1. Roy EASON

E82-10059

CR-161023

2. # AgRISTARS

7. SR-L0-04002
JSC-16830

NOV 10 1980

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

Supporting Research.

6. October 1980

5. NAS9-15800

PRELIMINARY EVALUATION OF SPECTRAL, NORMAL, AND METEOROLOGICAL CROP STAGE ESTIMATION APPROACHES

NASA CR-161023

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(E82-10059) PRELIMINARY EVALUATION OF SPECTRAL, NORMAL AND METEOROLOGICAL CROP STAGE ESTIMATION APPROACHES (Lockheed Engineering and Management) 74 p HC A04/MF A01 CSCL 02C G3/43 N82-19634 Unclas 00059

4. Lockheed Engineering and Management Services Company, Inc.
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SR-LO-04002
JSC-16830

TECHNICAL REPORT

PRELIMINARY EVALUATION OF SPECTRAL, NORMAL, AND METEOROLOGICAL CROP STAGE ESTIMATION APPROACHES

Job Order 73-312

This report describes Vegetation/Soils/Field Research activities of the Supporting Research project of the AgRISTARS program.

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LOCKHEED ENGINEERING AND MANAGEMENT SERVICES COMPANY, INC.

Under Contract NAS 9-15800

For

Earth Observations Division
Space and Life Sciences Directorate
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

October 1980

LEMSCO 14640

1. Report No.
SR-L0-04002; JSC-16830

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Preliminary Evaluation of Spectral, Normal, and Meteorological Crop Stage Estimation Approaches

5. Report Date
October 1980

6. Performing Organization Code

7. Author(s)
R. B. Cate, J. A. Artley, P. C. Doraiswamy, T. Hodges, M. C. Kinsler, D. E. Phinney, and M. L. Sestak

8. Performing Organization Report No.
LEMSCO-14640

9. Performing Organization Name and Address
Lockheed Engineering and Management Services Company, Inc.
1830 NASA Road 1
Houston, Texas 77058

10. Work Unit No.

11. Contract or Grant No.
NAS 9-15800

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058 Technical Monitor: J. D. Erickson

13. Type of Report and Period Covered
Technical Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
Several of the projects in the Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) program require crop phenology information, including classification, acreage and yield estimation, and detection of episodal events. This study evaluates several crop calendar estimation techniques for their potential use in the program. The techniques, although generic in approach, were developed and tested on spring wheat data collected in 1978. There are three basic approaches to crop stage estimation: historical averages for an area (normal crop calendars), agrometeorological modeling of known crop-weather relationships [agrometeorological (agromet) crop calendars], and interpretation of spectral signatures (spectral crop calendars). Normals serve as the baseline against which the skill of the other models may be tested. Agromet crop stage models require planting dates to initiate the accumulation of weather variables. When a data set does not include planting dates, these dates may be estimated with normal, agromet, or spectral starter models and used to start the agromet stage models. The 1978 spring wheat data set does not include planting dates. Consequently, five starter models and the normal planting date were used, including the Feyerherm and Stuff-Phinney agromet starter models and the Badhwar profile, color, and linear-discriminant spectral starter models. The planting date models were compared by using them to adjust the normal crop calendar to predict stages on dates for which ground truth is available. Two agromet models, the Robertson and Doraiswamy, were tested using normal, Feyerherm (the best agromet starter), and linear discriminant (the best spectral starter) planting dates. In all, 10 combinations of planting and biostage estimation models were evaluated. Dates of stage occurrence are estimated with biases between -4 and +4 days while root mean square errors range from 10 to 15 days. Results are inconclusive as to the superiority of any of the models and further evaluation of the models with the 1979 data set is recommended.

17. Key Words (Suggested by Author(s))
AgRISTARS, agrometeorological crop calendar, crop calendar, crop stage estimation, normal crop calendar, phenology, planting date, spectral crop calendar, spring-wheat, starter model weather/crop interactions

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
74

22. Price*

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1. INTRODUCTION

The Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) is a 6-year program of research, development, evaluation, and application of aerospace remote sensing for agricultural resources beginning in fiscal year (FY) 1980. The AgRISTARS program is a cooperative effort of the National Aeronautics and Space Administration (NASA), the U.S. Agency for International Development (AID), and the U.S. Departments of Agriculture, Commerce, and the Interior (USDA, USDC, and USDI).

The goal of the program is to determine the usefulness, cost, and extent to which aerospace remote sensing data can be integrated into existing or future USDA systems to improve the objectivity, reliability, timeliness, and adequacy of information required to carry out USDA missions. The overall approach is comprised of a balanced program of remote sensing research, development, and testing which addresses domestic resource management as well as commodity production information needs.

The technical program is structured into eight major projects as follows:

1. Early Warning/Crop Condition Assessment (EW/CCA)
2. Foreign Commodity Production Forecasting (FCPF)
3. Yield Model Development (YMD)
4. Supporting Research (SR)
5. Soil Moisture (SM)
6. Domestic Crops and Land Cover (DCLC)
7. Renewable Resources Inventory (RRI)
8. Conservation and Pollution (C/P)

The majority of these projects will make direct use of information on crop phenology. Specific areas of these projects to which phenological information is pertinent include classification, acreage and yield estimation, and detection of episodal events.

This report presents results of developmental studies directed toward the identification of crop calendar techniques suitable for use in AgRISTARS projects. Although most of the approaches are generic in nature, the focus has been on spring wheat, with the expectation that the initial user in the AgRISTARS program will be the FCPF project.

2. BACKGROUND

Prediction of crop growth stages (phenology) may be achieved through three independent methods: calculating historical averages for an area (normal crop calendars); agrometeorological modeling from knowledge of crop-weather interactions [agricultural-meteorological (agromet) crop calendars]; and interpretation of spectral signatures (spectral crop calendars). Models of these types have been and are currently being developed. The quantification of crop-weather-spectral relationships (spectromet crop calendars) in a single model is still in the early stages of research.

The nature of the crop stage estimation problem, however, allows for the development and testing of crop calendar systems which have components of different types. Typically, an agromet crop stage model requires knowledge of planting dates. Thus, a spectral approach which estimates planting dates could be used to initialize an agromet stage model. This kind of system may be considered a first generation spectromet model.

The following paragraphs provide an overview of the general characteristics of the major crop calendar components and systems which were examined in this study.

The normal crop calendars provide a baseline against which other methodologies can be evaluated. A simple measure of skill lies in the amount to which a candidate technique reduces the variance in stage estimates as compared to the reduction achieved by normal crop calendars.

Adjusted normal models utilize planting date estimates to shift the normal crop calendars in time. Agromet planting date models providing segment-level estimates were evaluated both independently and as part of such hybrid systems. Due to constraints in the available data, spectral planting date estimation systems providing field-level estimates were developed and evaluated only in the context of the adjusted normal model.

Normal, agromet, and spectral planting date models were evaluated in conjunction with two agromet crop development models due to lack of data sets suitable for independent evaluations.

Two spectral techniques which made direct estimates of crop growth stages on each Landsat acquisition date were developed and evaluated. The models were evaluated on a subset of 1978 crop-year data for which there were simultaneous ground truth and spectral observations. Each acquisition was considered independently for both techniques.

The spectral stage estimates for each acquisition were also used with a normal crop development scale to estimate planting dates. The average spectral planting date with respect to field was calculated for use in the previously mentioned spectromet and adjusted-normal models.

In contrast, but also falling into the adjusted-normal classification, a spectral technique which fit the multitemporal signature sequence was evaluated. For this technique, at least three spectral acquisitions for application were required. The technique provided an estimate of the date of maximum spectral response. The date of peak response was combined with a normal crop development scale to estimate the planting stage date as well as other growth stage dates. This approach was evaluated against ground truth observations of growth stages for those segments in which it could be applied.

The following sections provide a summary of the data used, specific models used, and evaluation results. In most cases, technical details of the models and developmental results have been placed in appendices of this document.

3. DATA

Two distinct data sets were available for use in evaluating crop stage models. The first set was collected at intensive test sites (ITS) of the Large Area Crop Inventory Experiment (LACIE) during crop years 1975 to 1977 (ref. 1). The second set was collected at the LACIE Transition Year (TY) blind sites during the 1978 crop year (ref. 2).

Limitations inherent in each of these data sets placed constraints on the nature of possible test runs. The data needed included field-level observations of planting date, periodic observations of phenology during the season, and multitemporal Landsat observations of the same fields along with representative daily meteorological data. The ITS data set was found to be suitable only for testing agroment planting date models. The number of spectral acquisitions was too small for evaluation of spectral models. The phenological observations were also few in number and were taken on a scale of limited usefulness. The ITS data set is shown in table 3-1.

The TY data set was complete except for inclusion of the planting dates. This data set was used to evaluate the spectral stage estimation models and the hybrid model systems. Data were collected for spring wheat at blind sites in Montana, North Dakota, South Dakota, and Minnesota. Ground truth observations were collected for special fields every 9 or 18 days. The development of the crops was observed using the Feekes scale. Table 3-2 gives a summary of the number of fields observed, the number of usable Landsat acquisitions, the number of ground truth observations, and the number of fields available for evaluation with the multitemporal profile (Badhwar) technique. The locations of the segments are shown in appendix A.

TABLE 3-1.- COMPONENTS OF EVALUATION DATA SET FOR PLANTING DATE MODELS

State	Segment	Year	Number of fields
North Dakota	1965	1975	8
Minnesota	1987	1975	45
South Dakota	1687	1976	9
North Dakota	1965	1976	8
North Dakota	1966	1976	31
North Dakota	1967	1976	5
Montana	1970	1976	2
Minnesota	1987	1976	12
South Dakota	1687	1977	10
Minnesota	1987	1977	11

TABLE 3-2.- BLIND SITE TRAINING/EVALUATION SET FOR SPRING WHEAT

State	Segment	Number of fields[a]	Number of Landsat acquisitions	Number of periodic observations	Number of usable observations
N. Dak.	1387	5	2	5	25
N. Dak.	1392	11	3	5	55
N. Dak.	1394	8 (3)	6	4	29
N. Dak.	1457	5 (5)	5	6	31
N. Dak.	1461	13 (12)	7	8	70
N. Dak.	1472	2	3	7	13
N. Dak.	1473	4	3	4	16
S. Dak.	1485	13	3	3	41
Minn.	1518	12 (12)	7	8	79
Mont.	1537	2 (2)	7	6	11
Mont.	1542	6 (6)	6	5	29
Mont.	1544	4 (3)	5	5	18
Mont.	1553	3 (3)	7	7	18
Minn.	1566	15 (8)	4	7	97
N. Dak.	1584	8	3	6	40
N. Dak.	1612	7 (3)	4	6	39
N. Dak.	1619	8 (7)	4	5	40
N. Dak.	1636	10 (10)	9	7	54
N. Dak.	1658	7	2	6	40
N. Dak.	1664	6	3	6	35
S. Dak.	1668	7 (3)	4	6	38
S. Dak.	1755	3 (2)	7	5	14
S. Dak.	1811	12 (10)	5	6	58
Minn.	1825	13 (13)	5	4	52
N. Dak.	1918	4	3	6	21
N. Dak.	1920	8 (7)	6	6	47
N. Dak.	1924	4 (4)	8	6	22
Mont.	1942	6	2	5	25
Total	28	206 (113)			1057

[a]Numbers in parentheses indicate number of fields usable for the Badhwar multitemporal profile fit.

4. MODELS

Three estimators of spring wheat planting dates were evaluated using as ground truth the planting dates of the fields in the ITS data set. One was the normal planting date as estimated from historical Crop Reporting District (CRD) dates. For Minnesota and South Dakota, the estimates are based on ten years of data. Only five years of data were available for North Dakota and Montana.

Two agromet planting date models, the Feyerherm and the Stuff-Phinney, were evaluated. Details of these models may be found in appendices B and C, respectively. Using weather data to estimate the rate of planting, segment-level planting dates were predicted by these models.

The model systems tested are described in the following paragraphs (sections 4.1 through 4.7). The available data set did not contain observations of planting dates. Therefore, a planting date estimation algorithm was tested in conjunction with a crop stage estimation algorithm. The mnemonic labels for each system indicate the starter model and the crop stage model that were used.

4.1 THE NORMAL-NORMAL MODEL

The basic concept of this model is that historical averages can be used to predict current year crop development. The mechanism by which this is done consists of applying the standardized crop development scale, described in appendix D, to the historical averages for the CRD's in which the various segments are located. The normal planting and harvest dates applicable to each segment are given in appendix E.

4.2 FEYERHERM-ADJUSTED NORMAL MODEL

The basic concept of this model is that the Feyerherm agrometeorological planting date model can be used to shift the normal model's standardized crop development scale (appendix D) backward or forward in time and thus account for a major portion of the year-to-year variability in crop development rate.

4.3 FEYERHERM-ADJUSTED ROBERTSON MODEL

The basic concept of this model is that the combination of two agrometeorological models will provide better estimates of growth stages than would either one used in conjunction with the normal model. The Robertson model is a triquadratic multiplicative model that uses photoperiod and maximum and minimum daily temperatures to estimate growth stages. It is initiated on the planting date estimated by the Feyerherm model. A description of the Robertson model is presented in appendix F.

4.4 FEYERHERM-ADJUSTED DORAISWAMY MODEL

The basic concept of this model is similar to the preceding one, with the additional assumption that performance of the Robertson model can be improved by making the coefficients more realistic than those originally derived by statistical fitting. Details on the Doraiswamy agromet model may be found in appendix G.

4.5 BADHWAR-ADJUSTED NORMAL MODEL

The basic concept of this model is that the model function, when fit to field spectral data, provides peak Kauth greenness dates which will improve the performance of the normal model. Further details on the development and adaptation of this model are provided in appendix H.

4.6 COLOR-ADJUSTED NORMAL MODEL

The basic concept of this model is that an empirical logic based on color-coded Landsat data can be combined with the normal model to provide improved estimates of growth stages. The independent performance of the color logic in predicting coincident ground truth biostages was also measured. Further details on the methodology of the color approach are in appendix I.

4.7 SPECTRAL LINEAR DISCRIMINANT-ADJUSTED NORMAL MODEL

The basic concept of this model is that the linear discriminant analysis of a set of training data can provide spectral stage estimates which can be combined with the normal model to provide improved estimates of growth stages.

The independent performance of the linear discriminant coefficients in predicting coincident ground truth biostages was also measured. Further details on the development of these models are given in appendix J.

4.8 COMMENTS ON ERROR ESTIMATES

All of the adjusted-normal and spectromet models were programmed to estimate the Julian date on which the observed ground truth biostages would occur. The estimates are for the midpoints of all the stages except planting and harvest, when beginning and end days of the crop calendar sequence are used. Each ground truth development stage has a finite length ranging from less than 2 days to nearly 13 days. If the ground truth observation is taken randomly from a uniform distribution, the variance, due to assuming it occurs at the midpoint, is $I^2/12$, where I is the duration of the stage. This "rounding error" ranges from near 0.5 days [root mean square (RMS)] to 3.75 days, depending on the stage. For the ground truth evaluation data set used in this study, the error for an algorithm that correctly estimated the stage of each observation would be approximately 2 days (RMS).

The color sequence logic and the linear discriminant models were programmed to estimate the Feekes growth stage in each field for each Landsat acquisition. The error of estimate for these models was calculated by converting both the estimate and the ground truth data to the percentage of normal development scale (see appendix D).

5. RESULTS

The normal and agromet planting date estimation models were evaluated using the Intensive Test Site (ITS) data set.

The predicted planting dates using the three estimators are presented in table 5-1. Error statistics were calculated for each field. Table 5-2 shows a summary of these statistics at the segment level for all segments.

No tests of significance have been performed. However, the Feyerherm model is clearly superior to the Stuff-Phinney model and shows a sizable reduction in bias and root mean square error (RMSE) when compared to the normal model.

Figure 5-1 indicates that the estimates of the Stuff-Phinney model are strongly correlated with those of the normal model, whereas the Feyerherm estimates are relatively independent. The Stuff-Phinney model was eliminated from further consideration. The Feyerherm model was selected as the best agromet planting date model for use in the evaluation of the model systems.

The results of the comparative evaluation of the growth stage estimation models are summarized in table 5-3. The table shows results for the normal, spectromet, agromet, and adjusted-normal models when they were applied to the TY data set. The results of the Badhwar-normal model are given for the fields upon which it could be applied. The results of direct growth stage estimates using the color sequence logic and the linear discriminant model are also shown. These models were evaluated on those observations which had coincident Landsat and ground-truth observations. Table 5-4 shows the performance of the seven models by segment and state. The remarks in the following paragraphs are based on these tables.

Evaluation of planting date estimation approaches may be made through comparison of their results when used in conjunction with the normal model as a biostage estimator. The discriminant spectral starter algorithm performed the best, showing over a 50 percent reduction in variance as compared to that of the normal model when averaged over all segments.

TABLE 5-1.- PREDICTED PLANTING DATES USED IN EVALUATION OF NORMAL AND METEOROLOGICAL STARTER MODELS

Segment	Year	Normal	Feyerherm	Stuff-Phinney
1965	1975	143	144	157
1987	1975	137	136	149
1687	1976	111	100	126
1965	1976	143	126	156
1966	1976	143	129	155
1967	1976	143	124	154
1970	1976	125	109	141
1987	1976	137	121	150
1687	1977	111	107	124
1987	1977	137	121	143

TABLE 5-2.- RESULTS OF STARTER MODEL EVALUATION

Segment	Year	N (a)	Normal		Feyerherm		Stuff-Phinney	
			RMSE	Bias (b)	RMSE	Bias (b)	RMSE	Bias (b)
1987	1975	45	5.993	2.489	5.651	1.489	15.339	14.178
1965	1975	8	8.254	.125	8.329	1.125	16.359	14.125
1967	1976	5	5.495	5.000	14.184	14.000	16.162	16.000
1970	1976	2	15.652	14.000	6.964	-2.50	30.806	30.000
1965	1976	8	4.213	-1.250	18.688	-18.250	12.420	11.750
1987	1976	12	34.0	33.6	18.3	17.6	46.9	46.6
1966	1976	31	21.579	19.710	10.477	5.710	32.904	31.710
1687	1976	9	23.840	19.889	15.868	8.889	37.283	34.889
1687	1977	10	9.654	-5.00	12.215	-9.00	11.500	8.00
1987	1977	11	31.700	31.182	16.217	15.182	37.616	37.182
Total		141	18.518	11.647	11.900	3.831	27.486	23.619

[a]N = number of fields used for evaluation.

[b]Error defined as estimated planting date minus observed planting date. Positive bias indicates model is late, while negative bias indicates model is early.

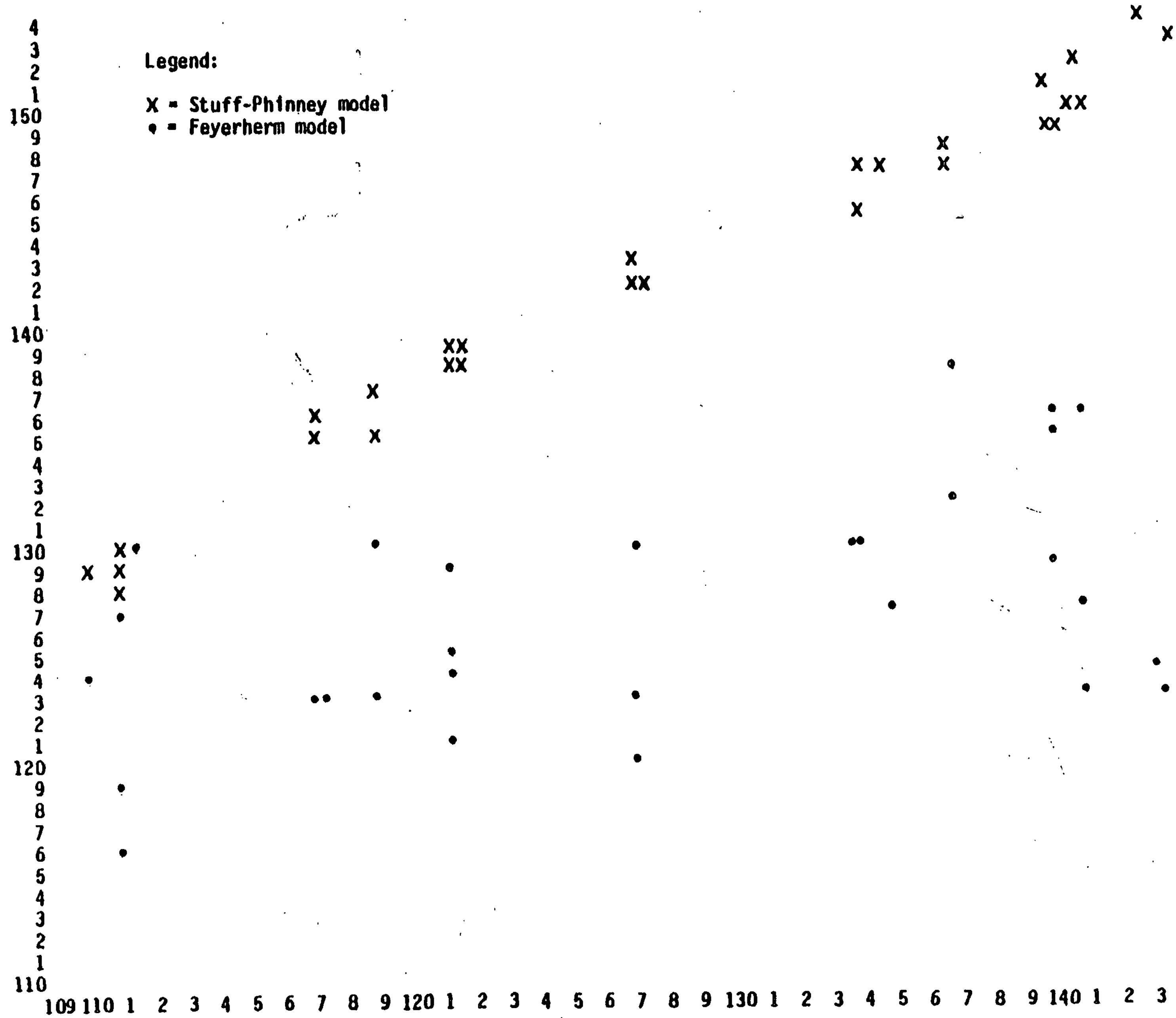

Figure 5-1.- Relationships of normal and meteorological model estimates of planting dates.

TABLE 5-3.- SUMMARY OF STATISTICS ON RESULTS OF APPLYING BIOSTAGE ESTIMATION MODELS TO THE GROUND TRUTH EVALUATION DATA SET

[N = total number of observations; N is 1057 unless noted]

Type of model	Planting estimator	Biostage estimator	Bias	RMSE	Comments
Normal	Normal	Normal	-2.1	14.8	Independent test
Adjusted — normal	Feyerherm	Normal	-4.3	13.7	Independent test
Agromet	Feyerherm	Robertson	3.6	15.4	Independent test
Agromet	Feyerherm	Doraiswamy	-2.5	14.2	Includes training set
Adjusted — normal	Color	Normal	4.1	12.2	Includes training set
Adjusted — normal	Discriminant	Normal	-1.5	10.3	Includes training set
Spectromet	Discriminant	Doraiswamy	0.6	10.1	Includes training set
Adjusted — normal	Badhwar (N = 681)	Normal	1.9	11.0	Field-by-field fits
Spectral	None (N = 453)	Color	-.6	11.5	Training set
Spectral	None (N = 464)	Discriminant	0.0	10.8	Includes training set

TABLE 5-4.- STATISTICAL COMPARISON OF BIOSTAGE ESTIMATES WITH FIELD GROUND TRUTH, BY SEGMENT, STATE, AND OVERALL[a]

[N = number of observations; total N is 1057]

State	Segment	N	Normal		Feyerherm + normal		Feyerherm + Doriswamy		Feyerherm + Robertson		Discriminant + Doraiswamy		Discriminant + normal		Color + normal	
			Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE
N. Dak.	1387	25	5.85	8.86	1.85	6.91	1.52	6.48	8.44	12.98	4.64	11.79	4.85	12.02	6.47	14.55
N. Dak.	1392	55	12.82	15.76	-1.18	9.24	-8.25	11.03	-2.31	10.58	-4.25	14.11	3.91	11.22	-15.10	17.70
N. Dak.	1394	29	-.38	7.42	-15.38	17.07	-16.93	17.60	-9.07	12.40	-2.72	6.09	-.66	7.14	6.46	9.80
N. Dak.	1457	31	-2.59	8.60	-18.59	20.32	-21.84	23.10	-15.26	17.77	-2.71	7.51	.79	7.80	6.49	10.91
N. Dak.	1461	70	8.54	13.33	-2.54	10.55	-3.60	21.09	6.87	14.27	1.66	7.80	4.76	11.04	8.04	12.95
N. Dak.	1472	13	3.75	8.19	-.25	7.28	4.92	7.93	11.85	14.62	9.54	11.75	4.52	8.91	12.82	14.76
N. Dak.	1473	16	5.61	7.12	1.61	4.67	5.50	6.02	9.44	11.45	3.88	4.77	-.39	4.61	5.48	13.51
S. Dak.	1485	41	-12.67	17.33	-6.67	13.57	3.83	9.96	9.37	17.00	.51	9.94	-10.06	16.00	2.60	15.73
Minn.	1518	79	4.15	12.60	5.15	12.96	-2.44	11.02	5.43	14.73	-7.58	12.82	-.14	11.27	6.30	13.08
Mont.	1537	11	-1.77	13.39	-9.77	16.48	-10.00	15.26	-3.82	14.44	-7.00	8.61	-7.05	10.42	.06	9.47
Mont.	1542	29	-10.69	18.25	-21.69	26.26	-25.34	30.00	-21.55	27.09	-8.45	14.92	-4.38	11.64	3.52	11.08
Mont.	1544	18	-4.28	10.70	-10.28	14.21	-8.61	11.86	-4.78	12.00	-2.00	6.94	-3.56	9.27	4.40	9.75
Mont.	1553	18	-6.72	12.20	-9.72	14.08	-5.57	10.93	1.17	12.13	-5.44	8.22	-9.28	11.66	-.03	14.96
Minn.	1566	97	-7.08	9.45	3.92	7.39	11.02	13.71	17.73	21.14	1.96	8.71	-5.37	8.23	1.30	7.60
N. Dak.	1584	40	4.23	8.58	-.77	7.50	-2.85	9.88	2.65	8.67	-0.93	8.08	1.43	6.21	5.63	11.50
N. Dak.	1612	39	12.63	15.34	-5.37	10.23	-11.13	13.24	-6.31	11.06	0.13	7.20	6.30	10.76	5.55	11.30
N. Dak.	1619	40	16.17	17.34	5.17	8.13	1.90	6.25	8.20	10.82	2.20	7.17	5.54	9.05	8.01	11.40
N. Dak.	1636	54	-2.72	8.73	-11.72	14.36	-9.30	12.32	-4.43	10.87	2.89	7.00	.85	7.46	3.59	10.26
N. Dak.	1658	40	-4.62	10.48	-2.62	9.76	7.75	11.11	13.58	18.19	8.48	10.91	-1.92	8.88	1.80	13.21
N. Dak.	1664	35	-4.43	10.33	2.57	9.68	13.31	15.66	18.80	21.84	10.49	12.16	-.51	7.05	4.96	9.91
S. Dak.	1668	38	-23.10	24.33	-17.10	18.72	-6.18	9.88	1.61	10.81	6.00	10.34	-5.47	9.85	-16.04	18.99
S. Dak.	1775	14	-12.95	15.40	-4.95	9.70	6.57	9.26	13.79	17.42	11.21	12.98	-.17	8.36	8.38	14.93
S. Dak.	1811	58	-22.33	23.37	-3.33	7.65	9.13	12.96	11.45	13.87	8.45	11.80	-6.52	9.73	1.00	6.91
Minn.	1825	52	15.13	18.46	10.13	14.65	5.63	8.14	10.13	15.20	-1.23	6.60	3.05	11.15	5.54	12.58
N. Dak.	1918	21	-16.54	19.17	-13.54	16.65	-2.90	12.02	5.24	17.05	.29	10.75	-10.54	13.66	-.65	11.67
N. Dak.	1920	47	-18.94	20.26	-25.94	26.92	-18.77	20.35	-14.42	16.34	-1.96	7.62	-9.11	11.56	-3.82	9.43
N. Dak.	1924	22	-15.62	17.89	-12.62	15.34	-4.08	8.18	.23	10.73	6.09	9.44	-2.84	8.61	9.94	12.77
Mont.	1942	25	-.36	8.13	-11.36	13.97	-12.36	14.42	-7.60	11.31	-12.12	16.10	-11.36	16.60	5.30	9.68
Mont.		[a]101	-5.31	13.36	-13.67	18.63	-13.95	19.53	-9.13	17.83	-7.52	12.52	-7.13	12.59	3.11	11.18
N. Dak.		[a]577	1.28	13.43	-5.72	13.69	-5.05	14.65	1.25	14.04	1.71	9.31	.85	9.57	5.94	12.40
S. Dak.		[a]228	-19.03	21.50	-7.85	13.02	3.60	11.13	8.63	14.49	5.93	11.09	-4.39	9.52	-2.17	14.03
Minn.		[a]151	1.88	13.07	5.76	11.42	5.13	11.71	11.74	17.83	-2.07	9.96	-2.47	12.36	4.00	10.95
Overall		1057	-2.12	14.78	-4.31	13.71	-2.47	14.17	3.57	15.38	0.62	10.06	-1.52	10.32	4.09	12.24

[a]Total number of observations per state.

The other spectral starter models showed intermediate results between those of the discriminant spectral starter model and the Feyerherm agromet model. It seems likely that the spectral techniques pick up at least part of the real field-to-field variaton.

The two agromet crop development models can be compared through their performance when combined with the same starter model. The results of the Feyerherm-Robertson and the Feyerherm-Doraiswamy models are shown in tables 5-3 and 5-4. The Feyerherm agromet starter model was used as a baseline. The Doraiswamy model showed a slightly better performance than did the Robertson model.

The performance of the basic adjusted-normal and agromet systems along with that of the normal model is given by growth stage in table 5-5. Examination of the normal models indicates that, although the crop was slow in development before the heading stage the season as a whole was near average. During heading and the early part of grain filling, the crop developed faster than normal, slowed during ripening, and was harvested somewhat before the normal date. The adjusted-normal models had the same development pattern. The agromet stage model picked up part of the weather-induced development variation, with the Doraiswamy model performing substantially better than the Robertson model in stages from heading to ripe. Appendix K contains additional details on evaluations of the two agromet stage estimation models.

Contrary to what might be expected, the (average) number of acquisitions in a segment had little effect on the error. This is demonstrated in table 5-6, which shows a comparison of the acquisition number with the RMSE, using the two models with the lowest RMSE overall. The explanation may be that the spacing of the acquisitions rather than their absolute number affects performance.

The discriminant spectral starter model was combined with the Doraiswamy model. This spectromet model showed the best performance of those models evaluated in this study (tables 5-3 and 5-4).

TABLE 5-5.- SUMMARY OF STATISTICS ON RESULTS OF APPLYING BIOSTAGE ESTIMATION MODELS TO GROUND-TRUTH EVALUATION DATA SET BY GROWTH STAGE

[N = number of observations; total N is 1057]

Feekes ground truth stage	N	Normal		Feyerherm + normal		Color + normal		Discriminant + normal		Feyerherm + Robertson[a]		Feyerherm + Doraiswamy[a]	
		Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE
0.0	26	-12.62	15.12	-8.69	13.33	-4.31	7.49	-11.35	12.20	-8.4	10.8	-9.5	12.1
1.0	98	-2.48	12.26	-8.32	12.74	3.50	10.73	-1.65	8.27	-5.8	16.8	-4.4	18.1
2.0	57	-6.43	13.31	-7.38	12.66	-0.20	11.09	-5.17	10.01	-3.5	13.5	-0.2	10.3
3.0	40	-9.63	18.13	-11.63	17.59	-5.60	12.74	-8.15	12.39	10.8	16.2	11.0	16.5
4.0	72	-5.51	14.45	-7.42	14.69	0.83	9.73	-5.47	10.42	-4.4	11.1	-3.3	10.6
5.0	58	-6.51	13.70	-9.29	13.98	-0.60	8.53	-7.51	11.01	-1.8	16.6	-5.2	15.9
6.0	24	-6.40	12.60	-10.36	13.62	-3.07	8.11	-10.61	13.30	-5.7	11.0	-5.0	10.7
7.0	20	-11.40	17.67	-8.52	14.15	-1.27	5.60	-9.72	12.03	2.2	12.1	1.8	11.6
8.0	18	-4.58	10.67	-2.47	8.66	2.03	8.19	-3.03	5.76	1.2	13.2	3.5	16.7
9.0	23	-9.81	16.83	-12.51	19.19	1.80	9.30	-6.73	10.39	-2.5	14.7	-6.0	16.2
10.0	31	-3.81	12.81	-7.58	14.05	0.61	10.15	-1.87	7.26	13.8	17.4	2.0	12.2
10.1	16	-3.29	13.07	-8.23	14.20	5.64	13.55	3.58	8.83	-11.3	16.7	-21.5	25.4
10.2	5	8.22	8.42	2.22	6.46	13.62	14.49	7.02	7.65	--	--	--	--
10.3	9	5.00	10.25	6.78	8.52	2.11	6.56	1.22	4.76	--	--	--	--
10.4	18	3.14	9.55	9.25	10.12	11.75	14.35	3.91	8.12	30.0	30.0	17.0	17.0
10.5	105	5.58	15.19	0.19	14.01	12.83	17.36	5.18	11.99	13.3	21.9	1.1	16.4
11.1	165	5.85	17.38	3.67	14.04	11.24	16.06	6.33	12.06	16.0	20.3	-2.1	12.0
11.2	37	0.84	13.75	-1.84	8.81	5.00	10.59	-0.30	7.48	11.3	12.6	-3.7	6.5
11.3	17	-4.59	14.75	-2.83	13.05	2.35	8.28	-0.83	5.80	6.0	14.3	1.0	9.7
11.4	48	-1.32	11.85	-2.30	13.18	7.01	11.05	1.36	7.80	12.1	17.1	4.9	13.9
11.5	170	-4.98	15.36	-6.32	13.74	1.34	10.73	-4.49	9.71	0.9	12.4	-3.2	12.6
Overall		-2.12	14.78	-4.31	13.71	4.09	12.24	-1.52	10.32	3.57	15.38	-2.47	14.17

[a]Due to computional problems, these statistics were calculated using the median ground truth for each segment.

TABLE 5-6.- EFFECT OF NUMBER OF ACQUISITIONS ON THE RMSE OF THE DISCRIMINANT-NORMAL AND DISCRIMINANT-DORAISWAMY MODELS

Number of acquisitions	Number of segments	RMSE, discriminant and normal	RMSE, discriminant and Doraiswamy
3	1	16.0	9.9
4	5	9.1	8.3
5	13	10.3	10.2
6	8	9.6	9.8
7	1	8.2	8.7

The two spectral stage estimation models showed similar performances. A summary of the overall results is given in table 5-3. Table 5-7 provides additional details on the results obtained with these models at the segment and state levels. The results of the Badhwar multitemporal stage estimator, which uses the date of peak greenness to adjust the normal crop calendar, are also shown. Comparisons of the results of these models and the results of the other systems may be made only indirectly due to the different sample sizes available for evaluation.

The following general observations on model performance were made.

a. The poor performance of the Robertson model is due largely to failure to detect more rapid than normal crop development in most segments during the heading and flowering stages.

b. The Doraiswamy model picks up some but not all of this speed-up in development. Future incorporation of a stress variable may improve the accuracy of the model.

c. The relatively poor performance of the adjusted-normal models is due largely to the fact that they are coupled with the rigid normal model.

d. However, even when the spectral models are used independently (on those observations which have both ground truth and spectral data) the accuracy is not high (approximately 11 days RMS), apparently because spectral growth stages correspond only roughly to physiological growth stages. This is to be expected since, for example, stress can produce premature chlorophyll disappearance while excess nitrogen can delay it. Similarly, different varieties could well have different spectral properties at a given physiological stage, or similar properties at different stages.

e. The real strength of the spectral models has not been measured in the evaluation technique employed in this study. This strength lies in their ability to identify multitemporal spectral sequences, which analysts tend to refer to as spectral crop calendars. All three spectral approaches can capture these multitemporal patterns.

TABLE 5-7.- SUMMARY OF STATISTICS FOR FITS OF BIOSTAGE ESTIMATION MODELS

State	Segment	Badhwar			Color			Discriminant		
		N (a)	Bias	RMSE	N (a)	Bias	RMSE	N (a)	Bias	RMSE
N. Dak.	1387	0			5	12.131	-5.78	5	-3.43	7.204
N. Dak.	1392	25	-0.80	9.592	32	10.798	-0.80	32	-4.30	14.466
N. Dak.	1394	16	2.00	7.228	12	5.693	1.69	16	2.72	4.684
N. Dak.	1457	31	3.90	13.109	17	9.720	-0.61	21	1.75	4.720
N. Dak.	1461	61	0.05	10.063	60	9.900	-2.06	38	-10.34	18.850
N. Dak.	1472	0			2	5.890	4.16	3	3.48	7.685
N. Dak.	1473	16	1.88	4.757	0			4	-3.49	4.737
S. Dak.	1485	0			2	2.810	-2.81	2	8.99	8.986
Minn.	1518	73	7.38	14.008	55	12.591	1.90	66	-0.79	9.361
Mont.	1537	11	-9.27	11.778	9	14.166	-0.35	7	2.14	6.943
Mont.	1542	29	-5.79	11.441	17	21.536	-10.29	17	-4.32	19.598
Mont.	1544	18	-5.06	10.195	10	7.741	0.93	11	4.86	10.930
Mont.	1553	18	14.06	16.487	11	16.686	3.90	9	4.13	6.789
Minn.	1566	42	-5.50	12.552	30	7.303	3.12	30	6.98	11.922
N. Dak.	1584	22	7.59	10.359	0			4	-1.98	2.287
N. Dak.	1612	27	4.59	9.907	12	7.400	-2.64	12	-3.09	4.846
N. Dak.	1619	35	7.31	10.709	16	9.756	-2.08	16	-1.65	5.628
N. Dak.	1636	49	-4.35	8.872	49	12.311	-1.84	40	-1.77	8.747
N. Dak.	1658	0			11	9.070	-1.63	12	-0.49	1.684
N. Dak.	1664	6	4.17	6.940	11	9.997	-3.33	12	-0.79	4.952
S. Dak.	1668	33	-1.76	8.385	18	8.737	1.20	24	8.44	12.287
S. Dak.	1755	0			5	12.926	-1.84	8	0.73	4.883
S. Dak.	1811	54	5.44	8.840	10	9.990	8.83	12	8.41	10.613
Minn.	1825	52	-0.94	10.613	23	4.770	2.85	26	-2.45	5.836
N. Dak.	1918	5	-0.20	3.376	4	10.256	-0.14	4	7.58	9.426
N. Dak.	1920	41	9.00	14.459	8	16.498	11.51	9	6.55	7.686
N. Dak.	1924	17	0.71	9.653	12	16.735	-15.31	12	-2.51	4.301
Mont.	1942	0			12	13.781	-1.31	12	9.09	14.990
Mont.		76	-1.42	12.610	59	2.44	10.020	56	2.52	14.20
N. Dak.		351	2.58	10.458	251	-2.40	16.256	240	-2.37	10.58
S. Dak.		87	2.71	8.670	35	-1.84	10.929	46	7.12	10.76
Minn.		167	1.55	12.668	108	2.72	9.596	122	89.61	9.47
Overall		681	1.90	11.094	453	-0.55	11.474	464	0.0	10.8

[a]N = number of observations.

In other words, all the models show that most of the fields follow a similar spectral sequence. What is not known is the extent to which these models can indicate contrasting patterns for nonwheat or nonsmall grain fields. The best way to test the models for capability in separating land-use categories is to use a ground truth data set involving several categories other than wheat.

6. CONCLUSIONS AND RECOMMENDATIONS

The results of this evaluation are not sufficiently conclusive to warrant the elimination of any of the models except the Stuff-Phinney starter model. The lack of definitive differences is due to several factors. First, no planting dates were available in the data set. Second, a majority of the segments did not depart substantially from normal, as evidenced by the relatively small figures for the normal model as shown in table K-1 (see appendix K). Third, the models that performed the best were those that had been fit, at least in part, on the same data set.

Because of the inconclusiveness of the results, it is recommended that all models be carried forward for independent tests using the 1979 blind site data set.

A further recommendation is that the spectral approach to planting date estimation used by the Environmental Research Instute of Michigan (ERIM) be evaluated in the same way as was the Badhwar model. In the ERIM spectral approach, peak greenness is used as a factor. Further testing of the Badhwar model should be delayed until the ERIM evaluation has been completed.

Finally, the 1979 data set should also be used to test the barley version of the Robertson model.

APPENDIX A

SEGMENT LOCATION MAPS

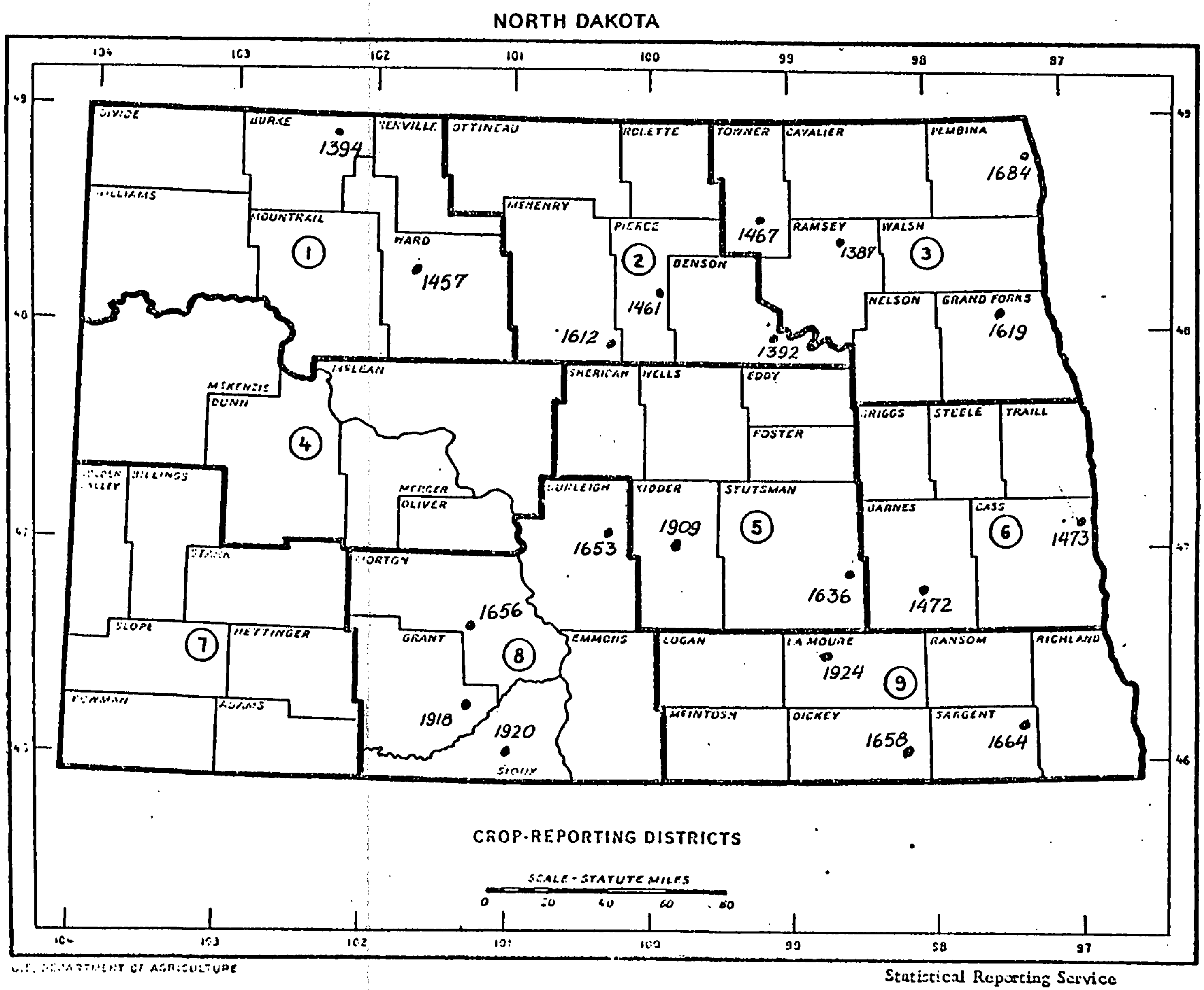

Figure A-1.- Segment location map for North Dakota.

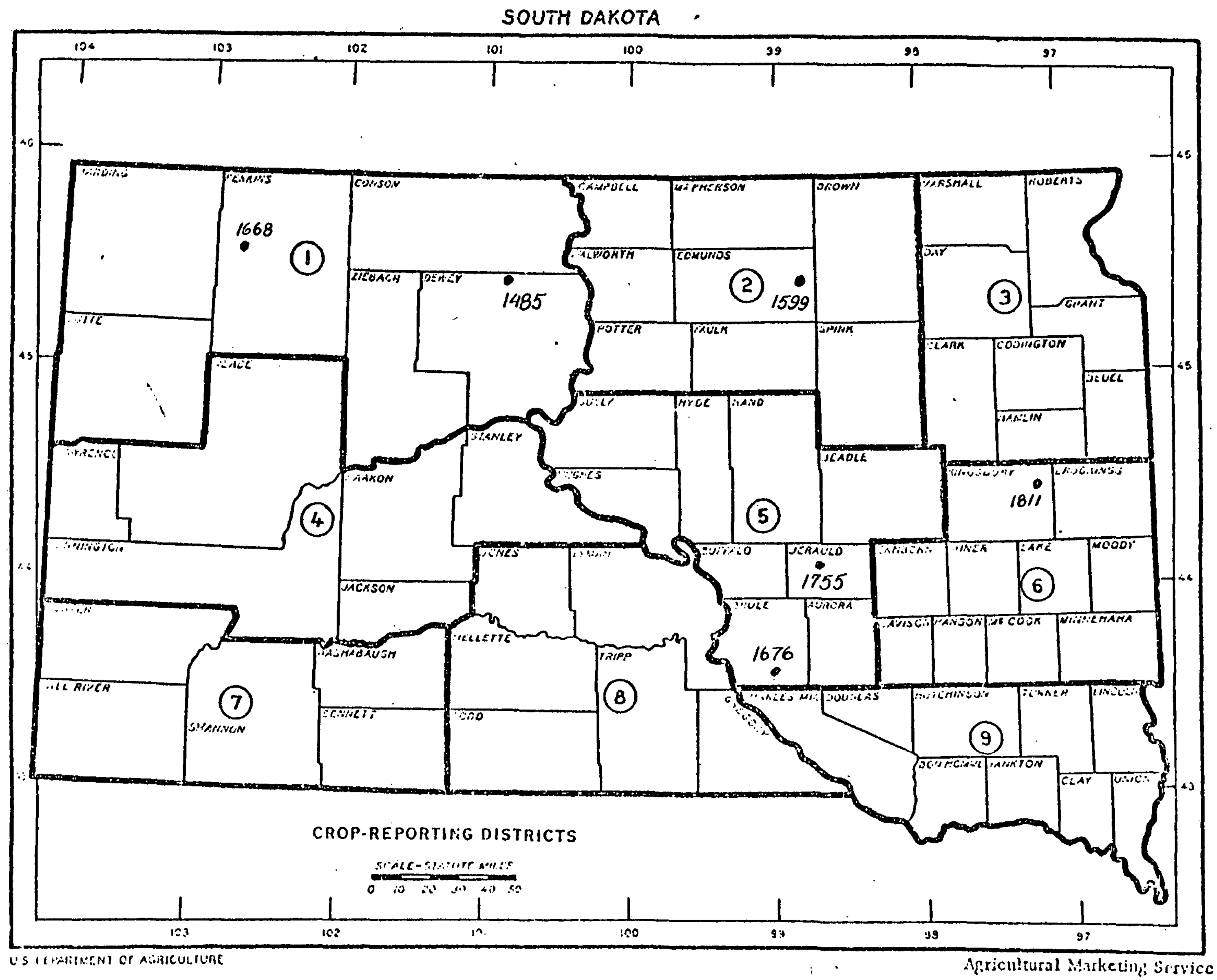

Figure A-2.- Segment location map for South Dakota.

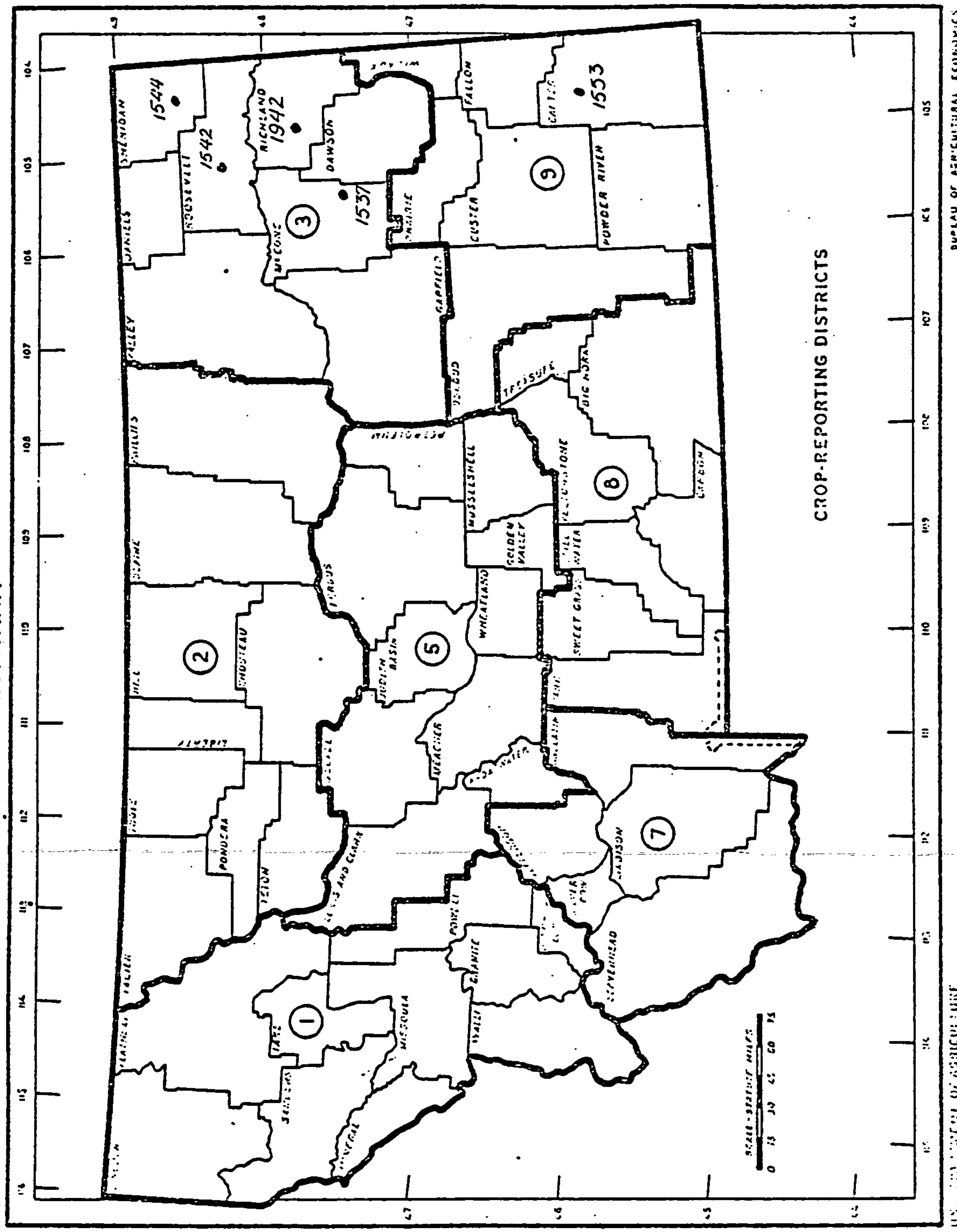

Figure A-3.- Segment location map for Montana.

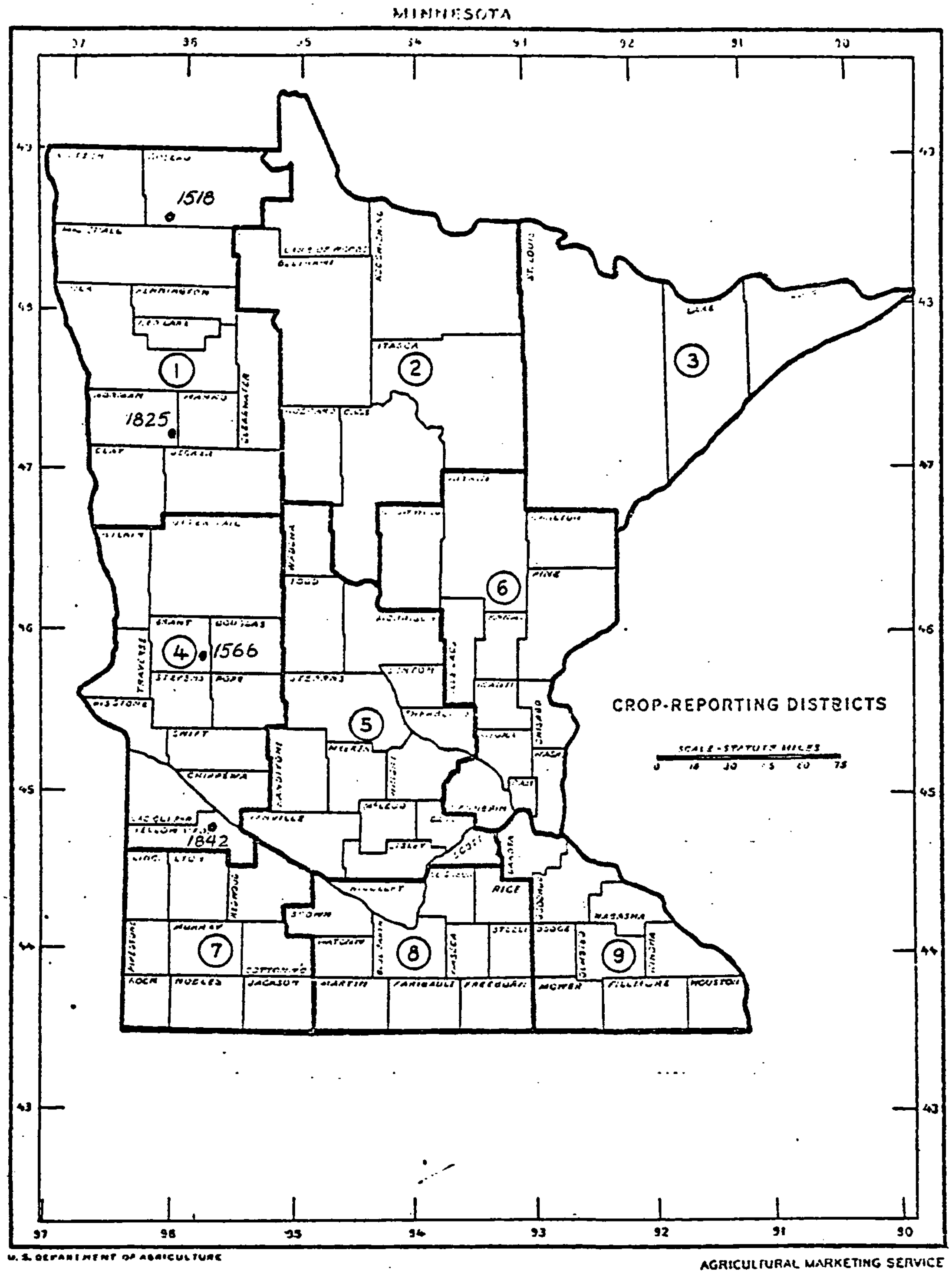

Figure A-4.- Segment location map for Minnesota.

APPENDIX B

THE FEYERHERM STARTER MODEL

APPENDIX B

THE FEYERHERM STARTER MODEL

Development of the Feyerherm spring wheat starter model (ref. 3) was based on the concept that a cool and wet early spring could delay planting while a warm and dry condition permits early planting. The weather variations among seasons and regions was defined as a warming and planting (W/P) day. Each W/P day is assigned a 0 to 1 value for each calendar day beginning January 19 (which is arbitrarily chosen and coincides roughly with the coldest time of the year in the northern hemisphere). Accumulated W/P days were then related to the percentage of wheat planted. When the accumulated W/P value reached 35.5, it was assumed that 50 percent of the crop had been planted.

The general form of the model was as follows:

$$W/P = 0 \text{ if } TA \leq 32$$
$$W/P = \alpha\ (TA-32)\ (PRE) \text{ if } 32 < TA \leq 32 + 1/\alpha$$
$$W/P = 1 \text{ if } TA > 32 + 1/\alpha$$

where

TA (°F) = the daily average air temperature [≈(max. + min.)/2]
α = the threshold value
PRE = a value between 0 and 1 as a function of the previous 3 days of precipitation

For spring wheat, Feyerherm assigned values of α = 0.1 and PRE = 1 since precipitation had an effect that was statistically insignificant.

APPENDIX C

THE STUFF-PHINNEY STARTER MODEL

APPENDIX C

THE STUFF-PHINNEY STARTER MODEL

For the Stuff-Phinney starter model (ref. 4), the 50 percent planting date for spring wheat was calculated from a regression equation using daily average air temperature (TA), precipitation (P), and normal planting date. The daily rate of planting (R) was defined as follows:

$$R = -0.77 + 0.045(TA) - 0.032(P) + 0.053(N)$$

where N equals the actual date minus the normal planting date. The summation of daily rates was made only for positive values of R.

APPENDIX D

STANDARDIZED CROP DEVELOPMENT SCALE

APPENDIX D

STANDARDIZED CROP DEVELOPMENT SCALE

Growth and development of spring wheat has been observed and described according to one of a variety of growth scales, including the Feekes scale, the Robertson scale, the ITS scale, and various stage descriptions used in state observation programs. Most of the stages in these scales can be assigned to one of the 24 Feekes scale stages (see table D-1 and figure D-1).

Crop development rate may also be estimated by phenology models from meteorological, spectral, or historical data. Because the Feekes stages vary in duration from about 2 days (stage designation 10.5.2-10.5.3) to about 10 days (stage designation 10.0-10.1), a difference of 5 days in an observed stage date and an estimated stage date may mean that there is no error in stage estimation or that there is an error of several stages. Comparison of different phenology models and testing against observed stage data can be facilitated by assigning numerical values to each stage on an approximately linear scale.

In figure D-1, a value for each Feekes scale stage has been derived from the average portion of the planting-to-harvest period required for spring wheat to reach that stage (i.e., planting-to-heading = 54.63 percent of the development period from planting to harvest). These values are based primarily on data from the U.S. Great Plains spring wheat region, where dates for planting, heading, and harvest stages (and sometimes the ripe stage) are recorded annually on a CRD level.

Percentage values were calculated for each of these stages (planting = 0 percent, heading = 54.63 percent, ripe = 99.44 percent, and harvest = 100 percent) based on 5 years of CRD-level data from Montana and North Dakota and on about 20 years of CRD data from Minnesota and South Dakota. Other stages were placed on the scale according to scattered historical CRD observations, experiment plot data, and by interpolation. The Robertson and ITS stages were assigned Feekes scale analogues based on definitions of the stages.

TABLE D-1.- RELATIONSHIPS BETWEEN FEEKES STAGES, ITS STAGES, AND ROBERTSON STAGES, WITH ESTIMATES OF PERCENTAGE OF NORMAL GROWTH SEASON OF EACH STAGE FOR SPRING WHEAT

Normal percentage of season		Feekes stages	ITS stages	Robertson stages	Description
Stage beginning	Stage midpoints				
0.0	0.0	0	2	1.0	Planted
8.33	13.88	1	3	2.0	Emergence
19.44	20.83	2	-	2.2	Beginning tillering
22.22	23.61	3	4	2.4	Tillers formed
25.0	26.85	4	-	2.6	Beginning pseudostem erection
28.7	30.55	5	-	2.8	Pseudostem strongly erected
32.41	33.80	6	-	3.0	Jointing
35.19	37.04	7	-	3.1	Second node formed; second-to-last leaf visible
38.89	40.28	8	-	3.25	Last leaf visible
41.67	43.52	9	-	3.35	Last leaf ligule visible
45.37	50.00	10.0	5	3.5	Boot
54.63	56.02	10.1	6	4.0	First heads just visible
57.41	58.80	10.2	-	4.1	One-fourth headed
60.19	61.11	10.3	-	4.2	One-half headed
62.04	63.42	10.4	7	4.25	Three-fourths headed
64.81	71.30	10.5	-	4.35	All plants headed
77.8	80.11	11.1	-	4.8	Milky ripe
82.41	84.70	11.2	8	5.0	Soft dough mealy ripe; kernel soft but dry
87.0	90.72	11.3	-	5.4	Kernel hard, but difficult to divide with thumbnail
94.44	97.22	11.4	9	6.0	Ripe
100.0	100.0	11.5	10	7.0	Harvested

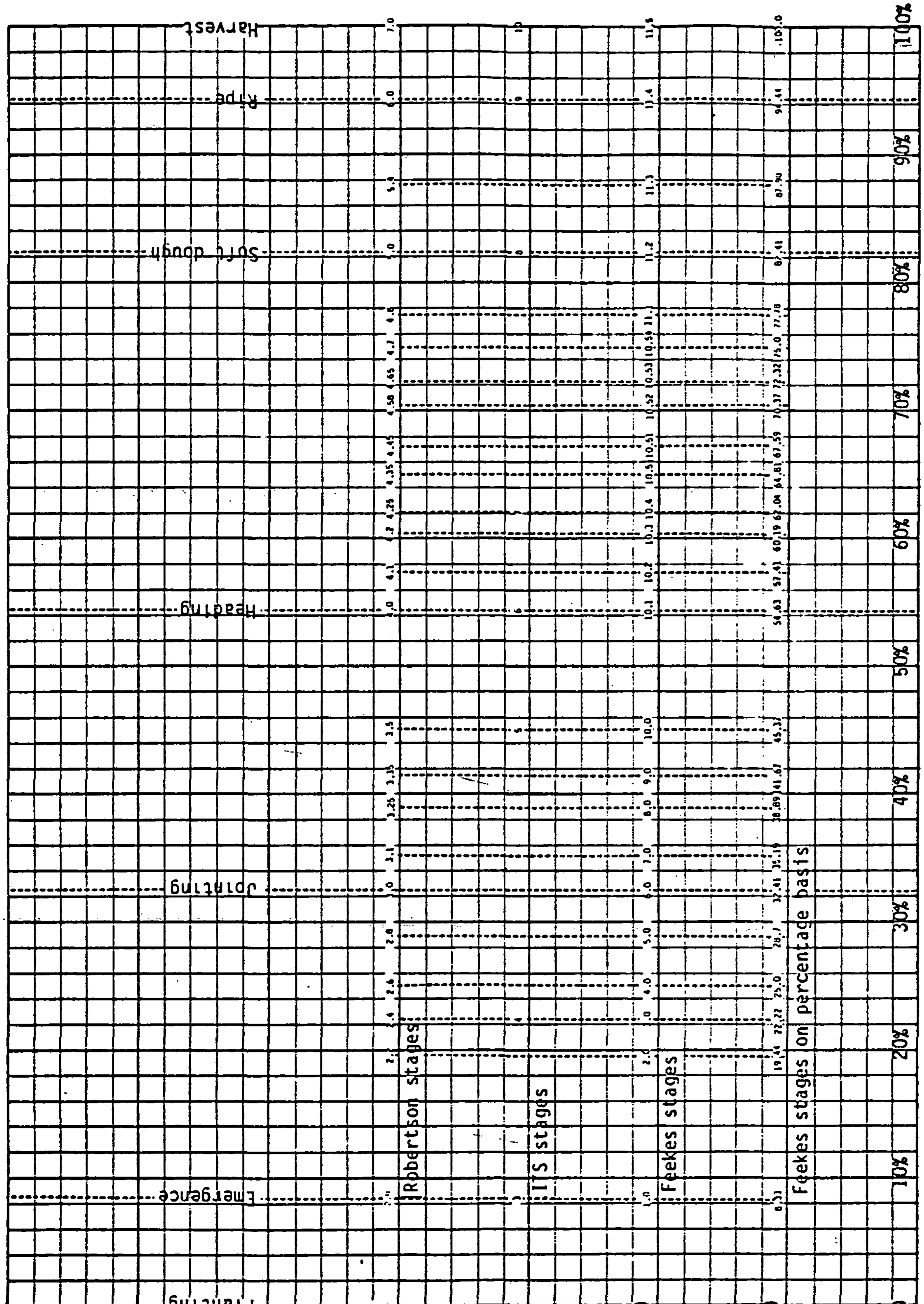

Figure D-1.- Spring wheat growth scales conversion chart.

APPENDIX E

NORMAL PLANTING AND HARVEST DATES

TABLE E-1.- NORMAL SPRING WHEAT PLANTING AND HARVEST DATES FOR SEGMENTS IN EVALUATION DATA SET

Segment	State	Planting	Harvest	Duration
1387	N. Dak.	140	235	95
1392	N. Dak.	141	240	99
1394	N. Dak.	143	242	99
1457	N. Dak.	143	242	99
1461	N. Dak.	141	240	99
1472	N. Dak.	134	228	94
1473	N. Dak.	134	228	94
1485	S. Dak.	117	219	102
1518	Minn.	137	243	106
1537	Mont.	128	236	108
1542	Mont.	128	236	108
1544	Mont.	128	236	108
1553	Mont.	121	231	110
1566	Minn.	119	224	105
1584	N. Dak.	140	235	95
1612	N. Dak.	141	240	99
1619	N. Dak.	140	235	95
1636	N. Dak.	135	227	92
1658	N. Dak.	122	219	97
1664	N. Dak.	122	219	97
1668	S. Dak.	117	219	102
1755	S. Dak.	111	207	96
1811	S. Dak.	110	209	99
1825	Minn.	137	243	106
1918	N. Dak.	127	222	95
1920	N. Dak.	127	222	95
1924	N. Dak.	122	219	97
1942	Mont.	128	236	108

APPENDIX F

ROBERTSON MODEL

APPENDIX F

ROBERTSON MODEL

Robertson's biometeorological time scale model (ref. 5) is based on photothermal effects on crop phenological processes. The nonlinear responses of photoperiod and day and night temperatures are represented in a triquadratic format. The effects of each environmental parameter are considered over short phenological periods (stages) when the physiological processes are uniform. These stages are planting, emergence, jointing, heading, soft dough, and ripe. Intermediate stages corresponding to those presented in the ground truth (Feekes scale) were also computed by interpolation from the normal crop calendar.

Maturity from one stage (S1) to the next (S2) is computed in the model as follows:

$$1 = \text{Maturity} = \sum_{S1}^{S2}\left\{\left[a_1(P - a_0) + a_2(P - a_0)^2\right]\right.$$

$$\left. X \left[b_1(T_{max} - b_0) + b_2(T_{max} - b_0)^2 + d_1(T_{min} - b_0) + d_2(T_{min} - b_0)^2\right]\right\}$$

where P is the daylength, T_{max} is the daily maximum temperature, and T_{min} is the daily minimum temperature.

Coefficients a_0, a_1, a_2, b_0, b_1, b_2, and d_2 are determined by an iterative regression technique which provides the best relationship between the three environmental factors and their interactions for the data set used. The coeffients are tabulated in table F-1.

The model was developed for Canadian spring wheat, and there are some weaknesses in the model that may limit its predictive capability in other locations. The responses of the model to the three environmental variables are not similar to expected responses for spring wheat varieties grown in the Midwest. One evidence of this is the prediction of almost the same duration from planting to ripe for a range of planting dates.

TABLE F-1.- REGRESSION COEFFICIENTS FOR THE ROBERTSON MODEL

Phenological period (a)	a_0	a_1	a_2	b_0	b_1	b_2	d_1	d_2
1	999.	0.	0.	44.37	0.01086	-0.0002230	0.009732	-0.0002267
2	8.413	1.005	0.	23.64	-.003512	.00005026	.0003666	-.00000428
3	10.93	.9256	-.06025	42.64	.0002958	0.	.00006733	0.0
4	10.94	1.389	-.08191	42.18	.0002458	0.	.00003109	0.
5	24.38	-1.140	0.	37.67	.00006733	0.	.0003442	0.

[a]1 = planting to emergence.
2 = emergence to jointing.
3 = jointing to heading.
4 = heading to soft dough.
5 = soft dough to ripe.

APPENDIX G

DORAISWAMY MODEL

APPENDIX G

DORAISWAMY MODEL

Examination of intermediate development stages predicted by the Robertson model and the unrealistic responses produced by the input parameters during a given crop stage indicated a need for modification of the model. The Robertson model computes the development period by combining all of the parameter responses, irrespective of their physiological or phenological significance. For example, the photoperiod effect on phenology is carried throughout all stages of plant development, although it has an insignificant effect after flowering. In general, the predictions of the Robertson model for the entire development period are close to the ground truth observations; however, the intermediate stage predictions are sometimes quite erroneous.

The Doraiswamy model, while using the same computational form of the Robertson model, separates parameter effects during each development stage. Certain coefficients are modified by comparison with the ground truth for a few randomly selected segments. Consequently, the new coefficients give more relevant weighting to the parameters; e.g., photoperiod is neglected ($a_1 = 0$ and $a_2 = 0$) during periods in which the crop is insensitive to it. The coefficients are given in table G-1.

TABLE G-1.- COEFFICIENTS FOR THE DORAISWAMY MODEL

Phenological period (a)	a_0	a_1	a_2	b_0	b_1	b_2	d_1	d_2
1	999.	0.	0.	44.37	0.01086	-0.0002230	0.009732	-0.0002267
2	8.413	1.005	0.	23.64	-.003512	.00005026	.0003666	-.00000428
3	999.0	0.0	.0	-8.55	.00055	.000000	.009732	-.0002267
4	10.94	1.389	-.08191	42.18	.0002458	0.	.00003109	0.
5	999.	0.0	0.	-8.75	.00035	0.0000000	.009732	-.00022

[a] 1 = planting to emergence.
2 = emergence to jointing.
3 = jointing to heading.
4 = heading to soft dough.
5 = soft dough to ripe.

APPENDIX H

BADHWAR-ADJUSTED NORMAL MODEL

APPENDIX H

BADHWAR-ADJUSTED NORMAL MODEL

The technique involved in the Badhwar-adjusted normal model consists of fitting field averages of Kauth greenness over at least three acquisition dates using the nonlinear expression

$$\rho(t) = A(t/t_0)^{\alpha} \exp \{\beta t_0^2 [1 - (t/t_0)^2]\}$$

where ρ is the spectral variable (Kauth greenness), t is time (Julian date of acquisition), A, α, β, and t_0 are coefficients to be fit, and exp denotes the exponential function. The acquisitions must be in the postemergence to preharvest period for an acceptable fit to the assumed function. Initial values for the coefficients and an acceptable step size which provide good convergence for the iterative fitting procedure are also needed. These have been chosen to give good results over a wide range of segments, and the values used for the evaluation data set are given in table H-1.

TABLE H-1.- BADHWAR INITIAL CONDITIONS

Values	Statistics
Initial coefficients	$a = 18.0$, $\beta = 2.0$, $t_0 = 1.5$
Coefficient step change	$1. \times 10^{-6}$
χ^2 convergence difference	$1. \times 10^{-5}$

APPENDIX I

COLOR-ADJUSTED NORMAL MODEL

APPENDIX I

COLOR-ADJUSTED NORMAL MODEL

The first step in the color adjusted normal model (ref. 7) normalizes Landsat pixel channel values to the segment channel means. Initially, one divides all pixel (or field mean) channel values (S_i) by scene (segment) channel means (CH_i) and multiplies them by five to obtain relative energies (X_i).

$$X_i = \frac{5S_i}{CH_i}$$

where i = 1 for channel 1, i = 2 for channel 2, and i = 3 for channel 4.

The resulting relative energies are transformed to the three color components of hue, value, and chroma as follows:

$$A = X_1^2 + X_2^2 + X_3^2$$

$$S = X_1 + X_2 + X_3$$

$$\text{Hue} = \cos^{-1}\left(\frac{2X_3 - X_1 - X_2}{2\sqrt{A - X_1X_2 - X_1X_3 - X_2X_3}}\right)$$

$$\text{Value} = S/3$$

$$\text{Chroma} = \sqrt{A - 1/3S^2}$$

Pixels (or fields) are then classified into the generalized color groups defined in table I-1. Additional groups may be defined as needed. For each field and spectral acquisition, the percentage of each color is calculated and subjected to a decision logic based on the temporal distributions of the percentages to estimate either the corresponding physiological stage midpoint or the biowindow equivalent.

TABLE I-1.- COLOR CODES DETERMINED FROM HUE, VALUE, AND CHROMA

Code	Hue in degrees	Value	Chroma
Green (G)	-120 to -180	0 to 10	0-8.165
Blue (B)	120 to 180	0 to 10	0-8.165
Purple (P)	60 to 120	0 to 10	0-8.165
Light Red (L)	0 to 60	5 to 10	0-8.165
Dark Red (R)	0 to 60	LT 5	0-8.165
Orange (O)	0 to -60	0 to 10	0-8.165
Yellow (Y)	-60 to -120	0 to 10	0-8.165

The stage estimate is extrapolated backward with the normal model to a planting date. The extrapolated values are averaged to predict a planting date which adjusts the normal model to predict occurrences of ground truth stages.

The biowindow estimation logic is given in table I-2, while table I-3 shows the stage estimation logic. The color codes and stage codes used in both these tables are fully identified and described below table I-2.

TABLE I-2.- LOGIC FOR SEPARATION OF SPRING SMALL GRAIN SPECTRAL RESPONSES INTO BIOWINDOW EQUIVALENTS USING THE COLOR MODEL[a]

Biostage	Description	Logic
Vegetated		Greater than (GT) 50% of all pixels are reddish (PLRO)
Nonvegetated		Less than (LT) 51% of all pixels are PLRO
Early nonvegetated		Those pixels preceding vegetated acquisitions
Late nonvegetated		Those pixels following vegetated acquisitions.
Ripe-harvest	Late nonvegetated acquisitions; Feekes 11.4-11.5, Robertson 6.0, biowindow 4	GT 30% of all pixels are blue (B) or GT 70% of all pixels are blue (B) or green (G)
Late flowering through soft dough ("turning") or "possible stress"	Feekes 11.1-11.3, Robertson 4.8-5.9, biowindow 3	A. Vegetated acquisitions in which: GT 35% of PLRO pixels are orange (O) or GT 35% of pixels are green (G) or GT 30% of pixels are orange (O) or GT 30% of pixels are yellow (Y) or GT 50% of pixels are orange (O) or yellow (Y) B. Late nonvegetated acquisitions in which: LT 30% of all pixels are blue (B) and LT 70% of all pixels are blue (B) or green (G)
Late tillering to midflowering	Feekes 3-10.5, Robertson 2.5-4.7, biowindow 2	Vegetated acquisitions not listed above
Preplowing to midtillering	Feekes 0-2, Robertson 1-2.4, biowindow 1	All early nonvegetated acquisitions

Color codes:

PLRO - percentage of all pixels that are purple, light red, red, or orange
BG - percentage of all pixels that are blue or green
P/PLRO - percent of PLRO pixles that are purple
O/PLRO - percent of PLRO pixels that are orange
G - percentage of all pixels that are green
B - percentage of all pixels that are blue
O - percentage of all pixels that are orange
Y - percentage of all pixels that are yellow
OY - percentage of all pixels that are orange or yellow

TABLE I-3.- LOGIC FOR SEPARATION OF SPRING SMALL GRAIN SPECTRAL RESPONSES INTO STAGES USING THE COLOR MODEL[a]

Stage code	Planting to emergence, PE,	Emergence to tillering, ET	Tillering to season midpoint (CRD normal), TM		Midpoint to dough, MD	Dough to ripe, DR	Ripe to harvest, RH
Feekes range	0-1	1-2	2-6	6-Midpoint	Midpoint-10.5	11.1-11.4	11.4-11.5
Percent range	0-8.33	8.33-19.44	19.44-32.41	32.41-50.00	50.00-75.00	75.00-94.44	94.44-100
Color criteria:							
PLRO GT 50%			X	X	X	X	
BG GT 50%	X	X				X	X
P/PLRO GT 30%	X	X				X	X
O/PLRO GT 35%	X					X	X
G GT 35%	X					X	X
B GT 30%	X						X
O GT 30%						X	X
Y GT 30%						X	X
OY GT 50%						X	X
BG GT 70%	X						X

All other acquisitions are either early (before midpoint, 0-50) or late (after midpoint, 50-100).

Color Codes:

PLRO - percentage of all pixels that are purple, light red, red, or orange
BG - percentage of all pixels that are blue or green
P/PLRO - percent of PLRO pixels that are purple
O/PLRO - percent of PLRO pixels that are orange
G - percentage of all pixels that are green
B - percentage of all pixels that are blue
O - percentage of all pixels that are orange
Y - percentage of all pixels that are yellow
OY - percentage of all pixels that are orange or yellow

Stage Codes:

PE - 8.33% on normal scale
PE-ET - 13.5% on normal scale
Early - 25.0% on normal scale
TM - 35.0% on normal scale
MD - 62.0% on normal scale
Late - 75.0% on normal scale
DR-RH - 87.5% on normal scale
RH - 100.0% on normal scale

APPENDIX J

LINEAR DISCRIMINANT BIOSTAGE ESTIMATION

APPENDIX J

LINEAR DISCRIMINANT BIOSTAGE ESTIMATION

The potential for use of linear discriminant functions in identification of crop development stages was demonstrated for wheat by Phinney et al. (ref. 8). For application to spring wheat, a training set consisting of coincident ground data and spectral data was compiled. The data were collected at 35 spring wheat segments in Montana, North Dakota, South Dakota, and Minnesota during the 1978 crop year. The total number of observations was 590. Table J-1 shows the number of observations available for each observed development stage. Data were pooled for Feekes stages 10.2 to 10.4. Although the number of available samples was small for several stages, the effect of pooling additional stages was not investigated. Eighteen different stage classes were considered.

Six different spectral transforms were used in addition to Sun-angle correction of the raw Landsat multispectral scanner (MSS) channel data. These transforms included the tasselled cap greenness and brightness, the normalized difference, the perpendicular vegetation index (PVI), relative energy, and the cubic colors. The spectral variables were summarized at the field level for each acquisition date.

Preliminary studies showed that fields near the beginning and end of the growth cycle were often confused when only spectral data were used. Hence, the difference between the acquisition date and the normal planting date for the segment's CRD provided a segment-level variable to complement the field-level variable.

The results of the fit to the training data set are shown in table J-2. The percent correct classification for each set of variables is shown for Feekes stage and by biowindow. Table J-3 shows the magnitude of the misclassification error in days. The normal growth season was used to convert error in stages to error in days.

TABLE J-1.- SUMMARY OF OBSERVATIONS USED FOR FITTING OF LINEAR DISCRIMINANT COEFFICIENTS BY DEVELOPMENT STAGE

Feekes stage	Number of observations
1.0	145
2.0	28
3.0	13
4.0	11
5.0	11
6.0	9
7.0	6
8.0	5
9.0	7
10.0	5
10.1	10
10.2	
10.3	3[a]
10.4	
10.5	55
11.1	94
11.2	35
11.3	13
11.4	26
11.5	114

[a]These three observations were pooled for Feekes stages 10.2, 10.3, and 10.4.

TABLE J-2.- RESULTS OF LINEAR DISCRIMINANT FITS TO THE TRAINING DATA

[Based on 590 observations]

Spectral variable	Number of variables	Percent correct classification					
		Feekes stage	Biowindow[a]				
			1	2	3	4	All
Color	8	53.9	93.1	79.3	63.4	93.6	82.9
MSS channel	5	54.7	91.9	77.0	73.9	93.6	84.6
Relative energy	5	54.1	94.2	74.8	73.2	90.0	83.7
Tasselled cap	3	53.6	90.8	74.1	67.6	94.3	82.2
Normalized difference	2	51.2	91.9	74.8	60.6	93.6	75.8
PVI	2	50.8	84.4	77.8	61.3	91.4	79.0

[a]Biowindow definition:

1 = Feekes stage 1-2
2 = Feekes stage 3-10.5
3 = Feekes stage 11.1-11.3
4 = Feekes stage 11.4-11.5

TABLE J-3.- MISCLASSIFICATION STATISTICS IN DAYS FOR RESULTS OF LINEAR DISCRIMINANT FITS TO THE TRAINING DATA

[Based on 590 observations]

Spectral variable	Bias	RMSE
Color	-1.1	12.41
MSS channel	-.9	9.72
Relative energy	-.9	9.46
Tasselled cap	-.6	9.79
Normalized difference	-1.0	10.90
PVI	-.2	12.97

The coefficients obtained from the training data were applied to a larger ground truth evaluation data set with 1057 observations. The training data set was a subset of the larger evaluation data set. There were 464 coincident observations of spectral ground data. Table J-4 shows the performance of the candidate model on the coincident data.

Estimates of planting dates were made for each field in each spectral acquisition. The estimated stage was calculated from the estimated stage by adjusting the normal crop calendar. A final planting date estimate for each field was made by averaging the individual acquisition estimates.

It should be noted that the date that a given ground truth stage occurred can be estimated by adjusting the normal crop calendar by the estimated planting date. The results of this approach are also shown in table J-4. Comparison of the direct estimates and the adjusted normal estimates indicate that no skill is lost by using the spectral model solely to estimate planting date.

The linear discriminant models were used to estimate planting dates for each field using all available spectral acquisitions in the ground truth evaluation data set. The estimated planting dates adjusted the normal model to estimate the date of occurrence of ground truth stages in the data set. There were 1057 such ground observations. Table J-5 shows a summary of the results.

Reviewing tables J-3, J-4, and J-5, it may be seen that the relative energy spectral transform provided the best results, and the tasselled cap and cubic color transform performed nearly as well. The relative energy transform was selected for comparison with other techniques, and its linear discriminant coefficients are given in table J-6.

For the relative energy transform, on each acquisition date, the variables for each field are calculated using the following methodology:

X(1) = relative energy for MSS channel 1
X(2) = relative energy for MSS channel 2
X(3) = relative energy for MSS channel 3
X(4) = relative energy for MSS channel 4
X(5) = acquisition date - normal planting date

TABLE J-4.- MISCLASSIFICATION STATISTICS IN DAYS FOR RESULTS OF LINEAR DISCRIMINANT MODELS APPLIED TO GROUND TRUTH EVALUATION DATA

[For 464 observations]

Spectral variable	Direct		Estimated planting date + normal	
	Bias	RMSE	Bias	RMSE
Color	-0.3	14.05	0.3	11.05
MSS channel	-.1	11.39	.2	10.43
Relative energy	.0	10.82	.1	10.08
Tasselled cap	.3	10.83	-.2	10.27
Normalized difference	.3	11.86	1.0	11.39
PVI	.4	14.05	.3	12.73

TABLE J-5.- SUMMARY OF STATISTICS FOR ADJUSTING NORMAL MODELS WITH PLANTING DATE ESTIMATES DERIVED FROM THE LINEAR DISCRIMINANT MODELS

Spectral variable	Bias	RMSE
Color	-0.9	10.85
MSS channel	-0.1	11.97
Relative energy	-1.5	10.32
Tasselled cap	-1.1	10.67
Normalized difference	0.2	12.54
PVI	0.1	13.18

TABLE J-6.- LINEAR DISCRIMINANT COEFFICIENTS FOR RELATIVE ENERGY

Group	Feekes stage	Relative energy by MSS channel				Days since planting	Constant
		1	2	3	4		
1	1.0	80.42	-30.00	-54.79	43.35	0.08	-98.64
2	2.0	83.65	-32.43	-52.22	41.56	0.16	-107.80
3	3.0	82.60	-31.94	-53.50	43.42	0.19	-108.44
4	4.0	82.77	-33.41	-49.65	39.97	0.28	-107.15
5	5.0	82.54	-34.89	-46.30	38.21	0.25	-106.68
6	6.0	78.91	-31.36	-52.97	44.28	0.27	-102.98
7	7.0	80.29	-33.63	-49.97	43.45	0.29	-112.92
8	8.0	79.69	-33.40	-52.92	48.17	0.34	-126.25
9	9.0	77.61	-31.28	-58.27	52.64	0.38	-122.92
10	10.0	81.12	-34.02	-48.64	41.76	0.38	-117.10
11	10.1	76.50	-30.93	-52.50	45.43	0.35	-106.28
12	10.2-10.4	79.46	-31.85	-53.37	44.05	0.34	-103.03
13	10.5	77.06	-30.25	-59.11	50.74	0.43	-110.76
14	11.1	74.61	-28.19	-62.16	53.19	0.48	-108.96
15	11.2	74.74	-27.83	-58.40	48.45	0.50	-107.02
16	11.3	70.91	-25.86	-54.86	45.42	0.51	-102.41
17	11.4	70.19	-25.35	-54.32	45.09	0.59	-109.48
18	11.5	76.84	-27.91	-56.11	45.65	0.68	-133.34

Calculate

$$S(i) = Const(i) + X(j)Coeff(i,j)$$

where Const(i) is the constant for the ith group and Coeff(i,j) is the coefficient for the ith group and jth variable.

The group which has the maximum likelihood of containing the observation will have the maximum value of S(i). Thus, the Feekes growth stage associated with the group with the maximum S(i) is the stage estimate.

The planting date is estimated as follows:

$$\text{planting date} = \text{acquisition date} - NP \times DUR$$

where NP is the percentage of the normal growing season to the midpoint of the estimated stage and DUR is the normal length of the growing season for the CRD containing the field.

The average planting date obtained from all acquisitions is then the final estimate of the planting date. In general, acquisitions outside the normal growing season should not be used.

APPENDIX K

EVALUATION OF THE ROBERTSON AND DORAISWAMY STAGE ESTIMATION MODELS

APPENDIX K

EVALUATION OF THE ROBERTSON AND DORAISWAMY STAGE ESTIMATION MODELS

The performances of the Robertson and Doraiswamy models are briefly discussed in conclusions 1 and 2 of the results section of this document. For a better understanding, the predictions of the two models and the normal crop calendar were tabulated for 25 days before and after the normal planting date. Tables K-1, K-2, and K-3 illustrate the observed improvement of the Doraiswamy model in segment 1918. The dates circled indicate the median occurrence of a particular growth stage observed in the ground truth. A crop phenology model having accurate predictions relative to the ground truth would have all the ground-truth observations distributed horizontally. Both the Doraiswamy and Robertson models and the normal crop calendar predictions suggest (1) a general increase in the development rate for crops during stages from heading to flowering and (2) a decrease in development during subsequent stages. The models are unable to effectively simulate this effect although the Doraiswamy model does better than both the Robertson model and the normal crop calendar. One of the possible explanations for this anomaly is that in 1978 a larger plant water stress affected the normal development of the crop.

TABLE K-1.- DATES OF STAGE OCCURRENCES FOR SEGMENT 1918 (GRANT COUNTY, N. DAK.)

AS PREDICTED BY THE NORMAL MODEL FOR PLANTING DATES

WITHIN 25 DAYS OF NORMAL

FEEKES:	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	10.1	10.2	10.3	10.4	10.5	11.1	11.2	11.3	11.4	11.5
ROBERTSON:	1.0	2.0	2.2	2.4	2.6	2.8	3.0	3.1	3.25	3.35	3.5	4.0	4.1	4.2	4.25	4.35	4.8	5.0	5.4	6.0	7.0
NORMAL:	0	13.9	20.8	23.6	26.8	30.6	33.8	37.0	40.3	43.5	50.0	56.0	58.8	61.1	63.4	71.3	80.1	85.2	91.2	97.2	100
	102	115	122	124	128	131	134	137	140	143	150	155	158	160	162	170	178	183	189	194	197
	103	116	123	125	129	132	135	138	141	144	151	156	159	161	163	171	179	184	190	195	198
	104	117	124	126	130	133	136	139	142	145	152	157	160	162	164	172	180	185	191	196	199
	105	118	125	127	131	134	137	140	143	146	153	158	161	163	165	173	181	186	192	197	200
	106	119	126	128	132	135	138	141	144	147	154	159	162	164	166	174	182	187	193	198	201
	107	120	127	129	133	136	139	142	145	148	155	160	163	165	167	175	183	188	194	199	202
	108	121	128	130	134	137	140	143	146	149	156	161	164	166	168	176	184	189	195	200	203
	109	122	129	131	135	138	141	144	147	150	157	162	165	167	169	177	185	190	196	201	204
	110	123	130	132	136	139	142	145	148	151	158	163	166	168	170	178	186	191	197	202	205
	111	124	131	133	137	140	143	146	149	152	159	164	167	169	171	179	187	192	198	203	206
	112	125	132	134	138	141	144	147	150	153	160	165	168	170	172	180	188	193	199	204	207
	113	126	133	135	139	142	145	148	151	154	161	166	169	171	173	181	189	194	200	205	208
	114	127	134	136	140	143	146	149	152	155	162	167	170	172	174	182	190	195	201	206	209
	115	128	135	137	141	144	147	150	153	156	163	168	171	173	175	183	191	196	202	207	210
	116	129	136	138	142	145	148	151	154	157	164	169	172	174	176	184	192	197	203	208	211
	117	130	137	139	143	146	149	152	155	158	165	170	173	175	177	185	193	198	204	209	212
	118	131	138	140	144	147	150	153	156	159	166	171	174	176	178	186	194	199	205	210	213
	119	132	139	141	145	148	151	154	157	160	167	172	175	177	179	187	195	200	206	211	214
	120	133	140	142	146	149	152	155	158	161	168	173	176	178	180	188	196	201	207	212	215
	121	134	141	143	147	150	153	156	159	162	169	174	177	179	181	189	197	202	208	213	216
	122	135	142	144	148	151	154	157	160	163	170	175	178	180	182	190	198	203	209	214	217
	123	136	143	145	149	152	155	158	161	164	171	176	179	181	183	191	199	204	210	215	218
	124	137	144	146	150	153	156	159	162	165	172	177	180	182	184	192	200	205	211	216	219
	125	138	145	147	151	154	157	160	163	166	173	178	181	183	185	193	201	206	212	217	220
	126	139	146	148	152	155	158	161	164	167	174	179	182	184	186	194	202	207	213	218	221
	127	140	147	149	153	156	159	162	165	168	175	180	183	185	187	195	203	208	214	219	222
	128	141	148	150	154	157	160	163	166	169	176	181	184	186	188	196	204	209	215	220	223
	129	142	149	151	155	158	161	164	167	170	177	182	185	187	189	197	205	210	216	221	224
	130	143	150	152	156	159	162	165	168	171	178	183	186	188	190	198	206	211	217	222	225
	131	144	151	153	157	160	163	166	169	172	179	184	187	189	191	199	207	212	218	223	226
	132	145	152	154	158	161	164	167	170	173	180	185	188	190	192	200	208	213	219	224	227
	133	146	153	155	159	162	165	168	171	174	181	186	189	191	193	201	209	214	220	225	228
	134	147	154	156	160	163	166	169	172	175	182	187	190	192	194	202	210	215	221	226	229
	135	148	155	157	161	164	167	170	173	176	183	188	191	193	195	203	211	216	222	227	230
	136	149	156	158	162	165	168	171	174	177	184	189	192	194	196	204	212	217	223	228	231
	137	150	157	159	163	166	169	172	175	178	185	190	193	195	197	205	213	218	224	229	232
	138	151	158	160	164	167	170	173	176	179	186	191	194	196	198	206	214	219	225	230	233
	139	152	159	161	165	168	171	174	177	180	187	192	195	197	199	207	215	220	226	231	234
	140	153	160	162	166	169	172	175	178	181	188	193	196	198	200	208	216	221	227	232	235
	141	154	161	163	167	170	173	176	179	182	189	194	197	199	201	209	217	222	228	233	236
	142	155	162	164	168	171	174	177	180	183	190	195	198	200	202	210	218	223	229	234	237
	143	156	163	165	169	172	175	178	181	184	191	196	199	201	203	211	219	224	230	235	238
	144	157	164	166	170	173	176	179	182	185	192	197	200	202	204	212	220	225	231	236	239
	145	158	165	167	171	174	177	180	183	186	193	198	201	203	205	213	221	226	232	237	240
	146	159	166	168	172	175	178	181	184	187	194	199	202	204	206	214	222	227	233	238	241
	147	160	167	169	173	176	179	182	185	188	195	200	203	205	207	215	223	228	234	239	242
	148	161	168	170	174	177	180	183	186	189	196	201	204	206	208	216	224	229	235	240	243
	149	162	169	171	175	178	181	184	187	190	197	202	205	207	209	217	225	230	236	241	244
	150	163	170	172	176	179	182	185	188	191	198	203	206	208	210	218	226	231	237	242	245
	151	164	171	173	177	180	183	186	189	192	199	204	207	209	211	219	227	232	238	243	246
	152	165	172	174	178	181	184	187	190	193	200	205	208	210	212	220	228	233	239	244	247

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TABLE K-2.- DATES OF STAGE OCCURRENCES IN 1978 FOR SEGMENT 1918 (GRANT COUNTY, N. DAK.)
AS PREDICTED BY THE ROBERTSON MODEL FOR PLANTING DATES
WITHIN 25 DAYS OF NORMAL

FEEKES:	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	10.1	10.2	10.3	10.4	10.5	11.1	11.2	11.3	11.4	11.5
ROBERTSON:	1.00	2.00	2.20	2.40	2.60	2.80	3.00	3.10	3.25	3.35	3.50	4.00	4.10	4.20	4.25	4.35	4.80	5.00	5.40	6.00	7.00
	102	124	136	141	142	146	150	157	161	165	176	184	186	187	189	196	204	208	214	222	225
	103	125	137	142	143	147	151	157	162	166	176	185	187	188	190	197	204	209	215	223	226
	104	126	138	143	144	148	152	158	163	167	177	186	188	189	191	198	205	210	216	224	227
	105	127	139	144	145	149	153	159	164	168	178	187	189	190	192	199	206	211	217	225	228
	106	128	140	145	146	150	154	160	165	169	179	188	190	191	193	200	207	212	218	226	229
	107	129	141	146	147	151	155	161	166	170	180	188	190	192	194	201	208	213	219	227	230
	108	130	142	147	148	152	156	162	166	171	181	189	191	193	195	202	209	214	220	228	231
	109	131	143	148	149	153	156	163	167	172	182	190	192	194	196	203	210	215	221	229	232
	110	132	143	148	149	153	157	164	168	173	183	191	193	195	197	204	212	216	222	230	233
	111	133	144	149	150	154	158	165	169	173	184	192	194	196	198	205	213	217	223	231	234
	112	134	145	150	151	155	159	165	170	174	185	193	195	197	199	206	214	218	224	232	235
	113	135	146	151	152	156	160	166	171	175	186	194	196	198	200	207	215	219	225	233	236
	114	136	147	152	153	157	161	167	172	176	187	195	197	199	201	208	216	220	226	234	237
	115	137	148	153	154	158	162	168	173	177	188	196	198	200	202	209	217	221	227	235	238
	116	138	149	154	155	159	163	169	174	178	189	197	199	201	203	210	218	222	228	236	239
	117	139	150	155	156	160	164	170	175	179	190	198	200	202	204	211	219	224	229	237	240
	118	140	151	156	157	161	165	171	176	180	191	199	201	203	205	212	220	225	231	238	241
	119	141	152	157	158	162	166	172	177	181	191	200	202	204	206	213	221	226	232	239	242
	120	142	153	158	159	163	167	173	177	182	192	201	203	205	207	214	223	227	234	240	243
	121	143	154	159	160	164	168	174	178	183	193	202	204	206	208	215	224	228	235	241	244
	122	144	155	160	161	165	169	175	179	184	194	203	205	207	209	216	225	229	236	242	245
	123	145	156	161	162	166	169	176	180	185	195	204	206	208	210	217	226	230	238	243	[illegible]
	124	146	157	162	163	167	170	177	181	186	196	205	207	209	211	218	227	232	239	244	247
	125	147	158	163	164	168	171	178	182	187	197	206	208	210	212	220	229	233	240	245	249
	126	148	159	164	165	169	172	179	183	188	198	207	209	211	213	221	230	234	241	247	250
	127	149	160	164	165	170	173	180	184	189	199	208	210	212	214	222	231	235	243	248	251
	128	150	161	165	166	171	174	181	185	190	200	209	211	213	216	223	232	237	244	249	252
	129	151	162	166	167	171	175	181	186	191	201	210	213	214	217	224	233	238	245	251	254
	130	152	163	167	168	172	176	182	187	192	202	211	214	215	218	225	235	240	246	252	255
	131	153	164	168	169	173	177	183	188	193	204	213	215	217	219	226	236	241	248	253	256
	132	154	165	169	170	174	178	184	189	194	205	214	216	218	220	228	237	243	249	255	258
	133	155	166	170	171	175	179	185	190	195	206	215	217	219	221	229	239	244	250	256	259
	134	156	167	171	172	176	180	186	191	196	207	216	218	220	223	230	240	246	252	258	261
	135	157	168	172	173	177	181	187	192	197	208	217	219	221	224	231	242	248	253	259	262
	136	158	169	173	174	178	182	188	193	198	209	218	220	223	225	232	243	251	255	260	263
	137?	159	170	174	175	179	183	189	194	199	210	219	221	224	226	234	245	253	257	262	265
	138	160	171	175	176	180	184	190	195	200	211	220	223	225	228	235	246	254	258	263	266
	139	161	172	176	177	181	185	191	196	201	212	221	224	226	229	236	248	255	260	264	267
	140	162	173	177	178	182	186	192	197	202	213	223	225	228	230	238	250	257	261	266	269
	141	163	174	178	179	183	187	193	198	203	214	224	226	229	232	239	252	259	263	268	271
	142	164	175	179	180	184	188	194	199	204	215	225	228	230	233	241	254	262	265	270	273
	143	165	176	180	181	185	189	196	200	205	216	226	229	232	234	243	257	264	266	272	275
	144	166	177	181	182	186	190	197	201	206	217	227	230	233	236	245	260	266	269	275	278
	145	167	178	182	183	187	191	198	202	207	219	229	232	235	237	246	262	269	272	279	282
	146	168	179	183	184	188	192	199	204	208	220	230	233	236	239	248	264	272	277	283	286
	147	169	180	184	185	189	193	200	205	209	221	231	234	237	240	250	267	278	282	287	290
	148	170	181	185	186	190	194	201	206	210	222	232	236	239	241	252	270	278	282	287	290
	149	171	182	186	187	191	195	202	207	212	223	234	237	240	243	253	274	278	282	287	290
	150	172	183	187	188	193	196	203	208	213	224	235	239	242	244	255	274	278	282	287	290
	151	173	184	188	189	194	197	204	209	214	226	236	241	243	246	257	274	278	282	287	290
	152	174	185	189	190	195	199	205	210	215	227	238	242	245	247	259	274	278	282	287	290

Interpolation (60%, 3.4)

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TABLE K-3.- DATES OF STAGE OCCURRENCES IN 1978 FOR SEGMENT 1918 (GRANT COUNTY, N. DAK.) AS PREDICTED BY THE DORAISWAMY MODEL FOR PLANTING DATES WITHIN 25 DAYS OF NORMAL

FEEKES:	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	10.1	10.2	10.3	10.4	10.5	11.1	11.2	11.3	11.4	11.5
ROBERTSON:	1.00	2.00	2.20	2.40	2.60	2.80	3.00	3.10	3.25	3.35	3.50	4.00	4.10	4.20	4.25	4.35	4.80	5.00	5.40	6.00	7.00
	102	126	137	142	143	147	150	154	156	159	156	173	174	175	176	180	184	191	203	213	216
	103	126	138	143	144	148	151	154	157	160	167	174	175	176	177	181	185	192	204	214	217
	104	127	138	144	145	149	152	155	158	161	168	175	176	177	178	182	186	193	205	215	218
	105	128	139	145	146	150	153	156	159	162	169	176	177	178	179	183	187	194	206	216	219
	106	129	140	145	146	150	154	157	160	163	170	177	178	179	180	184	188	195	207	217	220
	107	130	141	146	147	151	155	158	161	164	171	177	179	180	181	185	189	195	208	218	221
	108	131	142	147	148	152	156	159	162	165	172	178	180	181	182	186	190	196	209	219	222
	109	132	143	148	149	153	157	160	163	165	173	179	181	182	183	187	191	197	210	220	223
	110	133	144	149	150	154	157	161	164	166	174	180	182	183	184	188	192	198	211	221	224
	111	134	145	150	151	155	158	161	165	167	175	181	183	184	185	189	193	199	212	222	225
	112	135	146	151	152	156	159	162	166	168	176	182	184	185	186	190	194	200	213	223	226
	113	136	147	152	153	157	160	163	166	169	176	183	185	186	187	191	195	201	214	224	227
	114	137	148	153	154	158	161	164	167	170	177	184	185	187	188	192	196	202	215	225	228
	115	138	149	154	155	159	162	165	168	171	178	185	186	188	189	193	197	203	216	226	229
	116	139	150	155	156	160	163	166	169	172	179	186	187	189	190	194	198	204	217	227	230
	117	140	151	156	157	161	164	167	170	173	180	187	188	189	190	195	199	205	218	228	231
	118	141	152	157	158	162	165	168	171	174	181	188	189	190	191	196	200	206	219	229	232
	119	142	153	158	159	163	166	169	172	175	182	188	190	191	192	197	201	207	220	230	233
	120	143	154	159	160	164	167	170	173	176	183	189	191	192	193	198	202	208	221	231	234
	121	144	155	160	161	165	168	171	174	177	184	190	192	193	194	198	203	209	222	232	235
	122	145	156	161	162	165	169	172	175	178	185	191	193	194	195	199	204	210	223	233	236
	123	146	157	162	163	166	170	173	176	179	186	192	194	195	196	200	205	211	224	234	237
	124	147	158	163	164	167	171	174	177	180	187	193	195	196	197	201	206	212	225	235	238
	125	148	159	163	164	168	172	174	178	181	188	194	196	197	198	202	207	213	226	236	239
	126	149	160	164	165	169	173	175	179	182	189	195	197	198	199	203	208	214	227	237	240
	127	150	161	165	166	170	174	176	180	183	190	196	198	199	200	204	209	215	228	238	241
	128	151	162	166	167	171	175	177	181	184	191	197	199	200	201	205	210	216	229	239	242
	129	152	163	167	168	172	175	178	182	184	192	198	200	201	202	206	211	218	230	240	243
	130	153	163	168	169	173	176	179	183	185	193	199	201	202	203	207	212	219	231	241	244
	131	154	164	169	170	174	177	180	184	186	194	200	202	203	204	209	213	220	232	242	245
	132	155	165	170	171	175	178	181	185	187	195	201	203	204	205	210	214	221	233	243	246
	133	156	166	171	172	176	179	182	186	188	196	202	204	205	206	211	215	222	234	244	247
	134	157	167	172	173	177	180	183	187	189	197	203	205	206	207	212	216	223	235	245	248
	135	158	168	173	174	178	181	184	188	190	198	204	206	207	208	213	217	224	236	246	249
	136	159	169	174	175	179	182	185	189	191	199	205	207	208	209	214	219	225	237	247	250
	137	160	170	175	176	180	183	186	190	192	200	206	208	209	210	215	220	226	239	249	252
	138	161	171	176	177	181	184	187	191	193	201	207	209	210	211	216	221	227	240	250	253
	139	162	172	177	178	182	185	188	192	194	202	208	210	211	212	217	222	228	241	251	254
	140	163	173	178	179	183	186	189	193	195	203	209	211	212	213	218	223	230	242	252	255
	141	164	174	179	180	184	187	190	194	196	204	210	212	213	214	219	224	231	243	253	256
	142	165	175	180	181	185	188	191	195	197	205	211	213	214	215	220	225	232	244	254	257
	143	166	176	181	182	186	189	192	196	198	206	212	214	215	216	221	226	233	245	256	259
	144	167	177	182	183	187	190	193	197	199	207	213	215	216	218	222	227	234	247	257	260
	145	168	178	183	184	188	191	194	198	200	208	214	216	218	219	223	229	235	248	258	261
	146	169	179	184	185	189	193	195	199	202	209	215	217	219	220	224	230	237	249	259	262
	147	170	180	185	186	190	194	196	200	203	210	216	218	220	221	226	231	238	250	260	263
	148	171	181	186	187	191	195	197	201	204	211	217	219	221	222	227	232	239	251	262	265
	149	172	182	187	188	192	196	198	202	205	212	218	220	222	223	228	233	240	253	263	266
	150	173	183	188	189	193	197	200	203	206	213	219	221	223	224	229	234	242	254	264	267
	151	174	184	189	190	194	198	201	204	207	214	220	223	224	225	230	236	243	255	266	269
	152	175	185	190	191	195	199	202	205	208	215	221	224	225	226	231	237	245	257	267	270

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APPENDIX L

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SUPPORTING RESEARCH

SR-LO-04002
JSC-16830

"Preliminary Evaluation of Spectral, Normal, and Meteorological Crop Stage Estimation Approaches"

November 5, 1980

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SR-L0-04002; JSC-16830		

4. Title and Subtitle	5. Report Date
Preliminary Evaluation of Spectral, Normal, and Meteorological Crop Stage Estimation Approaches	October 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
R. B. Cate, J. A. Artley, P. C. Doraiswamy, T. Hodges, M. C. Kinsler, D. E. Phinney, and M. L. Sestak	LEMSCO-14640
9. Performing Organization Name and Address	10. Work Unit No.
Lockheed Engineering and Management Services Company, Inc. 1830 NASA Road 1 Houston, Texas 77058	11. Contract or Grant No. NAS 9-15800
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered Technical Report
National Aeronautics and Space Administration Lyndon B. Johnson Space Center Houston, Texas 77058 Technical Monitor: J. D. Erickson	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Several of the projects in the Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) program require crop phenology information, including classification, acreage and yield estimation, and detection of episodal events. This study evaluates several crop calendar estimation techniques for their potential use in the program. The techniques, although generic in approach, were developed and tested on spring wheat data collected in 1978. There are three basic approaches to crop stage estimation: historical averages for an area (normal crop calendars), agrometeorological modeling of known crop-weather relationships [agrometeorological (agromet) crop calendars], and interpretation of spectral signatures (spectral crop calendars). Normals serve as the baseline against which the skill of the other models may be tested. Agromet crop stage models require planting dates to initiate the accumulation of weather variables. When a data set does not include planting dates, these dates may be estimated with normal, agromet, or spectral starter models and used to start the agromet stage models. The 1978 spring wheat data set does not include planting dates. Consequently, five starter models and the normal planting date were used, including the Feyerherm and Stuff-Phinney agromet starter models and the Badhwar profile, color, and linear-discriminant spectral starter models. The planting date models were compared by using them to adjust the normal crop calendar to predict stages on dates for which ground truth is available. Two agromet models, the Robertson and Doraiswamy, were tested using normal, Feyerherm (the best agromet starter), and linear discriminant (the best spectral starter) planting dates. In all, 10 combinations of planting and biostage estimation models were evaluated. Dates of stage occurrence are estimated with biases between -4 and +4 days while root mean square errors range from 10 to 15 days. Results are inconclusive as to the superiority of any of the models and further evaluation of the models with the 1979 data set is recommended.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
AgRISTARS, agrometeorological crop calendar, crop calendar, crop stage estimation, normal crop calendar, phenology, planting date, spectral crop calendar, spring wheat, starter model weather/crop interactions	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	74	