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AN INITIAL MODEL FOR ESTIMATING SOYBEAN DEVELOPMENT STAGES FROM SPECTRAL DATA

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ABSTRACT

A model, utilizing a direct relationship between remotely sensed spectral data and soybean development stage, has been proposed. The model is based upon transforming the spectral data in Landsat bands to greenness values over time and relating the area of this curve to soybean development stage. Soybean development stages were estimated from data acquired in 1978 from research plots at the Purdue University Agronomy Farm as well as Landsat data acquired over sample areas of the U.S. Corn Belt in 1978 and 1979. Analysis of spectral data from research plots revealed that the model works well with reasonable variation in planting date, row specing, and soil background. The R^2 of calculated U.S. observed development stage exceeded 0.91 for all treatment variables. Using Landsat data the calculated U.S. observed development stage gave an R^2 of 0.89 in 1978 and 0.87 in 1979. No difference in the models performance could be detected between early and late planted fields, small and large fields, or high and low yielding fields.

I. INTRODUCTION

One application of remote sensing technology that has received considerable attention is in making large scale crop production estimates. The need for timely and accurate crop production information is becoming more critical which makes the role of remote sensing even more important. Current technology requires knowledge about the time of remotely sensed data acquisition in relation to the growing season of the crop or crops of interest. This is especially important for classification and identification of crops with similar growing seasons. Crop yield estimates are also a necessary part of the crop production equation. To accurately determine the influence of weather events upon the yield of a crop one must know the development stage of the crop at the time the event occurs. This is especially important for such key development stages as flowering and/or grain filling.

Previous literature reviews[1,2] have shown that there is very limited information concerning use of remotely sensed spectral data to estimate development stages of crops. Such an approach is considered feasible, however, by Seeley et al.[1] to complement the more widely used approaches of using normal or average development stages based upon historical observations of time in days between stages of meteorological methods based upon thermal or photo-thermal units required to proceed from one stage to another. Badhwar and Henderson[3] have outlined the possible advantages of using remotely sensed spectral data for development stage estimation and have described a model applicable for development stage estimation of corn (Zea maize).

The objective of work reported in this paper was to apply a similar technique for soybeans (Glycine max). It is felt that the spectral approach may be even more beneficial for soybeans than for corn because of the more complex photoperiodic nature of the crop and the narrow range of adaptability of specific soybean cultivars. The soybean spectral model that is proposed uses only spectral data and has the attributes of being applicable to individual fields and a wide geographic range as well as integrating reasonable differences in cultural methods and weather.

II. THEORY AND MODEL

The model for soybeans is basically the model that was used for corn crop. The details of this model can be found in previous research by Badhwar and Henderson[3]

Briefly, the four Landsat MSS bands are converted to Greenness of Kauth-Thomas[4], which has been shown to be strongly correlated to green vegetation of the crop. The greenness, $\rho(t)$, at various times, t, during the soybean growing cycle is fitted to the model form

$$\begin{aligned} \rho(t) &= \rho_0 (t/t_0)^{\alpha} \exp[\beta(t_0^2 - t^2)] & t \geq t_0 \\ &= \rho_0 & t < t_0 \end{aligned} \qquad (1)$$

where ρ_0 is the soil greenness before the crop emergence time t_0, and α and β are crop related constants. In case of corn, it was shown that

$$\zeta(t) \equiv 1 - \int_t^{t_s} \rho(t')dt' / \int_{t_0}^{t_s} \rho(t'')dt''$$

where t_s is the point in time when the greenness temporal profile crosses the soil line value ρ_0, is linearly related to the Hanway stage. The two unknown constants were fixed by requiring that at $t=t_0$ ($\zeta(t)=0$) corresponds to the first spectrally detectable stage and at $t=t_s$ ($\zeta(t)=1$) corresponds to physiological maturity. Applying this model to soybeans and using the 1979 NASA stage designations, one finds that,

$$\text{Calculated Development Stage} = 6.0 - 2.9 * \zeta(t)$$

where 6.0 is the stage representing maturity and 3.1 (6.0-2.9) is the stage corresponding to initial spectrally detectable stage. This is the model used in the work with soybean data described in the following pages.

III. MATERIALS AND METHODS

Data used in this study to verify the performance of the soybean development stage model came from two basic sources. First was plot level data in which spectral data was acquired by truck-mounted instruments and associated agronomic and cultural observations were made at the time of spectral data acquisition. The second source of data was Landsat multispectral data from 17 geographic locations in crop year 1978 and 9 locations in 1979. This spectral data also had agronomic and cultural observations similar to the plot data but in less detail.

The plot level data was acquired from soybean plots being grown at the Purdue University Agronomy Farm near West Lafayette, Indiana. Details of the data collection procedures and frequency of observations is given by Bauer et al.[5] Spectral reflectance measurements were made with an Exotech 100 radiometer at approximately weekly intervals throughout the growing season. Agronomic and cultural observations made coincidently with reflectance data included development stage, plant height, leaf area index and grain yield. Associated with the experiment were various agronomic treatments which included the following: 1) two soil types (Chalmers silty clay loam, typic arigiaquoll and Russell silt loam, typic hapludalf), 2) two row widths (25 and 75 cm), 3) two cultivars (Amsoy 71 and Williams), and 4) three planting dates (May 10, May 24, and June 15 for Chalmers and May 24, June 15, and July 3 for the Russell soil).

The Landsat Multispectral Scanner (MSS) data utilized in this study was acquired over two crop seasons (1978 and 1979). For 1978, 17 segments were used and each contained 10 specially designated soybean fields while in 1979, 9 segments were used and the number of fields varied from 5 to 15 per segment. During both years agronomic and cultural practice observations such as field size, planting date, crop emergence date, row direction, harvest date, and yield estimates were recorded as well as periodic observations on plant height, development stage, and percent ground cover. These "ground truth" observations were similar for the 2 years but did change in one significant observation, the scale used in recording soybean development stage. During 1978 soybean development stage was recorded using the scale reported by Fehr and Caviness[6]. In 1979 a simplified and less detailed scale was used. Table 1 gives the development scale designation used by ground observers for the 2 years and the corresponding crop development descriptions for the two scales. For convenience in numerical analysis the 1978 observations made according to Fehr and Caviness scale designations were translated to a numerical scale described by Kalton[7] in a manner suggested by Fehr et al.[8] While this numerical scale is less precise in describing the soybean development it is more convenient for numerical analysis.

Analysis of the 1979 data was performed using the simplified scale without translating it to the Kalton scale. In the author's viewpoint, the 1979 scale was sufficiently coarse in the stage intervals that further translation of the recorded values would only introduce further uncertainties in the ground observations.

IV. RESULTS

A. PLOT LEVEL DATA

The frequency of observation, controlled experimental conditions, and skill of trained agronomist making observations on the soybean plots makes this data set suitable for verification of the models performance over variations in planting dates, row spacing, cultivar, and background soil reflectance. The Exotech-100 spectral values were converted to greenness using the calibration of Rice et al.[9]

The calculated development stage using the model compared to observed development stage for all treatments of the soybean experiment conducted at the Purdue Agronomy Farm in 1978 gave a linear correlation coefficient of 0.96 (Table 2) which indicates a good fit. To verify the models applicability for soybeans being grown under various management practices the model was run using only data from selected treatments of the soybean experiment. Table 2 summarizes these results with the model working equally well on all of the various treatments. In all cases the linear correlation coefficient of the best fit straight line exceeded 0.90 with the bias (point of intercept) and slope of line being close to 0.0 and 1.0 respectively.

An even more rigorous examination of the results would be to determine how the model performed when estimating individual ground observed stages throughout the growing season. Table 3 shows the results of this analysis for observed stages 3.0 (fourth node) through stage 10.0 (beginning of maturity). The maximum error of 0.9 stages of development occurred at ground stage 7.0 (full pod). An error of this size would translate to about 8 or 9 days at that particular stage based upon an average rate of development shown by Fehr and Caviness.[6]

B. LANDSAT DATA

Landsat multispectral data for two crop years (1978 and 1979) from a number of locations were analyzed to determine how well the model would perform on a large scale which includes variations due to weather and cropping practices. Because of the differences in ground observed development stages discussed earlier, the results for the 2 years will be discussed separately. Using the 1978 Landsat data set the result of the models output showed a linear correlation coefficient of 0.894 with no bias between calculated and observed soybean development stages (Table 4a). This is somewhat poorer fit than observed for the Agronomy Farm results in Table 2. This is probably expected as the ground observations as well as spectral data taken from fields will have more uncertainty than data taken from experimental plots. It should be noted that except for early stages the observed data was recorded in increments of one complete stage making it possible to have measurement error of 1.0 stages of development and contributing to the scatter in the data that occurs at some of the ground observed stages.

As with the Agronomy Farm data, analysis was also conducted for individual ground observed stages for the 1978 Landsat data. Table 4 shows these results and indicates similar model performance at all ground observed stages with the largest discrepancy between ground observed and the mean of any calculated development stage being 0.6 stages occurring at full bloom.

Analysis results using 1979 Landsat data was performed to verify model performance over additional yearly variations due to different seasons. This analysis is given in Tables 4b and 6. Results of correlating the ground observed stage with model calculated stage is given in Table 4b, where, in addition to data from all fields, the data was subdivided into arbitrary categories of planting time, field size, and yield levels. The correlation coefficient was quite similar to that obtained from 1978 data but a bias did occur for the earliest stages for the various categories as well as for all fields combined. One possible explanation of this bias lies in the points of spectral emergence chosen to calibrate the model. Because of the differences in the development stages scale there is some uncertainty in trying to choose the same development stage for both years. In 1978, the stage was estimated to be about stage 2.3 (Kalton scale) or slightly after the fourth-node stage. For 1979 an attempt was made to keep the spectral emergence stage the same. Therefore, stage 3.1 (1979 NASA scale) was chosen as the stage of spectral emergence to calibrate the model. No attempt was made to use 1979 data to redefine the point of spectral emergence because of the desire to validate the original model on an independent set of data. Results obtained for 1979 data analysis shown in Table 4b did indicate consistent model behavior for a range of conditions such as planting date, field size, and yield levels. Data from each of these categories of fields had very similar correlations, intercept and slope. Table 6 shows the results of comparing the calculated development stage with specified ground observed stage. In this respect the model performed equally well as it did for 1978. The maximum discrepancy of 0.4 occurred at ground observed stages 3.8 and 4.0 (mid to full pod). The standard deviation of approximately 0.5 stages or less for all stages throughout the season indicates reasonable agreement of the calculated points about the mean.

Table 1. Relationship of Fehr and Caviness, 1979 NASA, and Kalton Soybean Development Scales and Approximately Crop Description at the Various Scale Designations

1978 Fehr & Caviness	1979 NASA Scale	Kalton Scale	Abbreviated Soybean Description
--	1.0	--	Planting
VE	--	--	Emergence
VC	2.0	--	Cotlydon Above Soil
V1	--	--	First Node
V2	--	1	Second Node
V3	--	--	Third Node
V4	3.0	2	Fourth Node
R1	3.4	3	Beginning Bloom
R2	--	4	Full Bloom
R3	3.6	5	Beginning Pod
R4	4.0	6	Full Pod
R5	4.5	7	Beginning Seed
R6	5.0	8	Full Seed
R7	5.5	9	Beginning Maturity
R8	6.0	10	Full Maturity

Table 2. Results of Computing Best Fit Straight Line of Calculated Stage Vs. Observed Stage Using Data from Purdue Agronomy Farm (1978) Grouped According to Experimental Treatments

Experimental Treatment	Treatment Description	Best Fit Straight Line		
		Intercept	Slope	Correlation Coefficient
Cultivar	Amsoy	-0.12	1.03	0.958
	Williams	0.05	1.00	0.962
Planting Date	1*	-0.08	1.04	0.970
	2*	0.10	0.99	0.963
	3*	-0.48	1.05	0.916
Soil Background	Chalmers	0.29	0.99	0.962
	Russell	0.25	1.03	0.959
Row Spacing	25 cm	0.23	1.00	0.970
	75 cm	-0.33	1.02	0.952
All Data	-	-0.04	1.01	0.960

*Planting dates on Chalmers soil were 1 = May 10, 2 = May 24, and 3 = June 15, for the Russell soil planting dates were 1 = May 24, 2 = June 15, and 3 = July 3.

Table 3. Mean, Standard Deviation, and Number of Observations of the Computed Development Stage for Given Ground Observed Stages (Fehr and Caviness Scale Converted to Kalton Scale) for 1978 Data Acquired from Purdue Agronomy Farm Soybean Plots.

Ground Observed Stage	Approximate Stage Description	Calculated Stage		
		Mean	Std. Dev.	No. of Observations
3.0	Fourth Node	3.3	0.42	23
4.0	Sixth Node	4.0	0.78	41
5.0	Full Bloom	5.2	0.62	21
6.0	Beginning Pod	6.7	0.72	13
7.0	Full Pod	7.9	0.30	21
8.0	Beginning Seed	8.3	0.60	26
9.0	Full Seed	8.9	0.58	50
10.0	Beginning Maturity	9.5	0.79	76

Table 4a. Results of Computing Best Fit Straight Line for Calculated Stage vs. Observed Stage Using 1978 Landsat MSS Data.

Year	Categories of Data	Best Fit Straight Line			
		Intercept	Slope	Correlation Coefficient	No. of Observations
1978	All data	0.18	0.99	0.894	670

Table 4b. Results of Computing Best Fit Straight Line for Calculated Stage vs. Observed Stage Using 1979 Landsat MSS Data That Has Also Been Grouped Into Various Categories for More Detailed Analysis.

Year	Categories of Data	Best Fit Straight Line			
		Intercept	Slope	Correlation Coefficient	No. of Observations
1979	All Data	0.71	0.86	0.873	956
1979	Early Planted Fields	0.67	0.88	0.876	345
	Late Planted Fields	0.75	0.85	0.871	490
1979	Small Fields	0.81	0.83	0.881	431
	Large Fields	0.61	0.87	0.868	438
1979	Low Yielding Fields	0.81	0.84	0.876	470
	Higher Yielding Fields	0.62	0.88	0.871	462

Table 5. Mean, Standard Deviation, and Number of Observations of the Computed Development Stage for Given Ground Observed Stages (Fehr and Caviness Scale Converted to Kalton Scale) Using 1978 Landsat MSS Data.

Ground Observed Stage	Approximate Stage Description	Calculated Stage		
		Mean	Standard Deviation	No. of Obs
3.0	Fourth Node	3.5	0.80	10
4.0	Sixth Node	4.2	1.22	79
5.0	Full Bloom	4.4	0.81	65
6.0	Beginning Pod	5.9	1.25	59
7.0	Full Pod	6.8	1.24	77
8.0	Beginning Seed	8.4	1.30	75
9.0	Full Seed	9.3	1.15	129
10.0	Beginning Maturity	10.0	0.89	74

Table 6. Mean, Standard Deviation and Number of Observations of the Calculated Development Stage for Given Ground Observed Stages (1979 NASA Development Scale) Using 1979 Landsat MSS Data.

Ground Observed Stage	Approximate Stage Description	Calculated Stage		
		Mean	Standard Devision	No. of Obs.
3.0	Fourth Node	3.2	0.09	76
3.4	Beginning Bloom	3.4	0.17	75
3.5	Full Bloom	3.5	0.22	55
3.6	Beginning Pod	3.8	0.32	60
3.8	Mid Pod	4.2	0.44	39
4.0	Full Pod	4.4	0.56	28
4.5	Beginning Seed	4.7	0.24	25
5.0	Full Seed	5.1	0.40	75
5.5	Beginning Maturity	5.4	0.34	35
5.8	Mid Maturity	5.8	0.23	42
6.0	Full Maturity	5.8	0.34	18

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