

Crop-Area Estimates from Landsat; Transition from Research and Development to Timely Results

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Abstract—The report describes how NASA earth resources monitoring satellites, Landsat II and III, were used with conventional USDA ground-gathered data to estimate planted crop areas for the 1978 Iowa corn and soybean crops. Estimates that used Landsat data and ground data jointly were substantially more precise than those made from ground data alone. These estimates were one of several data sources used in determining the official year end Annual Crop Summary for Iowa issued January 16, 1979, by USDA's Crop Reporting Board. Problems associated with total project cost, timely delivery of Landsat data to the USDA, and cloud cover must be solved prior to any planning for an operational program.

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I. INTRODUCTION

THE UTILITY OF Landsat data in developing data in crop-area statistics has been demonstrated by a number of investigators. Generally such studies have had "proof of concept" in a research and development (R & D) mode as their primary objective. Obtaining timely results for consumption by agricultural data users has been of secondary importance in most R & D studies. In contrast, this paper describes recent efforts by the Economics, Statistics, and Cooperatives Service (ESCS) of the USDA in developing *timely* crop-area estimates from Landsat with measurable and improved precision. The 1978 Iowa corn and soybean crops were the key items of interest for this project.

One of the functions of ESCS is to estimate crop areas planted at national and state levels. These estimates are published by ESCS's Crop Reporting Board starting on June 30 of the crop year. Estimates are updated monthly up until mid-January at which time final national and state estimates for the crop year are made. Estimates for individual counties and in some states for multicounty areas, called Crop Reporting Districts, are made by ESCS's State Statistical Offices (SSO's) in cooperation with state government agricultural agencies. Small area estimates, however, are often not published until April of the year following the crop year.

From 1972 to 1977, ESCS has investigated the ability of Landsat data to improve crop-area estimates at state, multicounty, and individual county levels. The results from these studies have been mixed. For winter wheat, substantial improvements in the precision of crop-area estimates were obtained in Kansas. For corn and soybeans, however, good results were obtained only for a subset of investigation areas. On the average, these previous R & D efforts took over a year to complete and thus the results were not useable for setting final area estimates for the current crop year. In 1978, on the other hand, ESCS strove to develop timely Landsat-based crop-area estimates to supplement current area survey estimates. These estimates were then input to the 1978 Annual Crop Summary released by the USDA's Crop Reporting Board on January 16, 1979. The estimates were also used by the Iowa SSO in making multicounty estimates.

II. STATISTICAL METHODOLOGY

A. Direct Expansion Estimation (Ground Data Only)

Aerial photography obtained from the Agricultural Stabilization and Conservation Service is visually interpreted using the percent of cultivated land to define broad land-use strata. Within each stratum, the total area is divided into N_h elementary area frame units. This collection of area frame units for all strata is called an area sampling frame. A simple random sample of n_h units is drawn within each stratum. ESCS conducts a survey in late May, known as the June Enumerative Survey (JES). In this general purpose survey, area devoted to each crop or land use is recorded for each field in the sampled area frame units (segments). The scope of information collected on this survey is much broader than crop area alone. Items estimated from this survey include crop area by intended utilization, grain storage on farms, livestock inventory by various weight categories, agricultural labor, and farm economic data. Intensive training of field statisticians and interviewers is conducted providing rigid controls to minimize nonsampling errors. The notation used for the stratified random sample is as follows.

Let $h = 1, 2, \dots, L$ be the land-use strata. For a specific crop (corn, for example) the estimate of total crop area for all purposes and the estimated variance of the total area is as follows: let Y = total corn area for a state (Iowa, for example), \hat{Y}_{DE} = estimated total of corn area for a state, and y_{hj} = total area in the j th sample unit in the h th stratum.

Then,

$$\hat{Y}_{DE} = \sum_{h=1}^L N_h \sum_{j=1}^{n_h} y_{hj} / n_h.$$

The estimated variance of the total is

$$v(\hat{Y}_{DE}) = \sum_{h=1}^L \frac{N_h^2}{n_h(n_h-1)} \frac{N_h - n_h}{N_h} \cdot \sum_{j=1}^{n_h} (y_{hj} - \bar{y}_h)^2.$$

Note that we have not yet made use of an auxiliary variable such as computer classified Landsat pixels. The estimator is commonly called a direct expansion estimate [1], and we will denote this by \hat{Y}_{DE} .

B. Regression Estimation (Ground Data and Computer Classified Landsat Data)

The regression estimator utilizes both ground data and classified Landsat pixels. The estimate of the total Y using this estimator is

$$\hat{Y}_R = \sum_{h=1}^L N_h \cdot \bar{y}_h(\text{reg})$$

where

$$\bar{y}_h(\text{reg}) = \bar{y}_h + \hat{b}_h(\bar{X}_h - \bar{x}_h)$$

and \bar{y}_h is the average corn area per sample unit from the ground survey for h th land-use stratum; \hat{b}_h the estimated regression coefficient for the h th land-use stratum when regressing ground-reported corn area on classified pixels for the n_h sample units; \bar{X}_h the average number of pixels of corn per frame unit for all frame units in the h th land-use stratum. Thus entire Landsat scenes must be classified to calculate \bar{X}_h . Note that this is the mean for the population and not the sample. X_{hi} is the number of pixels classified as corn in the i th area frame unit of the h th stratum; \bar{x}_h the average number of pixels of corn per sample unit in the h th land-use stratum; and x_{hj} the number of pixels classified as corn in the j th sample unit in the h th stratum.

The estimated (large sample) variance for the regression estimator is

$$v(\hat{Y}_R) = \sum_{h=1}^L \frac{N_h^2}{n_h} \frac{N_h - n_h}{N_h} \frac{1 - r_h^2}{n_h - 2} \sum_{j=1}^{n_h} (y_{hj} - \bar{y}_h)^2$$

where r_h^2 is the sample coefficient of determination between reported corn area and classified corn pixels in the h th land-use stratum:

$$r_h^2 = \frac{\left[\sum_{j=1}^{n_h} (y_{hj} - \bar{y}_h)(x_{hj} - \bar{x}_h) \right]^2}{\left[\sum_{j=1}^{n_h} (y_{hj} - \bar{y}_h)^2 \right] \left[\sum_{j=1}^{n_h} (x_{hj} - \bar{x}_h)^2 \right]}$$

Note that

$$v(\hat{Y}_R) = \sum_{h=1}^L \frac{n_h - 1}{n_h - 2} (1 - r_h^2) v(\hat{Y}_h)$$

and so $\lim v(\hat{Y}_R) = 0$ as $r_h^2 \rightarrow 1$ for fixed n_h . Thus a gain in lower variance properties is substantial if the coefficient of determination is large for most strata.

The relative efficiency of the regression estimator compared to the direct expansion estimator will be defined as the ratio

of the respective variances:

$$RE = v(\hat{Y}_{DE})/v(\hat{Y}_R).$$

Since the entire state of Iowa cannot be covered by Landsat imagery of the same date, it was necessary to define post-strata (analysis districts) which were wholly contained within a Landsat pass or scene. The formulas for the direct expansion estimate and regression estimate hold for post-strata as presented by Gleason *et al.* [2]. The regression estimator described above is called the separate form of the regression estimator. An alternate form for the regression estimator, called the combined form, is described by Craig *et al.* [3]. Conditions under which use of the combined form are appropriate are discussed by Cochran [1]. Several types of estimates have also been developed for individual counties [2], [4].

III. GROUND DATA

The ground data required were: land-use strata boundaries digitized from a latitude-longitude map base, individual field data for all fields in the JES sample segments, aerial photographs with accurate field boundary locations, and a follow-up survey of JES fields that were not yet planted at the time of the JES.

Digitization of the land-use strata boundaries began in mid-January. The land-use boundaries were located and digitized from Iowa County highway maps. The vertices were digitized from a latitude-longitude coordinate system and then transformed to the row-column system of Landsat data using each individual scene's registration transformation. The digitization of the land-use strata boundaries was completed in May. Average time to digitize an individual county was one day.

The sample segments had land use or crop type and area recorded for each field during late May and early June during ESCS's JES. The field boundaries were drawn onto ASCS aerial photographic prints with a scale of approximately 8 in = 1 mi. The field-level information was then recorded on a questionnaire and drawn onto an aerial photograph. In the Landsat study, a special edit of each field using photo and questionnaire data was done to insure accurate field boundary locations. The questionnaire data was collected, edited at the individual farm level, and keypunched by Iowa Crop and Livestock Reporting Service personnel. The data was then transmitted to Washington, DC, for individual field-level editing. After editing the JES data, a computer tape with all ground-data information was sent to Bolt, Beranek, and Newman (BBN) data processing facility in Cambridge, MA. However, at the time of the JES, all fields had not yet been planted. Thus a follow-up survey was conducted from July 21 to August 1. The follow-up survey questionnaire and aerial photography were used to determine the land cover for any fields that were not planted at the time of the JES. The follow-up survey data was then used to update the ground-data computer files at BBN.

Digitization of fields in the JES segments was the next step. All field boundaries were digitized from the aerial photographs using polygonal vertices which were transformed to latitude-longitude. Boundaries of 8600 fields from the 298 JES segments were digitized. The process began in mid-July and ended

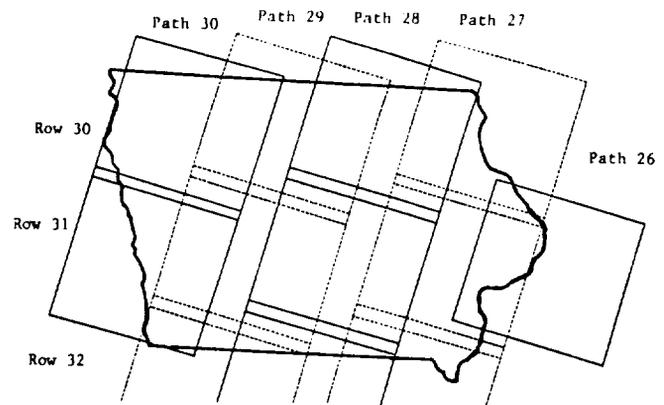


Fig. 1. Landsat imagery paths and rows.

TABLE I
IOWA LANDSAT SCENES USED IN CROP-AREA ESTIMATION

Path	Row	Date	Percent Iowa Cloud-Cover	Scene ID
30	30	August 19	0	30167-16274
	31	August 19	0	30167-16280
29	30	August 9	0	21295-16013
	31	August 9	40	21295-16020
	32	August 18	0	30166-16224
28	30	September 4	60	30183-16162
	31	September 4	0	30183-16164
	32	September 4	0	30183-16171
27	30	August 8	10	21293-15500
	31	August 8	15	21293-15502
	32	August 8	10	21293-15505
26	31	August 6	0	21292-15444

in mid-September. Average time to calibrate and digitize a segment was 1 hour.

IV. LANDSAT DATA ACQUISITION

Twelve Landsat scenes were required to virtually cover the state of Iowa. The Landsat scene covering the northwest corner of Iowa was not analyzed because only 200 km² of Iowa was not contained in Landsat scenes further to the east. This unimaged area in northwest Iowa was less than 0.2 percent of the total area of the state. The location of the twelve Landsat scenes can be seen in Fig. 1.

Based on ESCS's previous Landsat analysis experience in Illinois and on the 1978 planting times, Landsat imagery was desired during early to mid-August. Table I lists images which were registered for the Iowa project. Image dates ranged from August 7 to September 4, 1978. As can be seen from Table I, some of the registered images contained clouds.

Attempts to obtain cloud-free imagery were not successful. For path 29, row 31, both August 18 and September 5 were cloud free. However, the August 18 image was of poor quality, while the September 5 image was not delivered to ESCS by December 15, in time for it to be registered and analyzed by December 31. Consequently, the partially cloud covered August 9 scene was registered for path 29, row 31. Path 27 on August 16 was cloud free. However, this imagery was never received by NASA's Goldstone receiving station. Thus partially cloud-covered imagery for August 7 was used for path 27.

Because of the various dates of the Iowa Landsat imagery, the associated cloud-cover problems, and the different times at

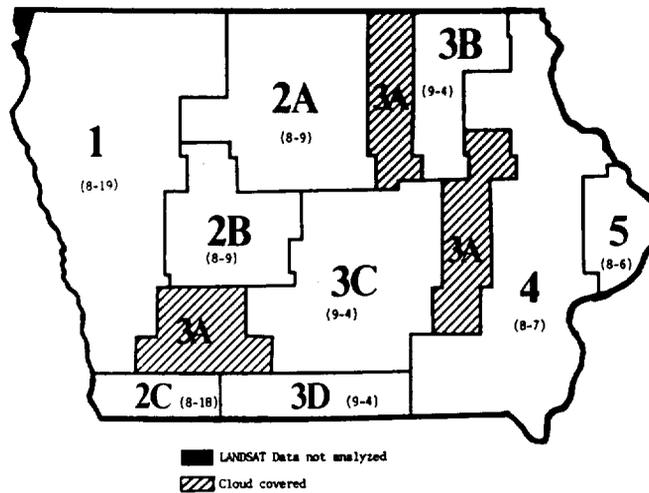


Fig. 2. Analysis districts and image dates.

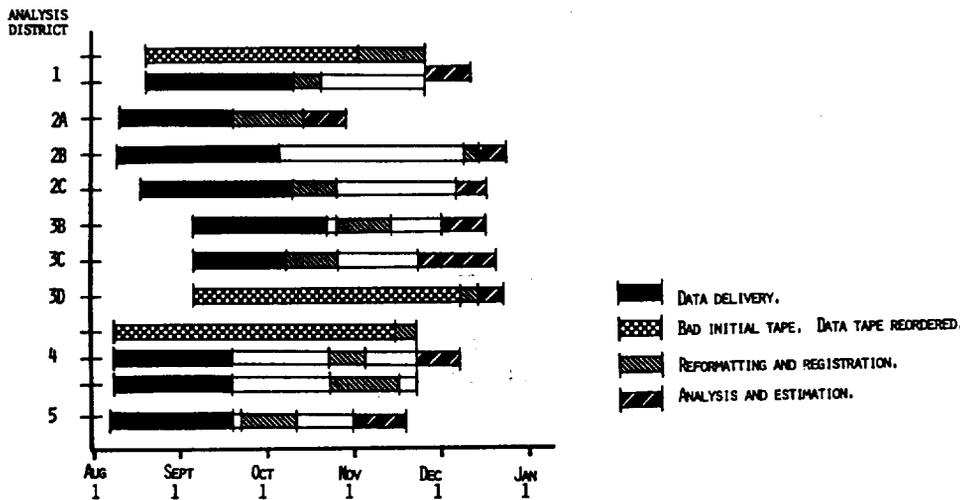


Fig. 3. Landsat data processing activities beginning and ending dates.

which ESCS received Landsat data, Iowa was partitioned into ten separate areas, called analysis districts (see Fig. 2). The smallest analysis district, number 2C, contained three counties; the largest, number 1, contained twenty counties. Analysis district 3A consisted of the thirteen cloud-covered counties.

A number of analysis districts—for example, 3B, 3C, and 3D—have the same image date. Separate analysis districts were formed in such cases instead of a single large one because the Landsat data were received by ESCS for the separate areas at different times. Because of time pressure, analysis districts were formed when data were received, instead of waiting until all data for a given image date were on hand.

For each Landsat scene used in crop-area estimation, three major processing activities transpired from time of satellite overpass to completion of crop-area estimates. These were 1) NASA delivery of Landsat data products to ESCS, 2) Landsat tape reformatting and scene registration, and 3) Landsat data displays and calculation of crop-area estimates.

Fig. 3 displays by analysis district the beginning and ending dates for the Landsat processing activities. The first analysis district to be completed was 2A on October 26; the last, 2B, was completed on December 21. Table II displays various

TABLE II
DURATIONS FOR LANDSAT DATA PROCESSING ACTIVITIES:
SUMMARY STATISTICS

Activity	Duration in calendar days			
	median	min	max	quartiles
Data delivery	49	32	93	37,66
Reformatting, Registration	16	4	25	8,20
Analysis, Estimation	13.5	7	26	10,18

summary statistics for the time required by each processing activity. As can be seen from Table II, on the average, data delivery took the longest and was the most variable in duration of the three processing activities.

By examining daily GOES satellite weather photos, ESCS was able to select candidate cloud-free Landsat scenes within one to two days after a Landsat overpass. Landsat computer compatible data tapes and 1:1 000 000 black and white transparencies were supplied to ESCS by NASA's Goddard Space Flight Center (GSFC). Twenty-four tapes were ordered from GSFC, twelve of which were registered for the calculation of

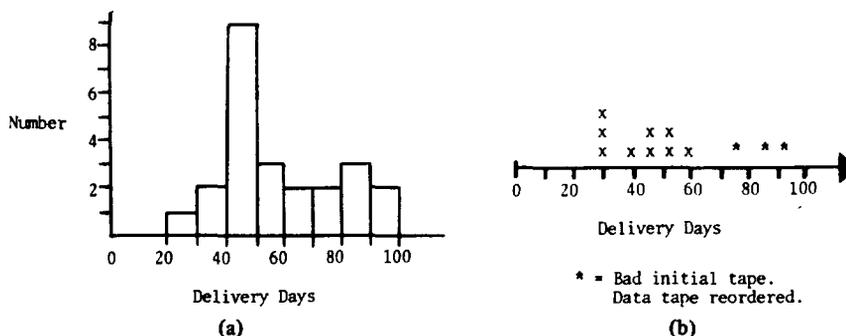


Fig. 4. Delivery times for Landsat tapes (measured in calendar days from date of satellite overpass to receipt by ESCS). (a) For all tapes ordered. (b) For tapes analyzed.

crop-area estimates. A histogram of delivery times, i.e., time from data of satellite overpass to receipt by ESCS, for the 24 ordered tapes is shown in Fig. 4(a). Fig. 4(b) displays the tape delivery times for the twelve scenes which were registered.

V. DATA PROCESSING SYSTEMS HARDWARE

ESCS purchases computer time on a number of different types of computers. These include 1) a PDP10 computer in Cambridge, MA (BBN), used by ESCS for interactive processing, such as photo and map digitization, Landsat analysis for sample segments, and calculation of crop-area estimates; 2) an IBM 370-168 at the USDA's Washington Computer Center (WCC) in Washington, DC, used for computer editing of ground-truth data, reformatting Landsat tapes, and batch printing of grey-scales; and 3) the ILLIAC IV computer in Sunnyvale, CA, used by ESCS for clustering and "wall-to-wall" classification of Landsat scenes.

For electronic data transmission ESCS uses Computer Science Corporation's INFONET data network and the Department of Defense's ARPANET computer network. Additional pieces of hardware used by ESCS for Landsat data analysis are the following: 1) two digitizer tablets; 2) Zoom Transferscope; 3) terminal plotter with controller; 4) leased phone line with multiplexor; and 5) fifteen KRS (keyboard send-receive) terminals of various types. The total purchase price of this equipment is approximately \$90 000.

Total IBM 370-168 computer charges for the Iowa project were \$7000 (includes usage for computer program testing). PDP10 computer usage for the Iowa project (including usage for development and testing of associated computer programs) was approximately \$69 000.

VI. SOFTWARE AND DATA MANAGEMENT

A. Software

All Landsat data analysis for Iowa was done using the EDITOR software system with the exception of reformatting tapes and some of the grey scale printing for registration. The latter functions were performed using the IBM 370-168 at WCC.

EDITOR [5] is an interactive image processing system which runs under the TENEX operating system. EDITOR provides a link via the ARPA network to the ILLIAC IV for large-scale batch processing. EDITOR is a large collection of programs all

called from a single main program using simple commands describing the function of the programs. The programs communicate with each other through various files. For the Iowa project, EDITOR was not changed in any substantial or basic manner. However, a number of improvements were made to facilitate its use.

B. Data Management

The overall flow of data for the Iowa project was as follows.

- 1) Ground-truth data was keypunched in Des Moines, IA, and transmitted via INFONET to WCC in Washington, DC.
- 2) Ground-truth data was edited in Washington, DC, and a ground-truth tape mailed to BBN in Cambridge, MA.
- 3) Landsat tapes from NASA's Goddard Space Flight Center in Greenbelt, MD, were reformatted and tapes mailed to Cambridge, MA, and Sunnyvale, CA.
- 4) The PDP10 in Cambridge, MA, was accessed via ARPANET, leased line, or Federal Telephone Service (FTS) dial-up for interactive processing of Landsat data for sample segments.
- 5) Classification parameters were transmitted to Sunnyvale, CA, via ARPANET for "wall-to-wall" Landsat scene classification.
- 6) Aggregated ILLIAC IV classification results were transmitted back to Cambridge, MA, over ARPANET for interactive calculation of crop-area estimates.

VII. LANDSAT SCENE REGISTRATION

Landsat data registration procedures used for the twelve scenes were data reformatting, selection of control points, determination of latitude-longitude from USGS quad maps and row-column from grey-scales, third-order polynomial regression analysis, and the matching of predicted segment locations with grey-scales for precise segment location. Root-mean-square errors for Landsat scene registration ranged from 45.3 to 91.7 m. Registration procedures took, on the average, two weeks to complete which was a considerable improvement over previous ESCS Landsat projects.

VIII. LANDSAT CLASSIFICATION

Prior to the classification of "wall-to-wall" Landsat data, ESCS analyzes the pixels inside or intersecting JES segments. One objective of this analysis is to train a pixel classifier, i.e., to estimate signature parameters and prior probabilities for a

TABLE III
1978 IOWA CORN RESULTS (PLANTED HECTARES)

Analysis District	\hat{Y}_{DE} = 1978 Direct Expansion	Coefficient of Variation for \hat{Y}_{DE}	\hat{Y}_R = 1978 LANDSAT Regression	Coefficient of Variation for \hat{Y}_R	Range of r^2 for $h=1, \dots, L$	Relative Efficiency
1	1,462,074	3.48	1,460,234	2.20	.57-.92	2.51
2A	828,772	4.47	818,892	2.50	.71	3.28
2B	332,050	11.50	454,252	3.40	.78-.94	5.98
2C	106,036	10.98	109,959	9.50	.30	1.24
*3A	657,462	4.36	-	-	-	-
3B	276,112	10.05	268,022	8.47	.38	1.49
3C	550,581	7.46	542,081	6.02	.34-.40	1.58
3D	83,658	17.76	82,798	18.65	.07	0.93
4	1,029,688	6.72	896,084	4.47	.65-.71	2.99
5	148,148	11.10	149,820	6.03	.75	3.32
State	JES= 5,525,807	2.3	5,439,604	1.5	.07-.94	2.43

*LANDSAT data not available.

set of classification categories. A second objective of this sample-level analysis is to test the developed classifier by estimating the r_h^2 squared correlations which appear in the variance formula for the regression estimator. Such classifier testing uses both JES field-interior pixels and JES field-boundary pixels, whereas classifier training uses only field-interior pixels. During 1978 in Iowa the average size of individual fields (estimated from JES data) was 12 ha for corn and 13 ha for soybeans. As a result, approximately 59 percent of the segment pixels within or intersecting a corn or soybean field were field-interior pixels.

To train the pixel classifier, ESCS uses a modified supervised approach [6] in which the collection of pixels used for training is first partitioned according to ground-truth cover type and then the data in the individual partitions are clustered. Each resulting cluster that contains more than some minimum number of pixels then represents a classifier category. The overall result is one or more classification categories for each ground-truth cover type. The pixel data that was used in this modification of supervised training was not always the set of all JES field-interior pixels. One subset used was only the field interior pixels for fields larger than 5 ha. Another reason that only a subset of the available field-interior pixels was used for training was to allow classifier training and testing on independent test sets. ESCS assumes that the Landsat data for a given category follows a multivariate normal distribution. Hence, the final step of classifier training is to estimate the mean vector, variance-covariance matrix, and prior probability for each category.

The fact that the JES is a probability survey makes it possible to calculate current estimates of cover type prior probabilities. These estimated prior probabilities for cover types are then prorated to the individual categories within the cover types on the basis of the number of pixels in the category's cluster of training data. In addition to estimating prior probabilities with JES data, pixel classifiers with equal prior proba-

bilities were also developed. In many cases the variance of the regression estimator based on equal prior classification was smaller than the variance of the regression estimator based on classification with estimated priors.

As previously mentioned, the variance of the regression estimator is minimized when the r_h^2 are maximized. Thus r_h^2 and not percent correct classification was the criterion for evaluating alternative classifiers. Though developing pixel classifiers was somewhat trial and error, a statistical criterion (r_h^2) was always the final tool for evaluating the resulting regression estimates. Some limited jack knifing and sample partitioning of JES segment data was performed as in previous ESCS Landsat studies [2], [3] to provide some assurance that r_h^2 did not have a significant positive bias.

IX. CROP-AREA ESTIMATES

Crop-area estimates for corn and soybeans were developed at the state, multicounty (analysis district), and individual county levels. At the state and multicounty level, improvements in precision for the regression estimate (Landsat and ground data) versus the direct expansion estimate (ground data only) were substantial. At the analysis district level, the range of relative efficiencies for corn was from 0.93 to 5.98 and soybeans ranged from 2.73 to 7.59. Specific values for all analysis district estimates and their corresponding relative efficiencies are listed in Tables III and IV. Clouds covered 13 of the 99 counties in Iowa for the available Landsat data. Loss of Landsat data for portions of a state during the optimum period for crop discrimination due to cloud cover isn't an unusual event. The conventional direct expansion estimate of ground data had to be used for the 13 county area in Iowa [7]. Individual county estimates had C.V.'s ranging from 7.1 to 59.9 percent for corn and 9.0 to 100 percent for soybeans. C.V.'s above 20 percent are not suitable for operational data use by ESCS.

The state-level estimates were input to USDA's Crop Reporting Board's 1978 Annual Crop Summary for Iowa. The

TABLE IV
1978 IOWA SOYBEANS RESULTS (PLANTED HECTARES)

Analysis District	\hat{Y}_{DE} = 1978 Direct Expansion	Coefficient of Variation for Y_{DE}	\hat{Y}_R = 1978 LANDSAT Regression	Coefficient of Variation for Y_R	Range of r^2 for $h=1$, ...L	Relative Efficiency
1	747,759	8.11	781,566	4.04	.58-.88	3.70
2A	655,049	6.75	675,293	3.42	.74	3.68
2B	256,944	12.91	255,540	6.11	.74-.98	4.55
2C	95,196	24.97	97,497	11.67	.80	4.37
*3A	401,671	9.20	-	-	-	-
3B	86,550	28.00	125,300	9.37	.79	4.26
3C	328,662	14.51	338,363	7.06	.77	3.98
3D	82,633	32.55	95,933	10.20	.89	7.59
4	441,032	12.68	424,782	7.97	.45-.83	2.73
5	47,060	29.20	48,580	12.53	.86	5.10
State	JES=3,205,320	3.91	3,244,525	2.50	.45-.98	2.38

*LANDSAT data not available.

analysis district estimates were input to the Iowa Crop and Livestock Reporting Service's multicounty level estimates. However, these Landsat based regression estimates were not the sole source of data in determining the state and multicounty estimates.

X. SUMMARY

The primary project goal of developing timely and precise crop-area estimates at the state and multicounty level utilizing both Landsat data and conventional ESCS ground data was accomplished. These estimates were used as input to official USDA crop reports for Iowa. The major benefit of Landsat regression estimates to ESCS is substantial improvements in precision with no increase in respondent burden associated with ground surveys. The repeatability of such an effort, however, is crucially dependent upon timely delivery of Landsat data to ESCS. It is important to note that these estimates must be considerably more precise than those provided by ESCS's efficient JES to be useful to USDA's Crop Reporting Board. Cloud cover is a serious problem in estimating crop areas at the substate level. At the individual county level the sampling errors associated with the crop-area estimates are generally too large to warrant use of the data.

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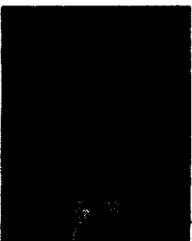


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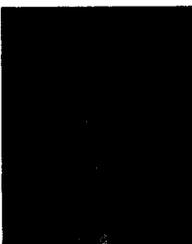
S. M. Carlyle, photograph and biography not available at the time of publication.

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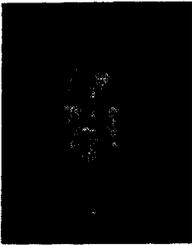
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