up of leaves, either unfurled and arching upwards or still furled into what might be called a pseudostem. As a result, there is a relatively dense and pure layer of green leaves at the top of the canopy at Stages 2.5 and 3.

In addition, while LAI is reported to peak at Stage 5, leaf enlargement is complete by Stage 3 [7]. Additions to LAI after this time must be the result not of additional leaf biomass or area but rather of the unfurling of the remaining leaves in the pseudostem. While furled, the leaves lack at least some of their green color [7], but should exhibit the same infrared reflectance properties as unfurled leaves. Thus at Stages 2.5 or 3, nearly all the green leaf area is present, and packed in a narrow layer at the top of the canopy. The high transmissivity of green leaves in the near-infrared will allow even those leaves that are still furled to contribute to IR-reflectance, and thus to Green Reflectance. At later stages, the leaf area is spread through a deeper, less dense layer, and more of the total leaf area is subject to shadowing by the stem, which is highly reflective but has little or no transmittance.

Another influence on the Green Reflectance of the corn canopy is the angular orientation of the leaves. Loomis, et al., [11] measured the angular orientation of that portion of the leaf area intercepting 90% of the incoming radiation, and reported an increase in vertical orientation in the interval between Stages 3 and 4 as compared to the interval between Stages 2 and 3. There is also, however, an increase in LAI between these two intervals. The effect of increased leaf droop, then, will depend on the relative changes in leaf angular orientation and LAI. If the drooping of leaves, even with an increase in LAI, reduces the percent cover in the scene, then Green Reflectance should decline. This effect of leaf droop has been demonstrated with modeling [14]. Unfortunately, the percent cover data collected for the LARS experimental plots is too sparse to allow precise determination of the effects of leaf droop. However, no strong indication of a reduction in percent cover between Stages 3 and 4 is evident.

Finally, the emergence of the tassels, which begins at Stage 4 and is completed a few days before Stage 5 [7], introduces a new element into the top layer of the canopy. Duncan, et al., [6] measured the proportion of incoming radiation intercepted by tassels in plots with a wide range of population densities. For densities corresponding to those in the LARS experiments, the tassels were found to intercept 5 to 12% of the total radiation. Tassels, like stems, should exhibit low transmittance and cast significant shadows in both the visible and infrared wavelengths. Inclusion of tassels in a corn canopy reflectance simulation caused a substantial decrease in IR-reflectance, and a less severe drop in visible reflectance [12], which would result in a lower Green Reflectance value.

The actual cause of the unexpectedly early peak in Green Reflectance and its subsequent gradual decline may be any or all of these factors, others not considered, or some combination thereof. Final determination of the cause will require more frequent and detailed field measurements of the spectral and canopy geometric properties of corn plots and/or use of a simulation system that links an appropriate corn development model with a canopy reflectance model.

4.2 STAGE AT PLATEAU END

Explanation of the development stage associated with the end of the plateau is less challenging. First, the determination of plateau end is much less precise than determination of the time of peak Green Reflectance. In light of this fact, one cannot expect, and should not attach, too much significance to the precise stage associated with the plateau end. It appears that the plateau end, the initiation of more rapid decline in Green Reflectance, occurs in response to the rapid dry matter accumulation in the kernels. The lag between initiation of kernel dry matter accumulation and plateau end can be explained by the fact that senescence progresses from the bottom of the plant to the top, and some time would be expected to pass before the senescence of the canopy exerted any significant effect on its Green Reflectance.

5

CONCLUSIONS

The association of spectral and developmental events as described in the previous section allows us to formulate a description of the spectral development of a typical corn field. Stated in terms of Green Reflectance, and based on data for Indiana corn plots, the general pattern should nevertheless hold for Landsat-MSS Greenness, and for corn grown in other locations, although regional variations, particularly in the time interval between planting and the various development stages, should be expected. By Stage 2 (eight leaves fully emerged), five to six weeks after planting, the field has attained half its maximum Green Reflectance, and thus should be clearly distinguishable. The addition of leaves continues to increase the Green Reflectance value until Stage 2.5 to 3 (ten to 12 leaves fully emerged), six to eight weeks after planting, where a peak in Green Reflectance is achieved. From this point Green Reflectance declines slowly, even though eight to ten additional leaves are added to each plant. The decline may be explained by a sequence of factors. From the peak until the point of tassel emergence, one and one-half to two weeks later, the leaves in the canopy droop more, reducing their horizontal area, and the progression of stem extension spreads the leaves over a larger vertical portion of the canopy, as well as casting more shadows on the green leaf surfaces. The emergence of the tassels, beginning at Stage 4, introduces a new canopy component which intercepts a considerable amount of incoming radiation, and thus further increases shadowing on the green leaves. One or two weeks after the beginning of rapid dry matter accumulation by the kernels (and 13 to 17 weeks after planting), the Green Reflectance of the field begins to decline more rapidly - a sign of advancing senescence. However, by Stage 9 (full dent stage), only about two weeks prior to physiological maturity, the Green Reflectance of the field is still at half its maximum value.

It should be remembered that several smoothing operations were involved in achieving the results as described. The conversion from text to numerical descriptions of development stages, the polynomial smoothing of the resultant data, and the use of the corn profile model to smooth the spectral observations, could each introduce a degree of error in the final result. Thus it would be irresponsible to conclude from this study that, for example, corn Green Reflectance peaks at exactly Stage 2.9, or that any of the spectral events occur exactly at any development stages. However, more general but no less important conclusions can be drawn. In particular, the strong indication that the peak in the Green Reflectance profile of corn occurs well before the expected peak in leaf area index, and also before tasseling, is an unexpected and significant result. This finding, and the general relationship between spectral and morphological/physiological development as described, can provide valuable insight to both crop identification and crop condition assessment research. More quantitative evaluation of the causes for the observed phenomena, as through the use of simulation and/or more detailed field measurements, could provide still further insight into this relationship, and thus further increase our ability to accurately detect and evaluate agricultural crops from space.

REFERENCES

1. Bauer, M. E., L. L. Biehl, C. S. T. Daughtry, B. F. Robinson and E. R. Stone. Agricultural Scene Understanding and Supporting Field Research. NASA Report SR-P9-00410. Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, IND, 1979.

2. Bauer, M. E., L. L. Biehl and B. F. Robinson. Field Research on the Spectral Properties of Crops and Soils. NASA Report SR-P0-04022. Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, IND, 1980.

3. Crist, E. P. Cultural and Environmental Effects on the Spectral Development Patterns of Corn and Soybeans - Field Data Analysis. NASA Report SR-E2-04224. Environmental Research Institute of Michigan, Ann Arbor, MI, 1982.

4. Dale, R. F., D. T. Coelho and K. P. Gallo. "Prediction of Green Leaf Area Index for Corn." Agronomy Journal, 72:999-1005, 1980.

5. Daughtry, C. S. T., M. E. Bauer, D. W. Crecelius and M. M. Hixson. "Effects of Management Practices on Reflectance of Spring Wheat Canopies." Agronomy Journal, 72:1055-1060, 1980.

6. Duncan, W. G., W. A. Williams and R. S. Loomis. "Tassels and the Productivity of Maize." Crop Science, 7:37-39, 1967.

7. Hanway, J. J. "Growth Stages of Corn (*Zea Mays*, L.)." Agronomy Journal, 55:487-492, 1963.

8. Kauth, R. J., P. F. Lambeck, W. R. Richardson, C. S. Thomas and A. P. Pentland. "Feature Extraction Applied to Agricultural Crops as Seen by Landsat." Proceedings of the Technical Sessions, Vol. II, the LACIE Symposium. JSC 16015, NASA Johnson Space Center, Houston, TX, 1979.

9. Kiesselbach, T. A. Progressive Development and Seasonal Variations of the Corn Crop. University of Nebraska, Agricultural Experiment Station, Lincoln, NEB, Research Bulletin 166, 1950.

10. Kollenkark, J. C., C. S. T. Daughtry and M. E. Bauer. Soybean Canopy Reflectance as Influenced by Cultural Practices. NASA Report SR-P1-04038. Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, IND, 1981.

REFERENCE (Continued)

11. Loomis, R. S., W. A. Williams, W. G. Duncan, A. Durant and F. Nunez A. "Quantitative Descriptions of Foliage Display and Light Interception in Field Communities of Corn." Crop Science, 8:352-356, 1968.

12. Malila, W. A. Information Extraction and Multi-aspect Techniques in Remote Sensing. Ph.D. Dissertation, The University of Michigan, Ann Arbor, MI, 1974.

13. Rosenthal, W. D., E. T. Kanemasu, R. J. Raney and L. R. Stone. "Evaluation of an Evapotranspiration Model for Corn." Agronomy Journal, 69:461-464, 1977.

14. Suits, G. H. "The Calculation of the Directional Reflectance of a Vegetative Canopy." Remote Sensing of Environment, 2:117-125, 1972.

15. Williams, W. A., R. S. Loomis, W. G. Duncan, A. Durant and F. Nunez A. "Canopy Architecture at Various Population Densities and the Growth and Grain Yield of Corn." Crop Science, 8:303-308, 1968.