SR-E2-04224
NAS9-15476

E82-10258

NASA-CR-167578

# AgRISTARS

A Joint Program for
Agriculture and
Resources Inventory
Surveys Through
Aerospace
Remote Sensing
January 1982

Supporting Research

TECHNICAL REPORT

# CULTURAL AND ENVIRONMENTAL EFFECTS ON THE SPECTRAL DEVELOPMENT PATTERNS OF CORN AND SOYBEANS — FIELD DATA ANALYSIS

E.P. Crist

(E82-10258) CULTURAL AND ENVIRONMENTAL EFFECTS ON THE SPECTRAL DEVELOPMENT PATTERNS OF CORN AND SOYBEANS: FIELD DATA ANALYSIS Technical Report, 15 Nov. 1980 - 14 Nov. 1981 (Environmental Research Inst. of
N82-24536
HC A04/MF A01
Unclas
G3/43 00258

ERIM
ENVIRONMENTAL RESEARCH
INSTITUTE OF MICHIGAN
ANN ARBOR, MICHIGAN

UCB
SPACE SCIENCES LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA

UNITED STATES DEPARTMENT OF AGRICULTURE

NASA

DEPARTMENT OF COMMERCE UNITED STATES OF AMERICA

U.S. DEPARTMENT OF THE INTERIOR MARCH 3, 1849

UNITED STATES OF AMERICA

# NOTICES

Sponsorship. The work reported herein was conducted by the Environmental Research Institute of Michigan under Contract NAS9-15476 for the National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas 77058. I. Dale Browne was Technical Monitor for NASA. Contracts and grants to the Institute for the support of sponsored research are administered through the Office of Contracts Administration.

Availability Notice. Request for copies of this memorandum should be referred to:

National Aeronautics & Space Administration
Scientific & Technical Information Facility
P.O. Box 33
College Park, Maryland 20740

TECHNICAL REPORT STANDARD TITLE PAGE

| | | |
|---|---|---|
| 1. Report No.<br>SR-E2-04224 | 2. Government Accession No. | 3. Recipient's Catalog No. |

| | |
|---|---|
| 4. Title and Subtitle<br>Cultural and Environmental Effects on the Spectral Development Patterns of Corn and Soybeans - Field Data Analysis | 5. Report Date<br>January 1982<br>6. Performing Organization Code |
| 7. Author(s)<br>E. P. Crist | 8. Performing Organization Report No.<br>152400-20-T |
| 9. Performing Organization Name and Address<br>Environmental Research Institute of Michigan<br>Infrared and Optics Division<br>P.O. Box 8618<br>Ann Arbor, Michigan 48107 | 10. Work Unit No.<br>11. Contract or Grant No.<br>NAS9-15476 |
| 12. Sponsoring Agency Name and Address<br>NASA/Johnson Space Center<br>Houston, Texas 77058<br>ATTN: I. Dale Browne/SG3 | 13. Type of Report and Period Covered<br>Technical Report<br>15 November 1980 -<br>14 November 1981<br>14. Sponsoring Agency Code |

15. Supplementary Notes

Dr. Glen Houston/SG3 served as NASA Technical Coordinator of the effort, which was carried out as a part of the Supporting Research Project of the AgRISTARS program.

16. Abstract

An overall approach to crop spectral understanding is presented which serves to maintain a strong link between actual plant responses and characteristics and spectral observations from ground-based and spaceborne sensors. A specific technique for evaluating field reflectance data, as a part of the overall approach, is also described. Results of the application of this technique to corn and soybeans reflectance data collected by and at Purdue/LARS indicate that a number of common cultural and environmental factors can significantly affect the temporal-spectral development patterns of these crops in Tasseled-Cap Greenness (a transformed variable of Landsat MSS signals).

| | |
|---|---|
| 17. Key Words<br>Profiles, Crop Spectral Characteristics, Crop Identification, Corn, Soybeans, AgRISTARS | 18. Distribution Statement |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
| Unclassified | Unclassified | xii + 69 | |

SR-E2-04224
NAS9-15476

TECHNICAL REPORT

# CULTURAL AND ENVIRONMENTAL EFFECTS ON THE SPECTRAL DEVELOPMENT PATTERNS OF CORN AND SOYBEANS - FIELD DATA ANALYSIS

By

E. P. Crist

This report describes results of research carried out in support of the Scene Simulation and Analysis Element of the Supporting Research Project.

Environmental Research Institute of Michigan
P.O. Box 8618
Ann Arbor, Michigan 48107

January 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 work reported herein was sponsored by the Supporting Research (SR) Project under the auspices of the National Aeronautics and Space Administration, NASA. Mr. Robert B. MacDonald, NASA Johnson Space Center, was the NASA Manager of the SR Project and Dr. Glen Houston was the Technical Coordinator for the reported effort.

The Environmental Research Institute of Michigan and the Space Sciences Laboratory of the University of California at Berkeley comprised a consortium having responsibility for development of corn/soybeans area estimation procedures applicable to South America within both the Supporting Research and Foreign Commodity Production Forecasting Projects of AgRISTARS.

This reported research was performed within the Environmental Research Institute of Michigan's Infrared and Optics Division, headed by Richard R. Legault, a Vice-President of ERIM, under the technical direction of Robert Horvath, Program Manager, and Dr. William A. Malila, Task Leader.

# TABLE OF CONTENTS

Section Page

## LIST OF ILLUSTRATIONS

## LIST OF TABLES

# 1

# INTRODUCTION

The evaluation of crop spectral characteristics as viewed by Landsat is hindered by a number of largely external factors. First, atmospheric effects, illumination geometry, and similar phenomena result in variations in signal values entirely removed from the characteristics of the crop being viewed. Second, misregistration and ground truth errors can create substantial problems with regard to obtaining a pure sample of a crop. Third, and for the present purpose most important, environmental conditions, cultural practices used, crop development stages, and similar pieces of data are unavailable and/or imprecise for the majority of Landsat data.

As a result of all these factors, conclusions drawn with regard to crop spectral characteristics, crop separability, or classification techniques which are based largely or entirely on Landsat data will be extremely dependent on the particular set of data employed. A better approach to deriving information about crop appearances in Landsat data is to begin as close to the plants themselves as possible and, in effect, to step back by increments, moving farther away from the plants or field at each increment, but utilizing the results of the previous higher-resolution steps as a context in which to evaluate information obtained at the present level.

This approach recognizes that the basic elements of interest in classification or interpretation of Landsat data for agricultural applications are not pixels, but rather collections of biological entities. The better we understand workings at the plant or plant population level, the better able we will be to understand and utilize Landsat data in deriving crop-related information.

In practice, this approach to crop spectral understanding consists of some or all of the following steps:

1) Determining relevant physiological, cultural, and environmental influences on those characteristics of plants or plant populations likely to influence their spectral appearance. This involves review of literature in the field of agronomic research and, frequently, gleaning of pertinent information from reports of experiments whose purposes are far removed from remote sensing interests.

2) Modeling the effects of these influences on crop spectra. A model such as that described in Reference [26] provides a means of assessing the spectral expression of particular changes in crop characteristics while keeping all other factors constant.

3) Evaluating field reflectance data to determine or confirm the effects of key factors on crop spectral characteristics. This step provides the crucial link between the modeled data and the real world, but maintains a fairly high degree of control over confounding effects. Results of modeling, and the plant-level information gathered at earlier steps, provide a context in which to understand the results obtained through field data analysis.

4) Evaluating Landsat data to adjust expectations and conclusions formulated at the other levels. Having established a foundation and context through the previous analyses, one can analyze Landsat data, in conjunction with whatever associated information is available (crop labels, weather data, etc.), and better understand and explain what is seen there. The quantitative results of the previous levels are combined with a Landsat data set that is probably larger, more geographically widespread, and more variable in terms of crop mix and growing conditions, to allow more comprehensive evaluation of crop spectral characteristics.

The following sections describe some results from the initial phases of this approach, namely, the review of agronomic research results, and the evaluation of field reflectance data.

# 2

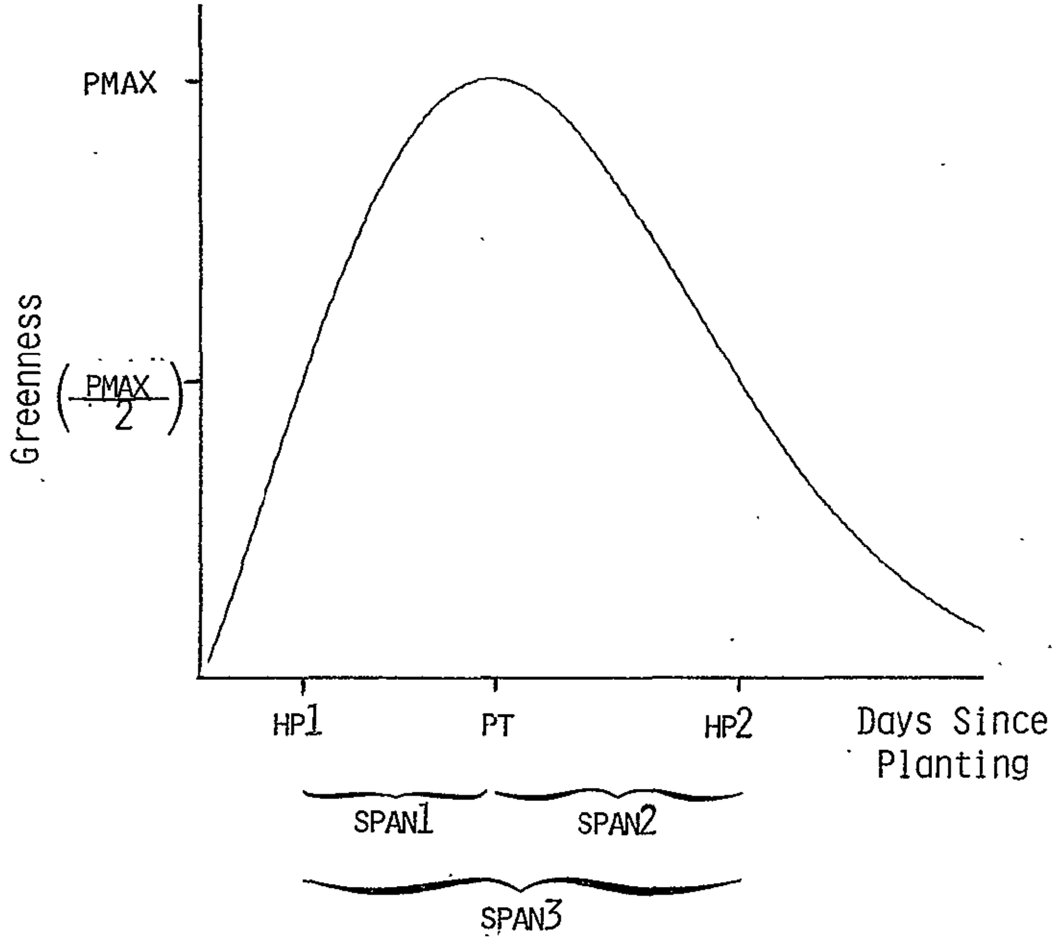
# TECHNIQUE FOR ANALYSIS OF CROP SPECTRAL DEVELOPMENT PATTERNS

Analysis of crop spectral data collected at discrete intervals, and particularly at irregular discrete intervals, is often restricted by the absence of observations at key times in the crop development cycle. In addition, comparison of data from different plots or locations is hindered by the temporal mismatch of observations between plots. Even when all plots are observed on the same days, planting date differences cause a mismatch of data with respect to some sort of 'effective day' time scale (e.g., days since planting). In order to make meaningful comparisons among several plots, some method must be devised by which the spectral characteristics of the plots may be described in a standard fashion.

The technique developed at ERIM for this purpose consists of two elements: a standard set of features, and a curve-fitting technique for deriving those features for any particular plot.

## 2.1 PROFILE FEATURES

Analyses carried out in FY81 used Tasseled-Cap Greenness as the spectral variable. The Tasseled-Cap transformation of Landsat MSS data and its adaptation to reflectance data are described in Section 3. Figure 1 shows a typical, simple Greenness profile, and illustrates the set of features used in the analyses. These features represent a basic set of parameters to describe any simple curve of more or less a bell shape. Particular crops may warrant additional features, although this standard set should still be appropriate. For example, corn data tend to appear as a flattened bell shape (Figure 2). This



| Feature | Description | Associated Agronomic Characteristic |
|---|---|---|
| PMAX | Maximum profile value | Maximum amount of green vegetation |
| PT | Time of PMAX | Rate of vegetative growth |
| HP1 | Time of first half-peak | Rate of emergence and early vegetative growth |
| SPAN1 | Time from HP1 to PT | Rate of later vegetative growth |
| HP2 | Time of second half-peak | Rate of development from planting to senescence (overall development time) |
| SPAN2 | Time from PT to HP2 | Rate of senescence |
| SPAN3 | Time from HP1 to HP2 | Rate of development after emergence |

FIGURE 1. GREENNESS PROFILE FEATURES

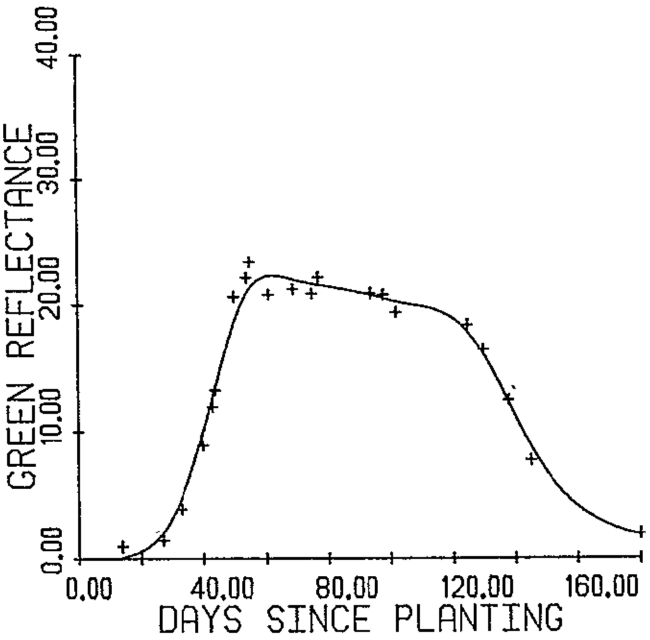


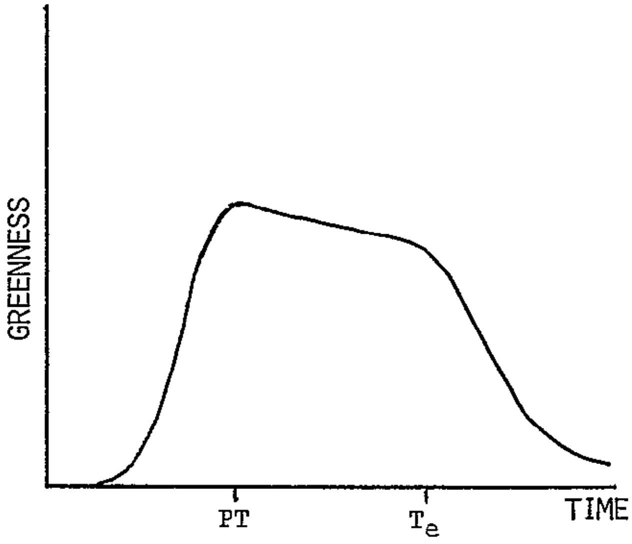
FIGURE 2. TYPICAL CORN GREENNESS PROFILE SHAPE

shape has been observed both in spectral data [9,24] and in other agronomic variables correlated to Greenness (e.g., Leaf Area Index [17]). While additional features were not used in the analyses described in Section 3, some possible additional features are described in Figure 3. Use of a spectral variable other than Greenness would simply require that a new set of features be defined.

## 2.2 CURVE-FITTING TECHNIQUE

In order to use the profile features just described, the intermittent spectral observations must be transformed into a smooth, continuous curve. At least three approaches could be taken at this point. First, data points could be connected by a series of straight lines or curves. However, the impact of data variations associated not with the field or plot being observed but rather with observation conditions themselves would not be reduced at all by such an approach, and would likely have a substantial impact on the derived profile features. Thus it is desirable to somehow reduce or remove the data variation associated with external influences. These influences, which include sun elevation, sun azimuth, atmospheric conditions, viewing location (elevation and azimuth), and wind, cause no changes in the actual reflectance of scene components, but rather affect the relative mix of those components (leaves, stems, soil, etc.) in the field of view, and the degree to which they are illuminated. Some work has been done to empirically model the effects of certain of these influences in reflectance data [9], but most are complex enough, and even more so when several occur together, that smoothing of data solely through empirical models is impractical, at least at this time.

A third approach which offers some smoothing without the complexity of the modeling approach is the use of a curve-fitting function to derive a new set of smoothed data based on the original observations.



1) $T_e$ = Time of plateau end

2) Duration of plateau = $T_e$ - PT

3) Slope of plateau = $\frac{\text{PMAX} - G(T_e)}{\text{PT} - T_e}$

FIGURE 3. ADDITIONAL FEATURES FOR CORN GREENNESS PROFILE ANALYSIS

As long as one can be reasonably confident that the majority of data taken over a particular plot are free from major external effects, that is, that the outliers in a set of observations are the contaminated rather than the pure data, then a curve-fitting technique can provide some less-precise correction of major externally-induced variations.

Work toward selecting a smoothing technique involved less an exhaustive evaluation of all possible approaches and more an evaluation of a few particular techniques which were readily available and comprised something of a sample from the range of possible approaches. Because the corn Greenness profile is a more complex shape and therefore a more challenging problem for curve-fitting, corn data were used in the comparison of curve-fitting approaches. The simpler nature of the soybean Greenness profile can be well described with a number of techniques.

Probably the simplest technique considered was a curvilinear regression model using orthogonal polynomials. This technique (represented by the IMSL routine RLFOTH [31] uses a model of the form

$$Y = C_o + C_1X + C_2X^2 + \dots + C_dX^d \tag{1}$$

and computes coefficients ($C_0 \dots C_d$) which provide the best fit to the data.

A second more sophisticated approach involves the use of cubic splines. Here the model form is

$$S_i = C_{j,3}*D + C_{j,2}*D + C_{j,1}*D + Y_j \tag{2}$$

where $D = U_i - X_j$

$U_i$ is in $[X_j, X_{j+1}]$

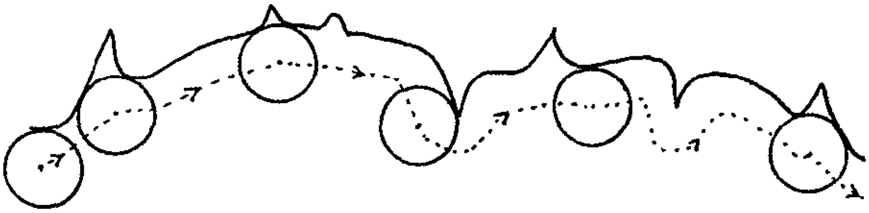
and $C_{1,1} \dots C_{n,3}$ are the coefficients of the spline in the interval $[X_1, X_n]$

Two routines utilizing cubic splines were considered. The first produces a least squares approximation using variable knots whose starting locations are specified by the user. The IMSL routine ICSVKU was used for this purpose [31]. The second routine, also in the IMSL package (ICSSCU) [31], places greater emphasis on producing a smooth curve, by balancing a smoothness function against a goodness-of-fit criterion [18]. This routine requires that a smoothing parameter be set by the user, but utilizes the data points themselves as knots.

A third technique considered was the Rolling Ball algorithm, a non-linear filtering technique developed at ERIM for three-dimensional processing in biomedical applications [40]. While the reference cited provides a detailed technical description of the algorithm, an intuitive description will suffice here. The algorithm can be thought of as rolling a sphere (or a disc in two dimensions) under a surface. The new curve is defined by the center of the ball as it rolls. Thus spikes in the data will be smoothed out if the ball diameter is such that it cannot roll into the opening created by the spike. Subsequent steps adjust for the offset resulting from this first roll. Figure 4 illustrates the concept. In practice, a set of spheres or discs of increasing diameter is used to achieve the desired degree of smoothing. Among the advantages of this approach are its ability to essentially ignore data spikes (as opposed to most other techniques which will produce curves that are bent somewhat toward such deviant points), and its ability to fit sudden changes in data values without "ringing".

In the current application, it was necessary to interpolate between the data points in order to obtain a continuous curve which could then be smoothed with the Rolling Ball algorithm. For this purpose, an interpolation method devised by Akima [1] was used, as implemented in the IMSL routine IQHSCU [31].

a) Original Data Curve



b) First roll - resultant curve is trace of ball's center.

c) Final curve - ball has been rolled from below and above curve, with correction for offset of ball's radius

FIGURE 4. THE ROLLING BALL ALGORITHM

Finally, two profile models were used. Such models have the advantage of providing a means to interpolate over large data gaps, and to restrict, to some degree, the nature of the curve produced. These same characteristics, however, make profile models less flexible and more crop-type dependent than other curve-fitting techniques. The first model, of the form

$$G(t) = at^{b}e^{ct^{2}} \qquad [14] \qquad (3)$$

where $G(t)$ = Greenness at time t

$a,b,c$ = model parameters

or

$$\rho(t) = \rho_s(t_o)(t/t_o)^{\alpha}e^{[\beta(t_o^{2} - t^{2})]} \qquad [5] \qquad (4)$$

where $\rho(t)$ = Greenness at time t

$\rho_s(t_o)$ = Greenness value at spectral emergence time $t_o$,

$\alpha,\beta$ = model parameters

was originally developed for use with small grains data, although the latter version has also been applied to corn and soybeans [6]. Equation (3) was used in the analyses reported here.

A second model was developed at ERIM specifically for corn data, and was intended to provide a first-cut mechanism for characterizing the flattened peak described earlier. This model is of the form

$$G(t) = \begin{cases} \dfrac{A}{1 + Q^{2}(t-t_p)^{2}}\,; & t \leq t_p \\[2ex] \dfrac{(A-25)*g(\alpha,\Delta)}{\pi}\,(\cot^{-1}[\alpha(t-t_p - \Delta)]) + 25; & t > t_p \end{cases} \qquad (5)$$

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 (1/HP1)

$\alpha$ = controlling factor for shape after peak (flatness of peak, steepness of decline)

$\Delta$ = time from peak to second half-peak (HP2)

and

$$g(\alpha,\Delta) \equiv \pi/\cot^{-1}(-\alpha*\Delta)$$

(provides continuity at $t = t_p$)

and will be referred to as the five-parameter or Corn model (the previous model being referred to as the three-parameter or Wheat model).

Several evaluations of the described techniques were carried out. All the techniques were applied to the set of corn reflectance data described in Table 1 of Section 3 (118 total plots from three years), with the previously described set of profile features computed in each case. Evaluation criteria included:

1) Ability to operate on the data. Because of the occurrence of plots with unusually noisy or sparse data, the techniques had to be robust and able to yield usable results in most such cases.

2) Ability to detect significant differences in profile features resulting from experimental treatments. Since this is the final goal of the curve-fitting approach being outlined in this section, it was important to detect those techniques that were less sensitive than others to plot variations.

3) Ability to characterize the flattened peak of corn Greenness profiles. The flattened peak or "plateau" of corn Greenness is not only one of the most distinctive spectral features of the crop, but one of the most difficult to extract with a curve-fitting approach. The ability of various techniques to catch this feature was determined through visual analysis of results, as well as through the evaluation of residual errors.

4) Residual errors. Particularly when data smoothing is the goal, a strict evaluation of residual errors is not justified - a smoothing technique will almost by definition produce some residual errors. However, systematic residual errors would suggest that a particular technique was incorrectly characterizing some portion of the spectral development pattern.

5) Overall quality of fit. General visual analysis of results provided a means of assessing the ability of the techniques to produce "reasonable" results. This analysis included looking for curve variations that might be mathematically but not biologically supportable, checking the quality of interpolations across large gaps in the data, etc.

It should be noted that the spline techniques and the Rolling Ball algorithm, as well as the polynomial technique to some extent, are usually used in an interactive mode, with parameters tuned for each individual curve fit. However, to be of use in the evaluation of many plots (as in this application), the techniques must be automated. Thus the degree of the polynomial, number and spacing of knots, smoothing parameter, and ball diameter sequence were all fixed, based on results of a more intensive interactive application of the techniques to a subset of the data.

## Comparison of Techniques

While all the techniques tended to detect most of the same treatment effects in the profiles, the profile models, or at least the nonlinear least squares technique used to fit them, were more likely to fail in attempting to fit a curve to any particular data set. All the other techniques successfully fit most or all of the data. Figure 5 provides an example of results obtained using the six curve-fitting techniques on the same set of data. These data provide a clear example of the flattened peak of corn, and include observations spaced throughout the growing period of the crop. The results displayed illustrate many of the findings of the curve-fitting comparison.

First, both polynomial regression and least squares approximation by cubic splines with variable knots tended to catch some of the flatness, but included extra loops or dips, particularly in the tails of the profile. Reducing the complexity of the curves (degree or number of knots) eliminated these extra slope inflections, but also reduced the ability of the functions to reproduce the flattened peak.

The Rolling Ball algorithm avoided the dips or ringing at the tails, but tended to smooth out the fairly sharp corners associated with the beginning of the flattened peak. The five-parameter or Corn model, on the other hand, tended to produce too sharp a corner and, in addition, tended to overestimate data values early in the season (not as clearly illustrated in this particular plot). The simple three-parameter or Wheat model failed to provide a flattened curve, since it has no mathematical mechanism to allow for such a result.

Of the six techniques evaluated, the cubic smoothing spline algorithm produced the most intuitively appealing results, captured the flattened peak most often, and accurately fit the data throughout the season.

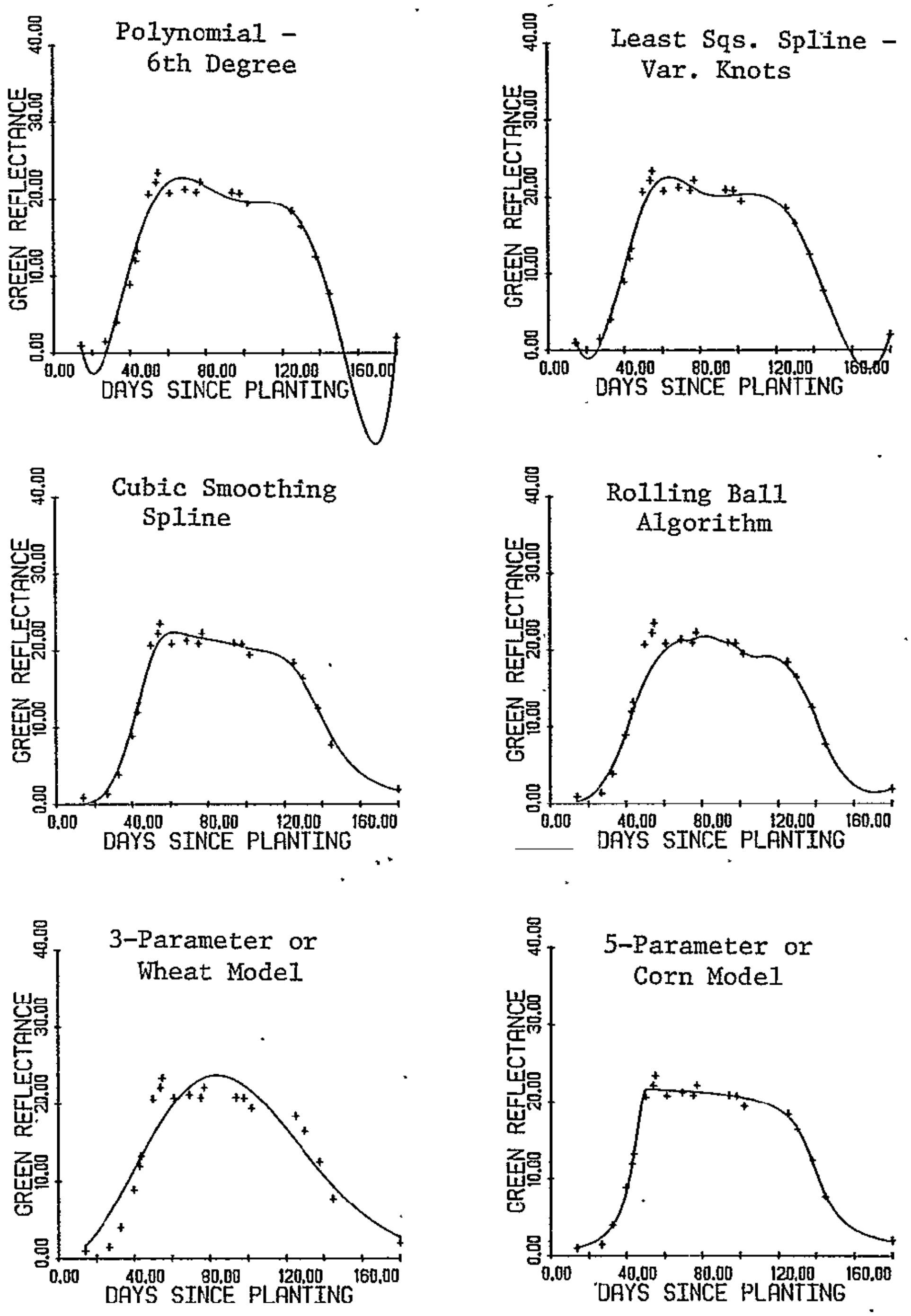


FIGURE 5. EXAMPLE CURVE FITS - PLOT 44, 1979 CORN CULTURAL PRACTICES EXPERIMENT

The final criterion, residual analysis, served primarily to confirm the results already presented. Figure 6 shows residual errors plotted against the number of days away from the estimated peak day for all corn data from 1979 and 1980. Most notable are the systematic errors obtained with the two profile models (Figures 6e and 6f). The errors resulting from the three-parameter model fit are indicative of its inability to fit a flattened peak. Figure 7 shows the same profile fit as in Figure 5, but with a plot of residual errors included, to aid in the interpretation of the combined residual plot. The model has underestimated data values before and after its peak, and overestimated the values at or near the peak, just as a curve fit through a straighter line would be expected to do. The five-parameter model errors indicate the previously mentioned overestimate of early season values.

The cubic smoothing spline was selected for use in subsequent analyses of field reflectance data. The same cubic smoothing spline technique was evaluated, in a more abbreviated fashion, for the soybeans data, and found acceptable. In the analyses reported in the following sections, all curve-fitting was done with this technique.

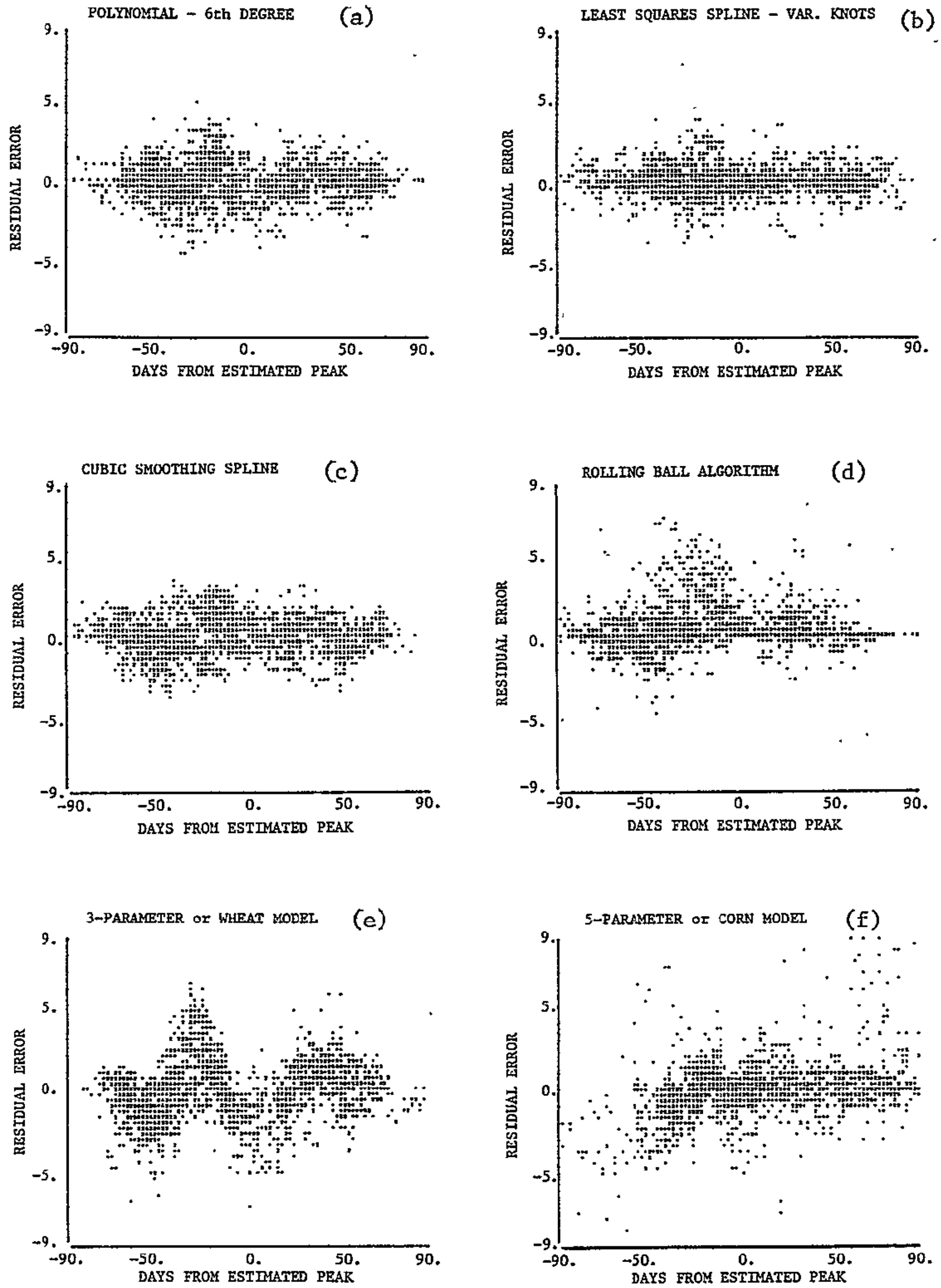


FIGURE 6. RESIDUAL ERRORS FROM CURVE FITS - 1979 AND 1980 CORN DATA

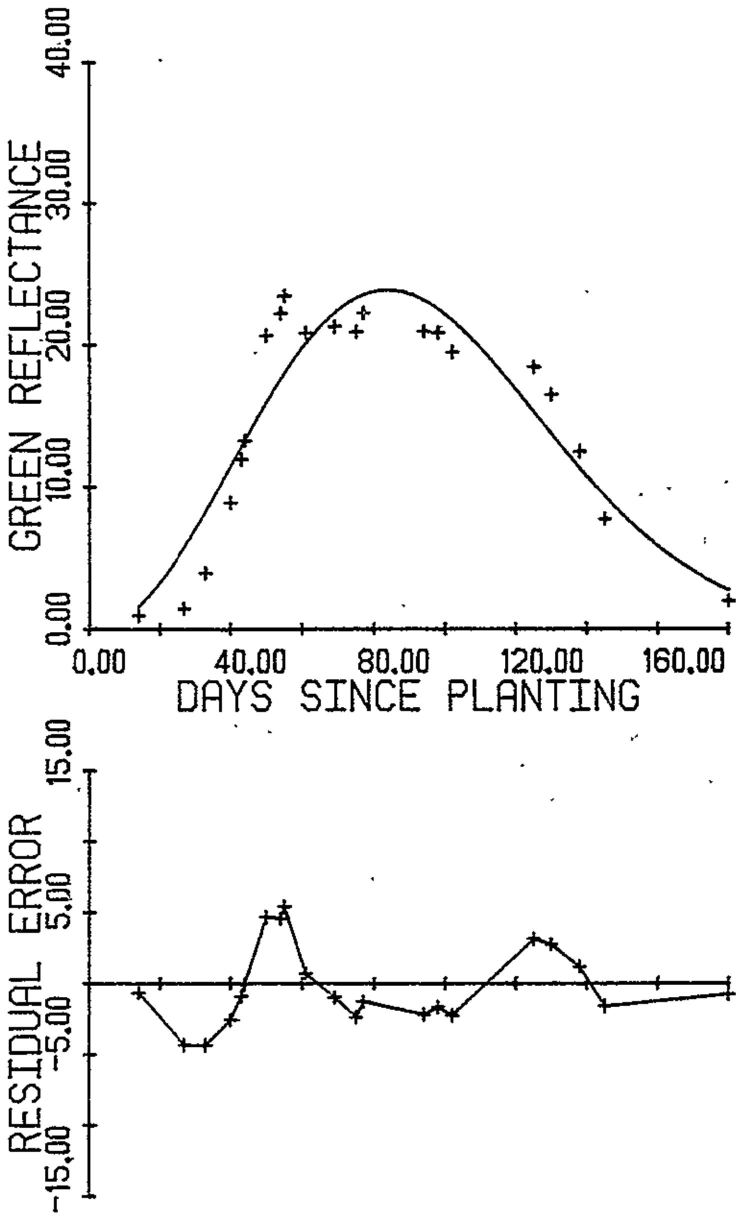


FIGURE 7. EXAMPLE OF 3-PARAMETER MODEL FIT WITH RESIDUALS - PLOT 44, 1979 CORN CULTURAL PRACTICES EXPERIMENT

## 3

## CULTURAL AND ENVIRONMENTAL EFFECTS ON CORN AND SOYBEANS SPECTRAL DEVELOPMENT PATTERNS

The curve-fitting technique described in Section 2 was applied to reflectance data collected over corn and soybeans plots by and at Purdue/LARS [7,8,9]. Included were data collected using an Exotech 100 Landsat band radiometer as well as data collected using an Exotech 20C spectroradiometer. Exotech 20C data were converted to Landsat band reflectances by multiplying by Landsat sensor relative spectral response curves and integrating over wavelength. Multiple observations of a single plot on a single day were represented by their mean.

In order to simplify analysis of the spectral data, and to provide spectral variables that are readily associated with physical phenomena, a transformation was used which captures the majority of data variability over agricultural regions in two variables. It was based on a transformation, derived for Landsat data, which is called the Tasseled-Cap transformation [32], and produces two variables which typically contain more than 95% of the total data variation in an agricultural scene. Brightness, the first variable, corresponds to the spectral direction in which the majority of soil brightness variation is found. The second variable, Greenness, is orthogonal to Brightness, and is an indicator of the amount of green vegetation present in the scene.

In order to approximate this transformation in reflectance space, the principle components of a set of reflectance data from corn, soybeans, and bare soil plots were determined. Figure 8a shows the first two components, which in this analysis included 99% of the data variability. Figure 8b shows the bare soil data in this principle

ORIGINAL PAGE IS
OF POOR QUALITY

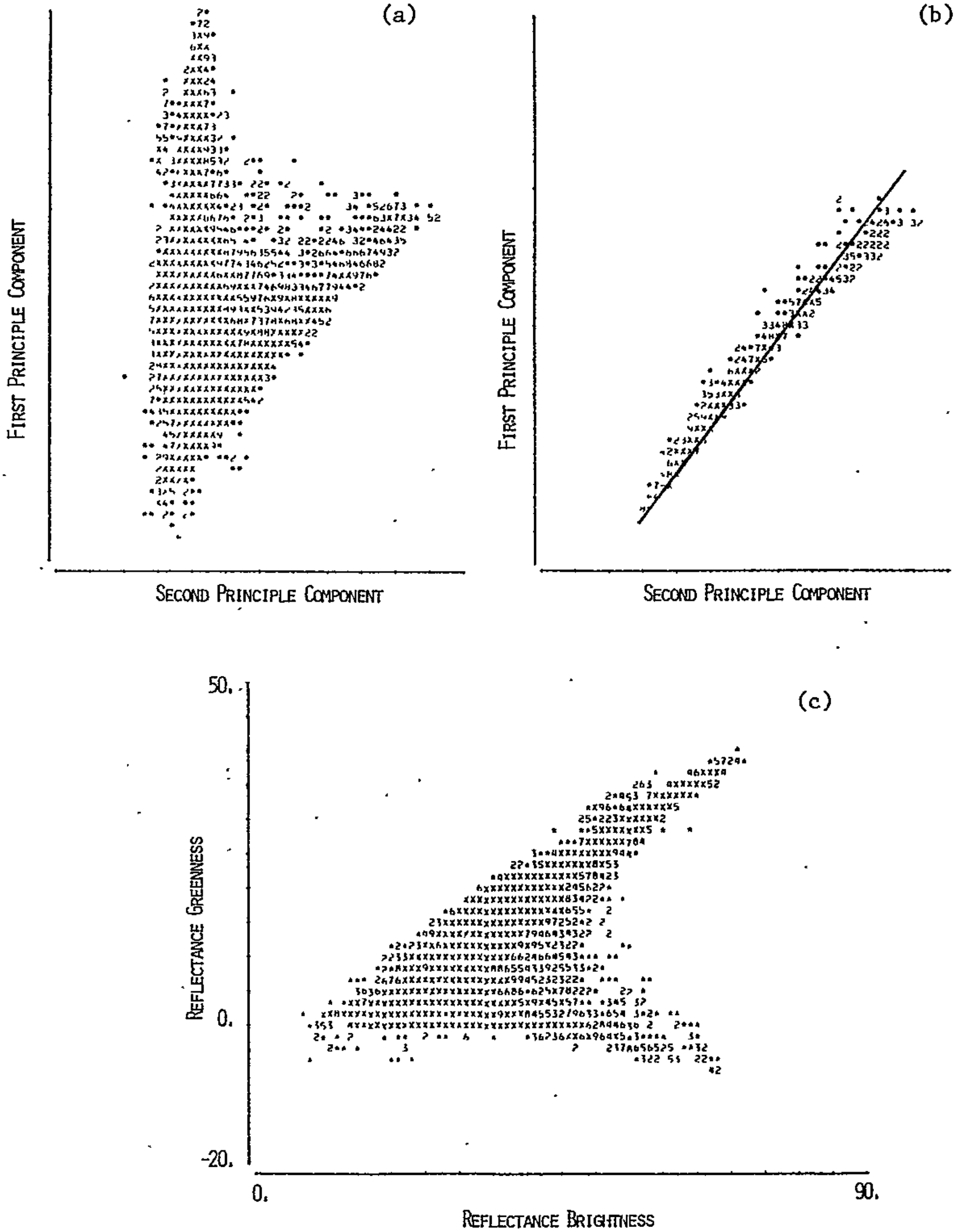


FIGURE 8. TASSELED-CAP EQUIVALENT TRANSFORMATION FOR CORN AND SOYBEANS REFLECTANCE DATA

components space. It will be observed that the data show a definite curvature, but are not so unlike a straight line that such a line cannot be used to approximate them. By means of linear regression, the best fit of a line passing through the soil data and the origin was derived, and a rotation matrix computed which would place this line along the x-axis. Figure 8c shows the resultant data distribution. The final transformation determined to derive Tasseled-Cap equivalent variables from the raw Landsat band reflectances is:

$$\begin{bmatrix} .3298 & .3996 & .5910 & .6182 \\ -.4778 & -.6486 & .0932 & .5851 \end{bmatrix} \times \begin{bmatrix} \text{Refl. Band 4} \\ \text{Refl. Band 5} \\ \text{Refl. Band 6} \\ \text{Refl. Band 7} \end{bmatrix}$$

$$= \begin{bmatrix} \text{Reflectance Brightness} \\ \text{Reflectance Greenness} \end{bmatrix} \qquad (6)$$

This transformation is similar to one developed previously using wheat data [34], and similar in general to the Landsat-based Tasseled-Cap transformation. While these similarities lend support to the extension of the Tasseled-Cap concept to field reflectance data, differences among the transformations do exist. Most notably, the previous reflectance-based transformation based on wheat data gave greater importance to Band 5 in the Brightness component and Band 6 in the Greenness component than does the transformation in Equation (6). Such differences are probably due, at least in part, to the low crop diversity in the data sets used. Certainly neither transformation can be called a general, all-purpose reflectance Tasseled-Cap transformation. Derivation of such a transformation should be based on data from a wide variety of cover types, including but not entirely comprised of cultivated crops.

A small amount of subjective data screening was also carried out. A few observations that were clearly abnormal were deleted, and several entire plots were deleted, either because they showed substantial noise overall or because they lacked acquisitions in a large and significant portion of the growing period. The resultant data set consisted of 118 corn plots and 171 soybean plots in eight experiments from 1978 through 1980, as detailed in Table 1.

After applying the techniques previously described, a series of one-way analyses of variance was carried out to determine the significance of effects of the various experimental treatments on the derived profile features. No higher order interactions were considered, but care was taken to insure that other significant treatments in an experiment were equally represented in the strata defined by the variable or treatment being analyzed. As a result, the degrees of freedom available in a particular analysis varied considerably, although at least two plots for every level of treatment were always available. All results reported as significant in the following sections were found to be so to the 0.9 level of confidence or better.

The results of the analyses will be presented in the following format. First, the expected effects of the treatment at the physiological, canopy geometric, and spectral levels will be briefly described, based on results published by researchers in the agronomic literature. Next the results of the analyses of variance will be presented, along with, or followed by, interpretation of those results and explanation of any inconsistencies between expected and observed effects.

TABLE 1. CORN AND SOYBEAN REFLECTANCE DATA USED IN ANALYSIS

| Year | Experiment Name | # Plots |
|---|---|---|
| 1978 | Corn Nitrogen | 13 |
| 1979 | Corn Nitrogen | 9 |
| 1979 | Corn Cultural Practices | 34 |
| 1979 | Corn Soil Background | 10 |
| 1980 | Corn Cultural Practices | 52 |

| Year | Experiment Name | # Plots |
|---|---|---|
| 1978 | Soybean Management | 69 |
| 1979 | Soybean Cultural Practices | 46 |
| 1980 | Soybean Cultural Practices | 56 |

## 3.1 CORN RESULTS

### 3.1.1 NITROGEN FERTILIZATION

Expectations. In general, deficiencies of essential nutrients in corn tend to lengthen the time intervals between pre-silking development stages [4,22] and reduce both the growth (especially early in the season) of [22], and the chlorophyll concentrations in [2] the leaves. As with moisture availability, soil fertility affects the amount of tillering which occurs, with high fertility favoring more tillering [22,42].

Deficiencies of Nitrogen result in stunted, spindly plants [25], greenish-yellow to orange-yellow leaves [4,25], gradual dieback of leaf tips [25], and premature senescence of lower leaves [22]. Fertilization with Nitrogen has, as expected, opposite effects, increasing the number and size of leaves, the rate of leaf emergence, and the longevity of green leaf area [20].

The spectral expression of the described effects would be expected to include an increased maximum Greenness value (PMAX in Figure 1) with increased Nitrogen fertilization, as a result of both greener plant parts and larger and more numerous leaves. In addition, the increased rate of early development and leaf emergence should be reflected in a more rapid increase in Greenness, suggesting that the first half-peak value (HP1) would be reached sooner with increased fertilization. Finally, the greater longevity of green leaf area associated with increased fertilization could be expected to result in a delay in the time of the second half-peak (HP2), and an increase in the time interval between the two half-peak values (SPAN3) and that between the peak and second half-peak value (SPAN2).

Observed Effects. Table 2 illustrates the levels of Nitrogen fertilization included in the corn experiments. Results of the analyses of variance confirm the effects of Nitrogen fertilization on the peak Greenness value, although these effects primarily were associated with very large amounts of Nitrogen. In 1978, only the jump from 134 kg/ha to 202 kg/ha produced significant increases in peak Greenness values, while in 1979 the increase from 67 kg/ha to 134 kg/ha produced the significant spectral effects. The four- to five-count difference in peak Greenness observed represents a 20 to 25% increase. No difference was observed in the time of the first half-peak value, and the sparsity of data after the peak made assessment of effects on the time of second half-peak impossible. The only other significant effect observed was on the time of peak Greenness, which was delayed three days with high fertilization levels in the 1979 experiment.

The lack of difference in time of first half-peak values between Nitrogen treatment levels appears to be a by-product of the higher peak Greenness value associated with Nitrogen fertilization. Visual comparison of the derived Greenness profiles shows a clear increase in the Greenness level throughout the period from planting to peak as Nitrogen fertilization level increases. However, since the peak is higher, the half-peak value is increased, and, as a result in this case, the time required to reach the half-peak is largely normalized.

Visual analysis also provides a probable explanation for the delay in maximum Greenness values in 1979. Because of the timing of acquisitions in this data, the corn profile "plateau" is not clearly defined, and the curve-fitting technique tends to produce a rounded peak somewhere in the middle of the apparent plateau. The results of drawing in flattened profiles by hand for these plots are a set of curves whose flattened tops lengthen as a function of Nitrogen fertilization level. This result is consistent with the increased green

TABLE 2. NITROGEN FERTILIZATION LEVELS IN CORN EXPERIMENTS

| Level | kg/ha of N |
|---|---|
| 1 | 0 |
| 2 | 67 |
| 3 | 134 |
| 4 | 202 |

leaf area longevity reported in the literature. As the duration of the plateau increases, a rounded curve drawn through the data points would tend to peak later, as was observed to be the case.

### 3.1.2 PLANTING DATE

Expectations. The effects of planting date are in large part the effects of temperature, since later planted crops encounter, as a rule, higher temperatures at a given stage of development. Planting date causes little difference in the number or size of leaves, but later planting has resulted in more rapid leaf emergence and leaf area development [20], very likely as a result of temperature differences. In general, temperature affects the rate of plant development, length of time between stages, and time from planting to emergence [22], with higher temperatures causing an increase in development rate.

In light of these expectations, one could predict that the times required to reach the half-peak values (HP1 and HP2) and the peak value (PT), as well as the time interval between the half-peak values (SPAN3), would all be reduced with later planting. The effect on the peak Greenness value should depend on the relative quality of the growing environment encountered by the differentially-planted crops. If later planting provides a more favorable environment, as could be the case when comparing very early to more normal planting dates, then the peak Greenness would be expected to increase. If, on the other hand, later planting subjects the plants to greater stresses, as might be the case when comparing normal to very late dates, then the peak Greenness value should decline.

Observed Effects. Table 3 lists the planting dates included in the experiments. The analyses of variance again confirm many of the expected results. the time of peak Greenness was earlier for later

TABLE 3. PLANTING DATES IN CORN EXPERIMENTS

| 1979 | 1980 |
|---|---|
| 2 May | 7 May |
| 16 May | 16 May |
| 30 May | 22 May |
| | 29 May |
| | 11 June |
| | 18 June |
| | 2 July |

planting in 1980, although delays past the end of May had no further effect. Planting delays from early to late May caused the peak Greenness value to occur as much as 15 days earlier. A similar trend was observed in 1979, but with less significance.

The peak Greenness value declined with late planting in 1980, though only between planting dates three to five weeks apart, while the maximum Greenness increased with later planting in 1979. A four count, or 22%, variation was observed in the peak Greenness value across planting dates. In addition, the time of first half-peak value decreased through the May dates, while the time of second half-peak value decreased in 1980 but increased in 1979. Finally, both the time span from peak to second half-peak (SPAN2) and the span between the two half-peak values (SPAN3) increased from the May dates to June in 1980.

As hypothesized, the variation in peak Greenness as a function of planting date seems clearly to be a function of the relative growing conditions encountered by plants planted at different times. USDA summaries of Indiana weather for the 1979 and 1980 crop years [29,30] indicate that 1979 was a wetter year, with early plant growth delayed as compared to 1980. Thus while the three planting dates used in 1979 correspond in terms of calendar time to the first three or four used in 1980 (see Table 3), they were in fact very early for the year, and progressed from early to normal by the last date. The increase in peak Greenness from early to late in 1979 thus probably reflects the progression to more favorable temperature and precipitation conditions. In 1980, on the other hand, the hot conditions in mid- to late summer [30] probably induced greater stress in later-planted plots, reflected in lower peak Greenness values. Here the planting date progression was from moderately early to moderately or very late.

The remaining results, namely the increase in the time to second half-peak and the increase in the peak-to-second-half-peak and half-peak-to-half-peak time spans appear to be more the result of the curve-fitting and/or lack of data than of actual crop characteristics. Many of the 1979 plots lacked late season acquisitions, making computation of the second half-peak and associated time spans impossible. In 1980, data were sparse enough at critical green-up times that the spline technique tended to produce a rounded as opposed to flattened peak. Again, visual evaluation of the data and hand-interpolation both suggested that, in fact, the rates of green-up and Greenness decline (represented by the features HP1, HP2, and SPAN2) increased, while the overall time of development (approximated by SPAN3) decreased as a result of later planting. These results are consistent with the expectations previously presented.

### 3.1.3 PLANT POPULATION

Expectations. Plant spacing within and between rows influences canopy characteristics directly, as well as indirectly by modifying the moisture and nutrient status in the field. Plant density affects both the development of the plants and the geometry of the canopy. Increases in plant density have resulted in reduced rates of leaf area production [45], faster early height increase [45], more rapid decline of leaf area after its maximum value has been reached [46], and extended time interval between pollen shedding and silking [4]. Early rates of leaf emergence are unaffected by density, but later rates decrease with increasing density [20].

Effects of increased plant density on canopy geometry include reduced final height [45], increased lodging [4,45], reduced tillering [20], thinner stalks and smaller ears [3], and increased numbers of barren stalks [3,45]. In addition, the number of leaves per plant is reduced, with a wider variation about the mean number of leaves per plant in the stand [20], the areas of individual leaves and the leaf area per plant are decreased [20], but the Leaf Area Index for the stand is increased [46] at higher populations.

The increase in leaf area associated with plant population increases should be expressed in an increased peak Greenness value, although the reduced rate of leaf area production on individual plants could lead one to expect a later occurrence of that peak value. For the same reason, the time of first half-peak would be expected to be later at higher populations, while the peak-to-half-peak span (SPAN2) should decrease in response to the expected more rapid decline in leaf area during senescence.

Observed Effects. Table 4 lists the populations included in the experiments analyzed. Results showed a number of differences between the two years (1979 and 1980) for which population was a treatment. The time to the first half-peak value decreased significantly from the lowest population to the two highest in 1979, but showed no significant effect of population in 1980. In contrast, the time to second half-peak and the time span from first half-peak to peak (HP2 and SPAN1) decreased in 1980, but were unaffected in 1979.

In both years, increasing population caused an increase in peak Greenness, and caused the peak value to occur earlier. While the peak increase was expected, since an increase in green biomass should accompany increases in population density, the earlier time of peak was not expected. A likely explanation for the earlier peak Greenness, and for the faster rate of green-up (earlier time of first half-peak in 1979, shorter half-peak-to-peak span in 1980) is the increased

TABLE 4. POPULATION LEVELS IN CORN EXPERIMENTS

| Level | Plants/Hectare | Plants/Acre (approx.) |
|---|---|---|
| 1 | 25,000 | 10,000 |
| 2 | 50,000 | 20,000 |
| 3 | 75,000 | 30,000 |

competition among plants. One would normally expect such competition to stimulate growth only until moisture or nutrients became limiting. If this did not occur before the peak Greenness value was reached, then the rate of green-up for higher populations could continue to exceed that of lower populations. Since both crop years were cool and wet at least through June [29,30], and 1979 remained cool throughout the growing year, the results obtained seem plausible.

### 3.1.4 SOIL CHARACTERISTICS

Three experiments provided data to assess the impact of soil reflectance on Greenness profiles. These are detailed in Table 5. No effect would be expected, since Greenness is by definition orthogonal to the axis of soil brightness variation. Two profile features were found to be significantly correlated to soil brightness in 1980, but this result is directly attributable to the bend in the soil line described previously. This soil line curvature produced unusually low Greenness values in the early growing period for a number of plots on the lighter-colored soil. These data distorted the profile shapes, and caused the differences observed. However, where soil brightnesses fell in the straight portion of the line, or that portion of the soil axis best represented by the regression line, no soil effects on the Greenness profiles were found.

### 3.1.5 CORN RESULTS - SUMMARY

The effects of Nitrogen fertilization, planting date, and plant population were evaluated with regard to their impact on features of corn Greenness profiles. All were found to significantly affect the Greenness development of the test plots.

TABLE 5. SOIL EFFECTS INCLUDED IN CORN EXPERIMENTS

| Experiment | Factor | Levels |
|---|---|---|
| 1979 Soil Background | Cultivation | 1 - None<br>2 - Cultivation |
| | Surface Moisture | 1 - Dry<br>2 - Wet |
| 1979 Cultural Practices | Brightness | 1 - Darker (Chalmers)<br>2 - Lighter (Russell) |
| 1980 Cultural Practices | Brightness | 1 - Darker (Chalmers)<br>2 - Lighter (Fincastle) |

Addition of Nitrogen, which promotes vegetative development and is required for chlorophyll synthesis, to a plot increased the peak Greenness values and the length or duration of the flattened portion of the profile. Both of these effects are indicators of more lush, vigorous vegetation. A 25% (5 count) difference in peak Greenness was observed from lower to higher fertilization levels.

The effects of planting date are largely those of temperature. Later planted crops will experience warmer temperatures early, but may also have more temperature-induced stress later in their development. Planting date differences were spectrally expressed in the time of occurrence and height of the peak profile value.

Later planting always caused the peak value to occur sooner, as emergence and early growth were promoted by warmer temperatures. Planting delays hastened the time of peak by as much as 15 days.

Variation in peak Greenness due to planting date was similar to that observed in the Nitrogen experiment, with 27% (4 counts) variation; however, the effect was variable with time. Peak Greenness values increased from very early to more medium planting dates, probably as a result of the colder, less conducive environment encountered by the earlier-planted plants. As planting was further delayed, peak Greenness values tended to decline again, probably an indication of the stresses encountered by later-planted crops in the heat of the summer.

Plant population also affected the height and time of occurrence of the peak Greenness value. Increasing the number of plants per hectare resulted in an earlier peak value, a reflection of increased competition and an accompanying increase in development rate, and also produced a higher profile peak. The higher peak was most likely the result of increased Green biomass, and reduced shadow and soil background in the sensor field of view. Not detected was an earlier decline in Greenness, which would be expected when the increased competition and associated increase in growth rate caused the plants to use up the available nutrients and water. This may have been an indication of the favorable growing conditions encountered by most of the plots during most of the vegetative phase (the latest planting dates were not included in this analysis).

Peak Greenness variation due to population ranged from 41 to 62% (7 to 8 counts) in 1980, but only 22 to 32% (4 to 6 counts) in 1979. Variations in time of peak were 11 to 33% (9 to 18 days) in 1980, and 14 to 32% (10 to 23 days) in 1979. Other profile features were found to be significantly affected in only one of the years, if at all.

## 3.2 SOYBEAN RESULTS

### 3.2.1 VARIETY

Expectations. Soybeans are classified into ten maturity groups (00-VIII) based on the region and daylength to which each cultivar is adapted [13]. The earlier-maturing classes (00-IV) tend to be indeterminate in growth, while the later classes (V-VIII) tend to be determinate [13]. However, both determinate and indeterminate varieties can be found in the same maturity class. Soybean varieties range from 90 to 160 days in time from planting to maturity [4]. Variability in days to maturity within a class can be as much as 15 days [13,28], and common varieties in Illinois (Classes I-IV) showed a range of 40 days in relative maturity date [28].

A number of characteristics are associated with soybean variety, of which a primary example is plant height [19]. Varieties in later maturity classes tend to be taller [16], although in a given region mid-season varieties tend to be taller than early- or late-season varieties [39]. Within a maturity class, semideterminate and determinate cultivars are on the average shorter than indeterminate lines [10,44]. However, the height of any particular variety will vary considerably with year or location [39].

Lodging too is a varietal trait [10,15,28], and is largely, though not exclusively, a function of plant height. Thus within a maturity class, the shorter determinate and semideterminate varieties lodge less than the indeterminate varieties [43], and later maturity classes display greater susceptibility to lodging than earlier classes, on the average [33].

Leaf characteristics including size, number, and orientation vary with variety [11,23]. Some varieties have more upright leaves, allowing greater penetration of light into the canopy [23]. Indeterminate varieties exhibit a range of leaf sizes, with lower leaves larger than upper leaves, while all the leaves of determinate varieties are more or less the same size [21].

The degree to which canopy closure occurs depends in part on variety. "Thin line" varieties have a more upright habit and won't generally fill in a 40-inch row, while "fat line" varieties are bushier and will fill in such rows [23]. Later varieties are usually more effective at achieving full closure than earlier varieties [39], and varietal differences in rate of accumulation and maximum leaf area and LAI also have been observed [11].

Varietal differences related to plant development include height at initiation of flowering. Indeterminate lines usually flower when they have reached only about half their final height, while determinate lines cease vegetative growth when flowering begins [21]. In addition, later varieties show less effect of planting delays on maturity date than earlier varieties [33,37,39]. Contradictory results are reported with regard to the effect of planting date on plant height relative to maturity class [33,37].

Observed Effects. Table 6 provides some basic information on the varieties used in the experiments included in this analysis. The 1978 experiment offers the widest contrast with Elf, a semi-dwarf determinate variety and Amsoy 71 and Wells, larger·and indeterminate. The 1979 and 1980 comparisons are primarily "thin line" (Amsoy 71) versus "fat line" (Williams). These two varieties also differ by one maturity class, Williams being later maturing.

Interacting with observed varietal differences are those spectral effects associated with row spacing, to which varieties respond differently [38,43]. Thus analysis of varietal effects was carried out for each row width independently.

Results indicate that some combinations of row width and variety produced significant differences in all the profile features in 1978. Major differences were, as expected, between Elf and the other two varieties. Also as expected, the response of varieties to row widths, which will be referred to again in a later section, was variable.

Varietal differences in peak Greenness ranged from two to four counts, or 6 to 12% of the lowest values, and occurred as much as five days apart. Elf, the semi-dwarf variety, had a higher peak Greenness, a more rapid green-up rate, and a later Greenness decline

TABLE 6. CHARACTERISTICS OF VARIETIES INCLUDED IN SOYBEAN EXPERIMENTS

| Variety | Maturity Group | Growth Habit[1] | % in 1979[2,3] | Relative Maturity[4,5] | Height (inches) | Lodging Score[5,6] | Comments |
|---|---|---|---|---|---|---|---|
| Wells | II | ID | 2.1 | 0 | 39 | 1.3,-- | |
| Amsoy 71 | II | ID | 5.9 | +3 | 42 | 1.8, 2.2 | A "thin line" variety |
| Elf | III | D | --- | +16 | 23 | 1.2, 1.1 | A semi-dwarf variety |
| Williams | III | ID | 25.6 | +16 | 43 | 1.5, 2.3 | |

---

[1] ID = Indeterminate, D = Determinate

[2] Percentage of Acreage Harvested in Ill., Ind., Iowa, Kan., Minn., Mo., Neb., and Ohio

[3] Source: Iowa Crop and Livestock Reporting Service

[4] Days to maturity following Wells.

[5] Source: Reference 28.

[6] Source: Reference 10.

at the same population levels and row spacing than the other varieties. At the widest row spacing, Elf tended to achieve peak Greenness later.

In 1979 no significant varietal differences were detected between Amsoy 71 and Williams, while in 1980, the same two varieties did have significantly different profile characteristics. The bushier Class III Williams variety achieved a higher peak Greenness (a three count or 9% difference) and declined in Greenness more slowly than the thinner Class II Amsoy 71.

All of these results are consistent with the characteristics of the varieties. The shorter, more compact Elf soybean plant would cast less shadow, and respond better to the narrower row spacing, thus allowing a higher peak Greenness value. The later time of peak at the widest row spacing again is indicative of the compact Elf growth habit, and the resultant delay in achieving full or near-full canopy closure. Finally, Elf is a Class III cultivar, and so it matures later than Amsoy 71 or Wells. This behavior is expressed in the later Greenness decline seen for Elf.

The differences between Williams and Amsoy 71 in 1980 can be attributed to the relative bushiness of the two varieties (fat and thin, respectively) and the resultant differences in canopy closure and amount of bare soil/shadow in the sensors field of view, as well as to the maturity class differences. However, the lack of varietal significance in the 1979 data may well be an indication of the interaction between varietal characteristics and overall seasonal conditions.

### 3.2.2 PLANTING DATE

Expectations. Generally speaking, delays in planting of soybeans cause less substantial delays in maturity. A common rule is one-day delay in maturity for every three-days delay in planting [36,37].

However, as the planting period progresses, this relationship approaches a one-for-one correspondence between planting delay and maturity delay [36]. The duration of the vegetative phase is more substantially affected than that of the reproductive phase [28,37]; a normal vegetative phase of 45 to 60 days may be reduced to 25 to 26 days with late planting [28]. These effects are less pronounced in later-maturing than in earlier-maturing varieties [33,39].

Plant height and tendency to lodge are both greater with medium planting dates, and decrease with early or late planting [15,33,37]. Rate of canopy closure follows a similar pattern, increasing and then decreasing as planting progresses from early through late [39].

Temperature is a primary influence on vegetative development of the soybean plant [12,21]. Although responses differ somewhat with variety [12], high temperatures tend to increase emergence, early growth, and vegetative development [12,28,35,37,39], although growth rates at the internodes may be reduced [12], producing shorter plants. Soybeans are fairly resistant to damage by temperature extremes [271].

Expected spectral effects of planting date include more rapid Greenness development (earlier time of half-peak and peak), but less difference in Greenness decline (HP2). Maximum Greenness values would be expected to increase and then decrease as planting progresses from early to late, following the patterns of plant height and rate of canopy closure.

Observed Effects. Table 7 lists the planting dates that were used in the experiments analyzed. As predicted, peak Greenness values increased in 1979 from early May planting through the 15 June planting, but decreased for the July planting date. A 16% variation in peak Greenness was observed, from 32 to 37 counts. Time of peak was

TABLE 7. PLANTING DATES USED IN SOYBEAN EXPERIMENTS

|  | 1979 |  | 1980 |
|---|---|---|---|
|  | 10 May | dark soil | 16 May |
| light soil | 24 May |  | 27 May |
|  | 15 June |  | 12 June |
|  | 3 July |  | 18 June |
|  |  |  | 7 July |
|  |  |  | 16 July |
|  |  |  | 30 July |

substantially hastened by later planting. Earliest planted plots (10 May) achieved peak Greenness an average of 96 days after planting, while those planted latest (3 July) reached their peak only 54 days after planting. Similar results were observed in 1980.

In both years, the times of half-peak occurrence were earlier with later planting, although the difference was about the same for the two half-peak times. However, the time interval from peak to the second half-peak value (SPAN2), an indication of the rate of Greenness decline after peak, was increased or unaffected by later planting, as one would expect based on a one-day maturity delay for three-days planting delay rule.

### 3.2.3 ROW SPACING

Expectations. The effects of row spacing, both in terms of yield and growth characteristics, differ from variety to variety [38,43]. Some varieties seem to do well in narrow row spacings while others do not. The rate of development of soybean plants is little affected by row width [43], and plant heights are affected (reduced) only at very narrow row spacings [16,41,43]. Increases in the Leaf Area Index of soybean fields occur more slowly with wider row spacing [16,43], and canopy closure occurs sooner with narrow rows [37,38].

Because of the differences in varietal response to row spacing, no specific predictions with regard to spectral effects can be made. One would expect in general to see later and lower peak Greenness values with wider rows, slower rates of Greenness increase, and more rapid declines in Greenness after peak, as more soil comes into view sooner.

Observed Effects. Table 8 lists the row spacings involved. Analyses were carried out separately for each variety. As expected, maximum Greenness values decreased for all varieties with wider rows, and in most cases, those peaks occurred later. Differences in peak values were about four counts or 12%, while delays in the time of peak were 8 to 11 days. The time of first half-peak was later in almost all cases with wider row spacings. In most cases, the rate of Greenness decline increased with wider row spacing, with a difference of 4 to 9 days. For the most part, significant differences in 1978 were found only between the two narrower row widths (15 and 46 cm) and the wider spacing (91 cm).

Some differences in varietal response to row width were also observed. Wells was on the whole less affected than Elf or Amsoy 71, while Amsoy 71 and Williams responded similarly. The reduced effect of row width on Wells is consistent with its bushier habit, as compared to the other varieties used in the same year.

### 3.2.4 POPULATION

Expectations. The effects of plant population, like those of row width, differ from variety to variety [38,43]. Vegetative development after the first month of growth is hastened with increasing population [19], and Leaf Area Index increases more rapidly and reaches a higher maximum with higher population levels [41,43]. Increases in plant population result in increases in plant height, and lodging, which is closely associated with height, responds in like manner [13,37,43]. Branching decreases with increasing population [13,16, 23,37,43]. Finally, higher population densities result in more rapid loss of lower leaves [43], thus causing a more rapid decline in LAI.

TABLE 8. ROW SPACINGS USED IN SOYBEAN EXPERIMENTS

| 1978 | | 1979 | | 1980 | |
|---|---|---|---|---|---|
| cm | inches | cm | inches | cm | inches |
| 15 | 6 | 25 | 10 | 25 | 10 |
| 46 | 18 | 76 | 30 | 75 | 30 |
| 91 | 36 | | | | |

The spectral effects of population should be very similar to those of row width. Increasing population should be accompanied by higher peak Greenness values and more rapid increase and decrease in Greenness, as the plants develop more rapidly.

Observed Effects. Table 9 lists the populations included in the analysis. Note that population was a treatment only in the 1978 experiment. Varieties were considered separately to avoid confusion with varietal response to population level.

Far fewer significant effects were noted than expected. Neither the value nor the time of peak Greenness were found to be significantly affected by population, although the peak Greenness values did tend to increase with population. An earlier half-peak was detected for Wells at the highest population level, which contributed to a significant decrease in the time span between half-peak values (SPAN3), but no other comparisons yielded significant differences.

Two factors are likely contributors to the lack of observed population effects on soybean Greenness profiles. First, soybeans tend to fill in the available space, adapting to greater or lesser spacing between plants. Thus the difference in canopy closure, an important element in Greenness, may be slight between population levels. Indeed the canopy closure data collected by LARS as part of the field experiment being analyzed bear this hypothesis out. There is little if any difference seen in the rate of closure, and thus there may be little if any difference in the rate of green-up.

Second, while a clear difference can be seen in the highest Leaf Area Indices achieved at the different population levels, much more variability exists among the plots with the highest populations, such

TABLE 9. POPULATIONS USED IN 1978 SOYBEAN EXPERIMENT

| Wells, Amsoy 71 | | Elf | |
|---|---|---|---|
| pl/ha | pl/a | pl/ha | pl/a |
| 111,000 | 45,000 | 18,000 | 75,000 |
| 185,000 | 75,000 | 259,000 | 105,000 |
| 259,000 | 105,000 | 334,000 | 135,000 |

that the lowest peak LAI's at these population levels are no greater than the peak LAI's reached at lower population levels. This will of course tend to reduce the statistical significance of any comparison of LAI and, since Greenness is well-correlated to LAI, a similar result should be seen in comparison of Greenness profile features.

Nonetheless, it can be said that the effects of the examined population levels on soybean Greenness profile characteristics are less than those of planting date, variety, or row width.

### 3.2.5 SOIL BRIGHTNESS

As previously stated, no effect of soil brightness on Greenness profiles would be expected. For the soybean data, no significant effect was found with regard to any of the profile features used.

### 3.2.6 SOYBEAN RESULTS - SUMMARY

The effects of variety, planting date, row spacing, and plant population on Greenness profile features were examined. All had some degree of impact, with population effects of least significance.

Soybean varieties differ considerably in growth habit, length of growing period, response to environmental changes, and other characteristics. Four varieties were available for comparison including samples from two maturity groups, a semi-dwarf determinate variety, and a "thin line" variety.

Although a seasonal effect was evident between 1979 and 1980, the Class III (later maturing) varieties generally showed a slower Greenness decline than the Class II (earlier maturing) varieties. The semi-dwarf, determinate, Class III variety reached higher peak Greenness values and exhibited a more rapid green-up rate than the larger, indeterminate, Class II varieties. The bushy Class III variety achieved a higher peak than the thin line Class II variety. In addition, differential responses to row width and plant population were noted. Varietal peak Greenness differences ranged from 6 to 12% (2 to 4 counts), and occurred as much as 5 days apart. These results are consistent with the described characteristics of the varieties.

Planting date effects are, as previously stated, strongly connected to temperature and its effects on emergence and vegetative development. Later planting tended to increase peak Greenness values, although very late planting was accompanied by a reduction in the profile peak. The time of peak was heavily influenced, occurring much earlier for later planted plots. Some indication of a reduced effect on maturity date as compared to vegetative development was seen in a lengthening of the Greenness profile after the peak for later planted plots, as would be expected. Planting-date-related variation in peak Greenness was about 16% (5 counts), while plots planted in early July reached their peak value in 42 fewer days than those planted in early May.

Increasing the row spacing in a soybean plot reduced peak Greenness, since more soil and shadow were in view. The rate of green-up was reduced, and the rate of Greenness decline increased, again largely due to the percentage of the field of view occupied by non-green components. A hastening of the time of peak Greenness was observed with narrower rows. This was probably due to an earlier achievement of complete canopy closure. If so, it should be noted that for soybeans, the time of peak Greenness cannot be clearly associated with any particular development stage. Varietal differences were observed. Peak Greenness values varied some 12% (4 counts), with 8 to 11 day delays in the profile peak.

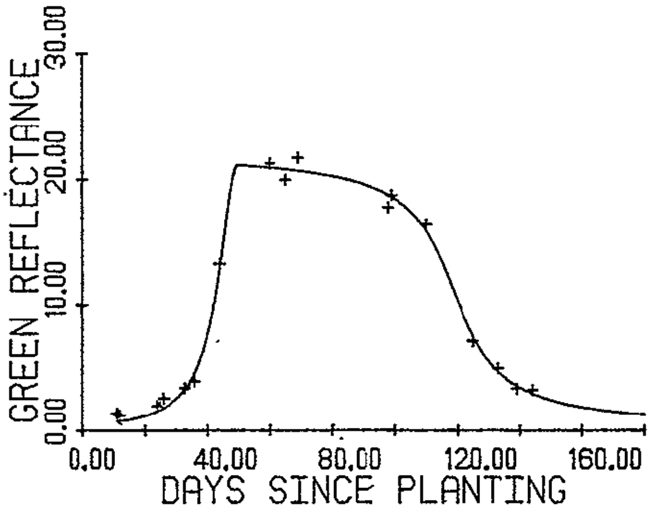
The impact of population should be of a similar nature to that of row width. However, possibly as a result of the soybean plant's tendency to fill in the available space, very little effect was detected. Peak Greenness values tended to increase with population, but the variability present at the highest populations rendered the increase statistically insignificant.

## 3.3 EVALUATION OF CURVE-FITTING TECHNIQUE

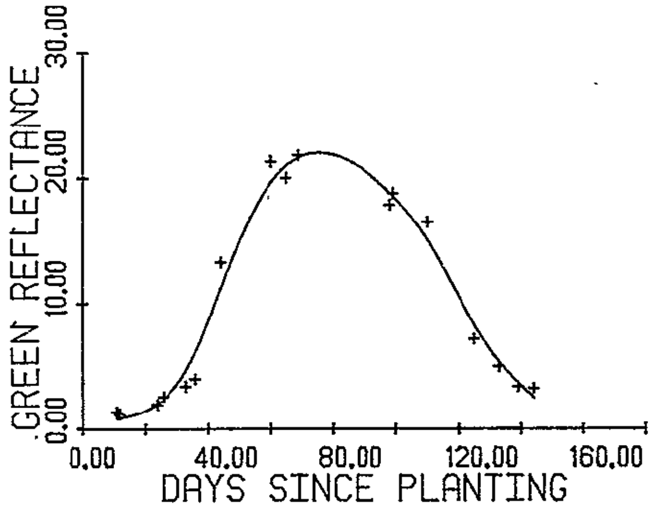
Overall, the technique described in Section 2 performed well. The cubic smoothing spline technique fit the soybean data, and much of the corn data, very well. The extraction of standard profile features allowed ready comparison of plots with different planting and/or observation dates, and characterized the continuous profile in a manageable number of variables. With these variables, quantitative analysis of experimental effects was greatly facilitated.

In the course of analysis, two improvements to the procedure were suggested. First, even the cubic smoothing spline algorithm failed to detect the flat peak of corn data when insufficient data points were available, especially when the sparse data occurred just before or on the plateau. Given the expectation of a flattened peak, one could often see such a feature in the data when the spline technique had not.

The five-parameter corn model, which is designed to function with a similar expectation, also detected flat peaks when other technique did not (Figure 9 provides an example), although that model had other weaknesses. Most desirable would be a curve-fitting function with the flexibility of the cubic smoothing spline, but also the prior expectation of crop development that would allow it to draw a "corn-like" or "crop-like" profile even with sparse data. Development of such a



a) 5-Parameter or Corn Model



b) Cubic Smoothing Spline

FIGURE 9. COMPARISON OF CURVE-FITTING TECHNIQUES - DETECTING THE FLATTENED PEAK OF CORN

function would greatly increase the power of this analysis technique for corn data.

The second suggested modification to the analysis technique used regards the rate-related features. As described, half-peak values are used as critical points in measuring time intervals. However, in some cases it appeared that treatment effects were missed because of significant increases in the peak value, which of course resulted in increased half-peak values. Time intervals related to half-peaks were thus based on the achievement of substantially different Greenness thresholds (a measure of relative rate of change), and rate differences between treatments were, at least to a degree, normalized. While times to half-peak may provide useful information, rates might better be computed, or at least also be computed, based on fixed thresholds (i.e., compute an absolute rate of change).

## 4

## CONCLUSIONS AND RECOMMENDATIONS

The analyses of field reflectance data presented in the previous sections provide a clear indication that a number of commonly varying field characteristics can exert a substantial influence on the spectral appearance of crops. Such key features as the maximum Greenness value and rate of green-up can be altered significantly by varying any one of a number of parameters such as Nitrogen fertilization, planting date, variety, and plant spacing. In a real-life situation where any or all of these characteristics may vary, the likely effects on crop spectral appearance will be considerable. Such variability must be taken into account in any crop identification technique, whether carried out by human analysts or computer algorithms. In addition, this type of information is of critical importance in the design and implementation of accurate, usable simulation systems.

The work presented is, however, only a first step. Expanding the Greenness profile analysis for corn to include the new features described in Figure 4, and applying a similar analysis technique to the understanding of Brightness profiles and their sensitivity to cultural and environmental factors, will provide still more insight. The derived profile features could also be used to determine, again on a quantitative basis, the similarities and differences between corn and soybeans profiles, and the effect of the various treatments on their separability.

Finally, of course, the insights gained through field data analysis must be applied to real Landsat data. The loss of control over crop parameters, the inclusion of an atmosphere, the degradation of resolution, and the mixing of the independently evaluated factors, as well as others not even considered, will likely cause some of the observed and/or predicted effects to be reduced, while others will be intensified.

Controlled experimentation provides a foundation and a context, but it cannot completely replace real data, nor can crop inventory techniques be derived from field data alone. It is the progression from physiological understanding through modeling and field data analysis to Landsat data analysis that brings the experimental data and understanding into the real world, while at the same time connecting the uncertain real world to some reliable, stable points of reference.

## REFERENCES

1. Akima, H. 1970. A New Method of Interpolation and Smooth Curve Fitting Based on Local Procedures. Journal of the Association for Computing Machinery. 17(4):589-602.

2. Al-Abbas, A.H., R. Barr, J.D. Hall, F.C. Crane, and M.F. Baumgardner. 1974. Spectra of Normal and Nutrient-Deficient Maize Leaves. Agronomy Journal. 66:16-20.

3. Alessi, J. and J.F. Power. 1967. Dryland Corn Growth and Water Relations. Farm Research. 24(12):4-7.

4. Arnon, I. 1972. Crop Production in Dry Regions. Vol. II: Systematic Treatment of the Principal Crops. Leonard Hill. London.

5. Badhwar, G.D. 1980. Crop Emergence Date Determination from Spectral Data. Photogrammetric Engineering and Remote Sensing. 46:369-377.

6. Badhwar, G.D. and K.E. Henderson. 1981. Estimating Development Stages of Corn from Spectral Data - An Initial Model. Agronomy Journal. 73:748-755.

7. Bauer, M.E., M.H. Hixson, L.L. Biehl, C.S.T. Daughtry, B.F. Robinson, and E.R. Stoner. 1978. Agricultural Scene Understanding. LARS Report 112578. Laboratory for Applications of Remote Sensing, Purdue University. West Lafayette, Indiana.

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

9. Bauer, M.E., L.L. Biehl, and B.F. Robinson. 1980. 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, Indiana.

10. Beaver, J.S. and R.R. Johnson. 1981. Yield Stability of Determinate and Indeterminate Soybeans Adapted to the Northern United States. Crop Science. 21:449-454.

11. Blad, B.L. and D.G. Baker. 1972. Orientation and Distribution of Leaves Within Soybean Canopies. Agronomy Journal. 64:26-29.

REFERENCES (Cont'd)

12. Cartter, J.L. and E.E. Hartwig. 1963. The Management of Soybeans. pp. 167-220. In Norman, A.G. (ed.), The Soybean, Academic Press. New York.

13. Chapman, S.R. and L.P. Carter. 1976. Crop Production: Principles and Practices. W.H. Freeman and Company. San Francisco. 566 pp.

14. Cicone, R.C., E. Crist, R. Kauth, P. Lambeck, W. Malila, and W. Richardson. 1979. Development of Procedure M for Multicrop Inventory, With Tests of a Spring Wheat Configuration. Final Report 132400-16-F. Environmental Research Institute of Michigan. Ann Arbor, Michigan.

15. Cooper, R.L. 1971. Influence of Soybean Production Practices on Lodging and Seed Yield in Highly Productive Environments. Agronomy Journal. 63:490-493.

16. Costa, J.A., E.S. Oplinger and J.W. Pendleton. 1980. Response of Soybean Cultivars to Planting Patterns. Agronomy Journal. 72:153-156.

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

18. DeBoor, C.B. 1978. A Practical Guide to Splines. Springer-Verlag. New York. 392 pp.

19. Doss, B.D. and D.L. Thurlow. 1974. Irrigation, Row Width, and Plant Population in Relation to Growth Characteristics of Two Soybean Varieties. Agronomy Journal. 66:620-623.

20. Eik, K. and J.J. Hanway. 1965. Some Factors Affecting Development and Longevity of Leaves of Corn. Agronomy Journal. 57:7-12.

21. Fehr, W.R. and C.E. Caviness. 1977. Stages of Soybean Development. Iowa State University, Cooperative Extension Service. Ames, Iowa. Special Report 80.

22. Hanway, J.J. 1971. How a Corn Plant Develops. Iowa State University, Cooperative Extension Service. Ames, Iowa.

23. Hanway, J.J. and H.E. Thompson. 1971. How a Soybean Plant Develops. Iowa State University, Cooperative Extension Service. Ames, Iowa. Special Report 53 (rev.).

REFERENCES (Cont'd)

24. Hay, C.M., C. A. Kuretz, J.B. Odenweller, E.J. Sheffner, and B. Wood. 1979. Development of AI Procedures for Dealing With the Effects of Episodal Events on Crop Temporal-Spectral Response and Development of AI Guidelines for Corn and Soybean Labeling. NASA Report SR-B9-00434. Space Sciences Laboratory, University of California. Berkeley, California.

25. Hoffer, G.N. 1941. Deficiency Symptoms of Corn and Small Grains. In Hambidge, G. (ed.), Hunger Signs in Crops, American Society of Agronomy and National Fertilizer Association. Washington, D.C.

26. Horvath, R. 1982. Research and Development of Landsat-based Crop Inventory Techniques, NASA Report MU-E2-04226. Environmental Research Institute of Michigan. Ann Arbor, Michigan.

27. Howel, R.W. 1963. Physiology of the Soybean. pp. 75-12. In Norman, A.G. (ed.), The Soybean. Academic Press. New York.

28. Illinois Agronomy Handbook. 1980. University of Illinois Cooperative Extension Service. Urbana, Illinois. Circular 1165.

29. Indiana Crop and Livestock Reporting Service. 1980. Annual Crop and Livestock Summary 1979. U.S. Dept. Agr. and Purdue University. West Lafayette, Indiana.

30. Indiana Crop and Livestock Reporting Service. 1981. Annual Crop and Livestock Summary 1980. U.S. Dept. Agr. and Purdue University. West Lafayette, Indiana.

31. International Mathematical and Statistical Libraries, Inc. 1980. Reference Manual LIB-008.

32. Kauth, R.J. and G.S. Thomas. 1976. The Tasseled-Cap -- A Graphic Description of the Spectral-Temporal Development of Agricultural Crops As Seen by Landsat. Proceedings of the Symposium on Machine Processing of Remotely Sensed Data, Purdue/LARS. West Lafayette, Indiana.

33. Leffel, R.C. 1961. Planting Date and Varietal Effects on Agronomic and Seed Compositional Characters of Soybeans. University of Maryland Agricultural Experiment Station. Bulletin A-117.

34. Malila, W.A. 1977. "Multicrop Remote Sensing Technique Development". Presented at NASA SR&T Quarterly Review. NASA Johnson Space Center. Houston, Texas. December 1977.

REFERENCES (Cont'd)

35. Major, D.J., D.R. Johnson, J.W. Tanner, and I.C. Anderson. 1975. Effects of Daylength and Temperature on Soybean Development. Crop Science. 15:174-179.

36. Ohio Crop Reporting Service. 1980. Ohio Weekly Crop-Weather Summary. 28 July 1980.

37. Pendleton, J.W. and E.E. Hartwig. 1973. Management. pp. 211-237. In Caldwell, B.E. (ed.), Soybeans: Improvement, Production, and Uses. American Society of Agronomy. Madison, Wisconsin.

38. Pepper, G.E. 1978. Narrow-Row Soybeans: What to Consider. University of Illinois Cooperative Extension Service. Urbana, Illinois. Circular 1161.

39. Smith, T.J., H.M. Camper, M.T. Carter, G.D. Jones, and M.W. Alexander. 1961. Soybean Performance in Virginia as Affected by Variety and Planting Date. Virginia Agricultural Experiment Station. Blacksburg, Virginia. Bulletin 526.

40. Sternberg, S.R. 1980. Cellular Computers and Biomedical Image Processing. Proceedings of the U.S.-France Seminar on Biomedical Image Processing. Grenoble, France.

41. Taylor, H.M. 1980. Soybean Growth and Yield as Affected by Row Spacing and by Seasonal Water Supply. Agronomy Journal. 72:543-547.

42. Wallace, H.A. and E.N. Bressman. 1928. Corn and Corn Growing. John Wiley and Sons, Inc. New York.

43. Weber, C.R., R.M. Shibles, and D.E. Byth. 1966. Effect of Plant Population and Row Spacing on Soybean Development and Production. Agronomy Journal. 58:99-102.

44. Wilcox, J.R. 1980. Comparative Performance of Semideterminate and Indeterminate Soybean Lines. Crop Science. 20:277-280.

45. Williams, W.A., R.S. Loomis, and C.R. Lepley. 1965. Vegetative Growth of Corn as Affected by Population Density. I. Productivity in Relation to Interception of Solar Radiation. Crop Science. 5:211-215.

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

## DISTRIBUTION LIST

| Name | Number of Copies |
|---|---|
| NASA/Johnson Space Center<br>Earth Resources Research Division<br>Houston, Texas 77058 | |
| Attn: Dr. G. Badhwar/SG3 | 1 |
| Attn: Mr. I. D. Browne/SG3 | 2 |
| Attn: Dr. J. W. Dietrich/SG3 | 1 |
| Attn: Dr. A. H. Feiveson/SG3 | 1 |
| Attn: Dr. F. G. Hall/SG3 | 1 |
| Attn: Mr. D. Hay/SG2 | 1 |
| Attn: Dr. R. P. Heydorn/SG3 | 1 |
| Attn: Dr. A. G. Houston/SG3 | 1 |
| Attn: Mr. R. B. MacDonald/SG | 1 |
| Attn: Dr. D. E. Pitts/SG3 | 1 |
| Attn: Dr. M. L. Steib/SG3 | 1 |
| Attn: Dr. D. Thompson/SG3 | 1 |
| Attn: CASPAN Library/SG | 2 |
| Attn: Mr. T. C. Minter/C09 | 4 |
| NASA/Johnson Space Center<br>Earth Resources Applications Division<br>Houston, Texas 77058 | |
| Attn: Mr. K. Baker/SH3 | 1 |
| Attn: Mr. R. M. Bizzell/SH3 | 1 |
| Attn: Mr. J. L. Dragg/SH3 | 1 |
| Attn: Dr. J. D. Erickson/SH | 1 |
| Attn: Dr. D. L. Henninger/SH3 | 1 |
| Attn: Mr. F. J. Herbert/SH3 | 1 |
| Attn: Mr. W. C. Jones/SH3 | 1 |
| Attn: Mr. R. McKinney/SH3 | 1 |
| Attn: Mr. T. W. Pendleton/SH2 | 1 |
| Attn: Mr. H. L. Prior/SH3 | 1 |
| Attn: Mr. M. C. Trichel/SH2 | 1 |
| Attn: Mr. L. C. Wade/SH3 | 2 |
| Attn: Dr. V. S. Whitehead/SH3 | 1 |
| Attn: Dr. B. L. Carroll/C09 | 4 |

## DISTRIBUTION LIST (Continued)

| Name | Number of Copies |
|---|---|
| NASA/Johnson Space Center<br>Technical Library Branch<br>Houston, Texas 77058 | |
| Attn: Mr. M. P. McDonough/JM6 | 4 |
| NASA/Johnson Space Center<br>Technical Support Procurement Branch<br>Houston, Texas 77058 | |
| Attn: Ms. E. McAnelly/BB63 | 1 |
| NASA/Johnson Space Center<br>Space and Life Sciences Directorate<br>Houston, Texas 77058 | |
| Attn: Mr. W. E. Rice | 1 |
| NASA/Johnson Space Center<br>NOAA Liaison Office<br>Houston, Texas 77058 | |
| Attn: Mr. M. Helfert/SK | 1 |
| NASA/Ames Research Center<br>Moffett Field, California 94035 | |
| Attn: Dr. D. M. Deerwester | 1 |
| NASA/Goddard Space Flight Center<br>Greenbelt, Maryland 20771 | |
| Attn: Dr. J. Barker/923 | 1 |
| Attn: Mr. W. Alford/563 | 1 |
| Attn: Mr. F. Gordon/902 | 1 |
| NASA Headquarters<br>Washington, D.C. 20546 | |
| Attn: Mr. Howard Hogg/ER-2 | 1 |
| Attn: Mr. James Welch/ER-2 | 1 |

## DISTRIBUTION LIST (Continued)

| Name | Number of Copies |
|---|---|
| NASA/Goddard Institute for Space Studies<br>New York, New York 10025 | |
| Attn: Dr. S. G. Unger | 1 |
| Agency for International Development<br>Office of Science and Technology/SA-18<br>Washington, D.C. 20523 | |
| Attn: Dr. C. K. Paul | 1 |
| Colorado State University<br>College of Forestry and Natural Resources<br>Fort Collins, Colorado 80523 | |
| Attn: Dr. J. Smith | 1 |
| Earth Resources Laboratory<br>National Space Technology Laboratory<br>Bay St. Louis, Mississippi 39520 | |
| Attn: Dr. D. W. Mooneyhan | 1 |
| EROS Data Center<br>U.S. Department of Interior<br>Sioux Falls, South Dakota 57198 | |
| Attn: Mr. G. Thorley | 1 |
| Attn: Mr. A. Watkins | 1 |
| Environmental Protection Agency<br>Western Environmental Research Laboratories<br>P.O. Box 15027<br>Las Vegas, Nevada 89114 | |
| Attn: Chief of Technical Support | 1 |
| General Electric Company<br>Space Division<br>4701 Forbes Blvd.<br>Lanham, Maryland 20801 | |
| Attn: Dr. A. B. Park | 1 |

## DISTRIBUTION LIST (Continued)

| Name | Number of Copies |
|---|---|
| NOAA<br>Chief, Climatic Impact Assessment Division<br>3300 Whitehaven, NW<br>Page Bldg. 2, Rm. 140<br>Washington, D.C. 20250 | |
| Attn: Dr. Russell A. Ambrosiak | 1 |
| NOAA/NESS<br>Office of Research<br>Department of Commerce<br>Washington, D.C. 20233 | |
| Attn: Dr. Harold Yates | 1 |
| NOAA/Code OAX-1<br>Environmental Data and Information Services<br>Washington, D.C. 20235 | |
| Attn: Dr. Thomas Potter | 1 |
| NOAA<br>CEAS Federal Building<br>Columbia, Missouri 65201 | |
| Attn: Dr. W. Wilson | 1 |
| North Dakota State University<br>Plant Pathology Department<br>Fargo, North Dakota 58102 | |
| Attn: Dr. V. Pederson | 1 |
| Oregon State University<br>Environmental Remote Sensing Applications Laboratory<br>Corvallis, Oregon 97331 | |
| Attn: Dr. Barry J. Schrumpf | 1 |

## DISTRIBUTION LIST (Continued)

| Name | Number of Copies |
|---|---|
| Pennsylvania State University<br>Space Science and Engineering Laboratory<br>Office for Remote Sensing of Earth Resources<br>220 Electrical Engineering West Building<br>University Park, Pennsylvania 16802 | |
| Attn: Dr. Gary W. Peterson | 1 |
| Prairie View A&M University<br>College of Agriculture<br>Prairie View, Texas 77445 | |
| Attn: Dr. E. Brams | 1 |
| Purdue University<br>Purdue Industrial Research Park<br>1220 Potter Drive<br>West Lafayette, Indiana 47906 | |
| Attn: Dr. Marvin Bauer | 3 |
| South Dakota State University<br>Director, Remote Sensing Institute<br>Agriculture Engineering Building<br>Brookings, South Dakota 57006 | |
| Attn: Mr. Victor I. Myers | 1 |
| Attn: Dr. J. C. Harlan | 1 |
| Texas A&M University<br>Department of Mathematics<br>College Station, Texas 77843 | |
| Attn: Dr. L. F. Guseman, Jr. | 1 |
| U.S. Department of Agriculture<br>Grassland, Soil & Water Research Laboratory<br>P.O. Box 748<br>Temple, Texas 76501 | |
| Attn: Dr. J. T. Ritchie | 1 |

## DISTRIBUTION LIST (Continued)

| Name | Number of Copies |
|---|---|
| Texas A&M University<br>Remote Sensing Center<br>Teague Building<br>College Station, Texas 77843<br>Attn: Dr. James Heilman | 1 |
| U.S. Department of Agriculture<br>SEA/AR<br>Bldg. 005, Rm. 125<br>BARC-West<br>Beltsville, Maryland 20705<br>Attn: Mr. Carl W. Carlson | 1 |
| U.S. Department of Agriculture<br>SEA/NPS<br>Bldg. 005, Rm. 233A<br>BARC-West<br>Beltsville, Maryland 20705<br>Attn: Mr. Jerry Ritchie | 1 |
| U.S. Department of Agriculture<br>Forest Service<br>240 W. Prospect Street<br>Fort Collins, Colorado 80521<br>Attn: Dr. Richard Driscoll | 1 |
| U.S. Department of Agriculture<br>FAS-CCAD<br>1050 Bay Area Blvd.<br>Houston, Texas 77058<br>Attn: Mr. James Hickman | 2 |
| U.S. Department of Agriculture<br>AgRISTARS/EW<br>1050 Bay Area Blvd.<br>Houston, Texas 77058<br>Attn: Dr. G. O. Boatwright | 1 |

DISTRIBUTION LIST (Continued)

| Name | Number of Copies |
|---|---|
| U.S. Department of Agriculture<br>Economics and Statistics Service<br>Washington, D.C. 20250 | |
| Attn: Mr. Rich Allen | 1 |
| Attn: Mr. Charles E. Caudill | 1 |
| Attn: Mr. Galen F. Hart | 1 |
| Attn: Mr. William E. Kibler | 1 |
| U.S. Department of Agriculture/SCS<br>1943 Newton Square East<br>Reston, Virginia 22090 | |
| Attn: Dr. R. H. Gilbert | 1 |
| U.S. Department of Agriculture<br>Soil & Water Conservation Research Division<br>P.O. Box 267<br>Weslaco, Texas 78596 | |
| Attn: Dr. Craig Wiegand | 1 |
| U.S. Department of Interior<br>Geological Survey<br>1925 Newton Square East<br>Reston, Virginia 22070 | |
| Attn: Mr. Fred Doyle | 1 |
| U.S. Department of Interior<br>Geological Survey<br>Federal Center<br>Denver, Colorado 80225 | |
| Attn: Dr. Harry W. Smedes | 1 |
| University of Arkansas<br>Mathematics Department<br>Fayetteville, Arkansas 72704 | |
| Attn: Dr. Jack D. Tubbs | 1 |

## DISTRIBUTION LIST (Continued)

| Name | Number of Copies |
|---|---|
| University of California at Berkeley<br>Forestry Department<br>Berkeley, California 94720 | |
| Attn: Mr. Robert Colwell | 1 |
| University of California t Berkeley<br>260 Space Sciences Laboratory<br>Berkeley, California 94720 | |
| Attn: Ms. Claire M. Hay | 3 |
| University of Nebraska<br>Agricultural Meteorology Section<br>211 Agricultural Engineering<br>Lincoln, Nebraska 68583 | |
| Attn: Dr. B. L. Blad | 1 |
| University of Texas at Dallas<br>Box 688<br>Richardson, Texas 75080 | |
| Attn: Dr. Patrick L. Odell | 1 |
| University of Tulsa<br>Mathematics-Sciences Department<br>600 South College<br>Tulsa, Oklahoma 74104 | |
| Attn: Dr. W. A. Coberly | 1 |
| Kansas State University<br>Evapotraspiration Laboratory<br>Manhattan, Kansas 66506 | |
| Attn: Dr. Edward T. Kanemasu | 1 |
| University of California<br>Department of Geography<br>Santa Barbara, California 93106 | |
| Attn: Dr. John E. Estes | 1 |

DISTRIBUTION LIST (Continued)

| Name | Number of Copies |
|---|---|
| U.S. Department of Agriculture<br>Forest Service/NFAP<br>1050 Bay Area Blvd.<br>Houston, Texas 77058 | |
| Attn: Dr. F. P. Weber | 1 |
| NASA/Johnson Space Center<br>Houston, Texas 77058 | |
| Attn: Mr. Fred Barrett<br>Mail Code SK/USDA | 3 |