THE ROLE OF LANDSAT DATA IN IMPROVING U.S. CROP STATISTICS*

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ABSTRACT

Landsat data are used in two ways to improve U.S. crop statistics. Landsat color-composite images are used to stratify areas of land with regard to land use. This stratification is used as a technique to improve the efficiency of an area sampling frame. Also, Landsat digital data are classified and the classified results are used as supplementary information to an agricultural survey. The combination of Landsat classification results and survey data improves the precision of the estimates made.

1.0 Introduction

The Statistical Reporting Service (SRS) is the agency of the U.S. Department of Agriculture responsible for current statistics describing domestic crop and livestock production. For the most part, these statistics are estimates based on sample surveys conducted by SRS personnel.

A major source of data for SRS is its nationwide June Enumerative Survey (JES). It is in conjunction with the JES that SRS uses data from the Landsat satellites. Landsat data are used to improve the precision of the estimates obtained from the JES in two different ways. One use of Landsat data is in the development of an area sampling frame from which the JES sample is selected. A second use is as current, supplemental information that, when combined with the data collected during the JES, increases the precision of calculated area estimates.

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2.0 Use of Landsat Imagery in Area Frame Construction

2.1 Concepts

In area-frame sampling the sample units are pieces of land called segments. The boundaries of segments are well-defined, physical features -- such as roads, footpaths, rivers, and railways -- that can be both delineated on maps and aerial photographs and also readily identified by data collection personnel in the field. An area-sampling frame is a complete list (or more frequently a set of specifications that would generate a complete list) of segments that cover a geographical area of interest, such as a state or province. This geographical area of interest is called a population.

An area sampling frame is a basic tool for collecting agricultural statistics. It is used in a number of countries to estimate acreage and yield of agricultural products as well as farm-economics parameters such as prices and labor for the current year. Area frame sampling provides accurate information by taking representative samples from only a small portion of the total land area. Estimates can be available five to six weeks after the beginning of data collection.

The construction of an area sampling frame consists of several steps [Houseman, 1975]. The first step is the delineation on a base map of stratum blocks. These are large contiguous areas of homogeneous land use. In addition to the mapping symbols on the base map, information from satellite imagery, aerial photography, and other maps are used in this stratification step. All of the stratum blocks of the same land use constitute a stratum. Like segment boundaries, the delineated strata boundaries must be identifiable in the field. The purpose of stratification is to increase the precision of sample survey estimates.

The next step is to divide the strata blocks into smaller areas called primary sampling units (PSU's). The PSU's vary in size depending on the stratum but generally contain from 5 to 20 potential segments. Out of each stratum a suitable number of PSU's will be randomly chosen with probability of selection proportional to the area of the PSU.

The purpose of the PSU's is to serve as an intermediate delineation between the large strata blocks and the individual segments. By delineating PSU's all of the segments in the population need not be delineated. Instead, only the segments in the randomly selected PSU's are delineated by subdividing the PSU into the appropriate number of segments based on the area of the PSU and the target segment size. In strata that are predominantly cultivated land, the target segment size is typically one square mile. After the selected PSU has been subdivided, one segment is randomly selected from the PSU for field enumeration.

Desired data are then collected from the sample segments by interviewing farmers who operate land inside the segment. Since the segments within each stratum are statistically representative of the stratum, the data collected from the segments can be expanded to the total area of the stratum. The desired estimate for the entire population is then obtained by summing the results for each stratum.

2.2 SRS Experience

SRS has constructed and maintains an area frame for each of the 48 contiguous states. Since the construction of an area frame for a state is a major effort, SRS is only able to construct approximately three new area frames per year. Once an area frame for a state is constructed, it is used annually for anywhere from 10 to 20 years before it is revised or replaced.

The majority of SRS's area frames contain five basic strata: cultivated land, range and pasture, water, nonagricultural land, and cities and towns. The cultivated land in most states is further stratified by separating "intensively" cultivated land from "extensively" cultivated land. (In Nebraska there are two intensively-cultivated-land strata.) In addition to the five basic land-use strata, the area frames in California and Texas each contain one or more "crop specific" strata. The SRS area frames in Washington, Oregon, and Idaho have strata for dryland grain. [Geuder, 1984]

The use of Landsat imagery to stratify SRS area sampling frames was first demonstrated by Hanuschak and Morrisey [1977]. In this study, county maps at a scale of 1:126,720 were photographically reduced to a scale of 1:250,000 on mylar and overlaid on 1:250,000-scale, color Landsat imagery produced on paper by the EROS Data Center. The Landsat image was photo-interpreted to provide land-use information, whereas the overlaid county map provided physical features for delineating stratum blocks and PSU's. This procedure was then used by SRS in 1979 to construct a new area frame for the state of California [Fecso and Johnson, 1981]. Since 1979, SRS has photo-interpreted Landsat images for constructing new area frames in Arizona, Colorado, Florida, Idaho, New Mexico, Oregon, Texas, Washington, and Wyoming. The majority of these new frames have been in the western United States where much of the cultivated land is irrigated and can thus be readily identified on Landsat images.

In 1982, SRS updated the Nebraska area frame by restratifying the urban stratum and areas where rangeland had been converted to cropland. Used in this restratification effort were plots giving the location of all pivot irrigation in 58 counties. These plots were developed by the University of Nebraska from Landsat data, administrative records for well permits, and field observations by county agents. [Hale, 1983]

Burns [1983] has demonstrated the use of <u>digital</u> Landsat data for updating SRS sampling frames in an area in Louisiana. In this study, unsupervised clustering of the Landsat data was performed, and then stratum labels were assigned to the clusters by an analyst using an interactive image processing system. SRS is further evaluating this procedure for stratifying area sample frames in Wyoming and Florida [Geuder, Blackwood, and Radenz; 1983].

3.0 Landsat Data as Supplemental Information

3.1 Background

SRS conducts the JES annually in late May and early June. The JES survey procedure requires that information be obtained for all the land within each of the sampled segments. To insure that all the land is accounted for, aerial photographs, at a scale of 1:8,000, are used as an enumeration aid. The boundaries for each segment are drawn on individual non-current photographic prints. These segment photographs and corresponding questionnaires are sent to field enumerators for data collection. As part of the data collection procedure, each enumerator is instructed to draw the boundaries of all fields, within each segment, on the segment photograph (a field is defined as a continuous block of land containing the same crop or land cover). On the corresponding questionnaire the enumerator records the cover and size of each field, as well as livestock numbers and other agricultural information obtained from the operator. The information collected during the JES is aggregated to the segment level and direct expansion estimates are then calculated to obtain state level estimates for crop hectares. The formulas for the direct-expansion estimator and its variance are as follows:

Let $\hat{Y}_c$ = the direct expansion estimate for the hectares of crop c

$$\hat{Y}_c = \sum_{s=1}^{S} \frac{N_s}{n_s} \sum_{j=1}^{n_s} y_{jsc}$$

where:

y_{jsc} = the hectares reported to crop c, in segment j, for strata s

n_s = number of segments sampled in strata s

N_s = the total number of potential segments in stratum s

S = the total number of strata

The estimated variance is:

$$V(\hat{Y}) = \sum_{s=1}^{S} \frac{(N_s - n_s)\ N_s}{n_s\ (n_s - 1)} \sum_{j=1}^{n_s} (y_{jsc} - y_{.sc})^2$$

where:

$$y_{.sc} = \sum_{j=1}^{n_s} \frac{y_{jsc}}{n_s}$$

In 1972 SRS personnel started to investigate the potential of using digital Landsat data to improve the precision of the estimates obtained from the JES. The procedure developed consists of the following steps:

- Analysis District Selection: Landsat data are selected and boundaries of Landsat analysis districts defined.

- Signature Development: Data collected during the JES and corresponding Landsat data are used to develop a maximum likelihood classifier for each analysis district.

- Small Scale Processing: The Landsat pixels representing the area within each segment contained in an analysis district are classified. A relationship is developed between the number of pixels classified to a crop and the hectares recorded for that crop on the JES.

- Full Frame Processing: All of the Landsat pixels within the analysis district are classified. Estimates are calculated at the analysis district level by applying each crop regression relationship to the all-pixel classification results.

- State Level Accumulation: The estimates for all analysis districts are combined to create a state level estimate for each crop of interest.

3.2 Analysis District Selection

An analysis district is an area of land covered by Landsat imagery of the same overpass date. A separate Landsat analysis is done for each analysis district. Depending on the location and availability of Landsat data, each state is divided into a number of analysis districts. The Landsat analysis district location is treated as a geographical post-stratification imposed on the original area frame. As a result of this post-stratification, SRS personnel must determine the number of frame units and the sampled segments which fall into each post-stratum. This results in two types of strata categories:

1) The first stratum category corresponds to the area of the state for which there is no Landsat coverage. This area may be non-contiguous. The portion of each land-use stratum within these geographical areas makes up the post-strata. We let

M_s = the total number of segments in the non-Landsat area in land use strata s, and
m_s = the number of sampled segments in the non-Landsat area in land use strata s.

2) The second stratum category corresponds to the areas of the state where the land-use strata and the analysis districts are defined. In these areas each stratum consists of the area of intersection between the land use strata and a Landsat analysis district. Here, we let

M'_{as} = the number of frame units in analysis district a, land use strata s, and
m'_{as} = the number of sampled segments in analysis district a, land use strata s.

3.3 Signature Development

Signature development is done independently for each analysis district and consists of four phases. The first phase is segment calibration and digitization. Segment calibration is a first-order linear transformation which maps points on the segment photograph to a map base (in our application this map base is the U.S. Geological Surveys quadrangle map series, which uses the latitude/longitude coordinate system of reference). Segment digitization is the process by which field boundaries drawn on the segment photograph are recorded in computer-compatible form. The combined process of calibration and digitization gives us the capability of digitally locating every JES field relative to a map base.

The next phase in signature development is the registration of each Landsat scene. SRS's Landsat registration process is a third-order linear transformation that maps each Landsat pixel within a scene to a map base [Cook, 1982]. Corresponding points selected on a two-degree map and a 1:250,000 Landsat image are used to generate this mathematical transformation. The combination of segment calibration, digitization and Landsat registration provides the capability to locate each JES segment in its corresponding Landsat scene (to within about 5 pixels of the correct location). Since this registration is not accurate enough for selecting training data, line plots of segment field boundaries and corresponding greyscale prints are overlaid and each segment is manually located to within 1/2 pixel of the correct location. With this process we are able to accurately identify all of the pixels associated with any JES field. The result of this is a set of pixels labeled by JES cover.

The third phase of signature development is supervised clustering. In supervised clustering all of the pixels for each cover are processed through one of two available clustering algorithms: Classy or Ordinary Clustering. Classy is a maximum likelihood clustering algorithm developed at Johnson Space Center in Houston, Texas [Lennington and Rassback, 1972]. Ordinary Clustering is an algorithm derived from the ISODATA algorithm of Ball and Hall [1967]. Each clustering algorithm generates several spectral signatures (categories) for each cover. Each spectral signature consists of a mean vector and the covariance matrix for the reflectance values for that category.

In the fourth phase, the statistics for all categories from all covers are reviewed and combined to form the discriminant functions of the maximum likelihood classifier. The formulas for the discriminant functions are as follows:

The <u>maximum likelihood classifier</u> with equal priors:

Classify pixel k to category c if $D_{ck} \geq D_{ik}$ for all $i \neq c$

The <u>maximum likelihood classifier</u> with priors:

Classify pixel k to category c if $D^p_{ck} \geq D^p_{ik}$ for all $i \neq c$

where:

$D_{ik} = -\log_e(|Z_i|) - (X_k - U_i)' Z_i^{-1} (X_k - U_i)$

$D^p_{ik} = D_{ik} + \log(p_i)$

U_i = the mean vector for category i

Z_i = the covariance matrix for category i

p_i = the prior probability for category i

X_k = the reflectance value for pixel k

3.4 Small Scale Processing

In small-scale processing each pixel associated with a JES segment is classified to a category. This classification is usually done using both the classifier with priors and the equal priors classifier. For each classifier, pixels classified to each category are summed to segment totals. The category totals corresponding to crops of interest are summed to segment crop totals. These crop totals are used as the independent variable in a regression estimator. Correspondingly, the hectares reported on the JES for each crop are summed to segment totals and used as the dependent variable. The segment totals are used to calculate least-squares estimates for the parameters of a linear regression. Two sets of regression equations are developed for each crop within each stratum (one for the classification with priors, one for the classification with equal priors).

The linear regression equations for analysis district a, strata s, and crop c are of the form:

$$y_{jasc} = b_{0asc} + b_{1asc}\, x_{jasc}$$

where:

y_{jasc} = the reported hectares of crop c, from segment j, analysis district a, land use stratum s

x_{jasc} = the crop total classification for segment j, analysis district a, land use strata s

b_{0asc}, b_{1asc} = least squared estimates of the regression parameters for crop c, analysis district a, land use strata s

3.5 Full Frame Processing

The regression equations developed in small-scale processing are evaluated and the classifier giving the best overall regression relationship is selected. This classifier is used to classify every pixel in the analysis district. The classified results are tabulated by category and land-use stratum. For each crop of interest the category totals are summed to stratum crop totals. From these totals the population averages per segment are calculated. Using the population average, a stratum-level regression estimate is made for that analysis district for each crop.

Let $\hat{Y}'_{asc}$ be the analysis district level regression estimator for crop c and stratum s.

Then:

$$\hat{Y}'_{asc} = M'_{as}\,[y_{.asc} + b_{1sc}(X_{.asc} - x_{.asc})]$$

where:

$$y_{.asc} = \sum_{j=1}^{m'_{as}} \frac{y_{jasc}}{m'_{as}} \quad \text{and} \quad x_{.asc} = \sum_{j=1}^{m'_{as}} \frac{x_{jasc}}{m'_{as}}$$

M'_{as} = previously defined (3.2)

m'_{as} = previously defined (3.2)

x_{jasc} = previously defined (3.4)

y_{jasc} = previously defined (3.4)

$X_{.asc}$ = the population average for crop c in analysis district a land use stratum s

The estimated variance is:

$$V(\hat{Y}'_{asc}) = \frac{(m'_{as}-1)}{(m'_{as}-2)}\,(1-r_{asc}^{2})\,\frac{(M'_{as}-m'_{as})M'_{as}}{m'_{as}(m'_{as}-1)} \sum_{j=1}^{m'_{as}} (y_{jasc}-y_{.asc})^2$$

where:

r^2_{asc} = the sample correlation between y_{jasc} and x_{jasc}

3.6 State Level Accumulation

The final step of our Landsat analysis is the combining of all of the estimates (one for each post strata) into a state-level estimate of the area of the desired crop.

Let $\hat{Y}'_c$ be the final state level estimate for the hectares of crop c.

Then:

$$\hat{Y}'_c = \sum_{a=1}^{A} \sum_{s=1}^{S'_a} \hat{Y}'_{asc} + \sum_{l=1}^{L} M_l \, y_{.lc}$$

where:

$$y_{.lc} = \sum_{j=1}^{m_l} \frac{y_{jlc}}{m_l}$$

M_l, m_l previously defined (3.2)

$\hat{Y}'_{asc}$ is as defined earlier (3.5)

y_{jlc} = the hectares reported to crop c for segment j in the non-Landsat post strata l

S'_a = The number of land use strata in analysis district a

A = The number of analysis districts

L = The number of land use strata that exist in the area where wedo not have Landsat coverage

The estimated variance is:

$$V(\hat{Y}'_c) = \sum_{a=1}^{A} \sum_{s=1}^{S'} V(\hat{Y}'_{asc}) + \sum_{l=1}^{L} \frac{(M_l-m_l)M_l}{m_l(m_l-1)} \sum_{j=1}^{m_l} (y_{jlc}-y_{.lc})^2$$

3.7 Evaluation of the Landsat Estimate

Landsat data are used as supplemental information to improve the precision of the area estimates obtained from the JES. Unlike area frame construction, the effectiveness of this use of Landsat data can be measured. The measure used is the efficiency of the Landsat estimator relative to the JES direct expansion estimator. This relative efficiency (RE) is defined as the ratio of the variance of the direct expansion to the variance of the Landsat estimate. Equivalently, this is the factor by which the sample size would have to be increased to produce a direct expansion estimate with the same precision as the Landsat estimate.

$$RE = \frac{V(\hat{Y}_c)}{V(\hat{Y}'_c)}$$

3.8 Implementation

The basic concepts of SRS's Landsat analysis were developed during the 1972-1979 time period. In 1980 as part of the AgRISTARS Domestic Crop and Land

Cover Project, SRS's Remote Sensing Branch began making current-year, state-level area estimates for winter wheat, corn and soybeans in selected states. This move to a pseudo-operational mode meant that current year Landsat data (May for winter wheat, August for corn and soybeans) had to be processed to produce estimates by late-November and late-December for winter wheat and corn/soybeans respectively. The original implementation plan called for including two states in 1980 and adding two more states each year to a total of 10 states by 1984. In 1980 winter wheat estimates were produced for Kansas, corn and soybean estimates for Iowa. Table 1 shows the states included in the project, the crops for which estimates were made, and the number of Landsat scenes needed to cover each state. In 1983, SRS deviated from the original plan by adding only one state to the project. No new states were added in 1984. These modifications were necessary due to personnel ceilings and limitations of current processing capabilities. In 1984, under the modified plan, SRS expects to process about 2,000 JES segments contained in 66 Landsat scenes covering most of seven states (Table I).

3.9 Results

The JES direct expansion and Landsat estimates are two of many indications used to determine the official USDA area estimates. For most major crops the JES direct expansion is the key indication used for setting the preliminary area estimates in July. The Landsat estimates for the states in the project (available at the end of the crop year) are reviewed when the final end-of-season estimates are made.

Tables II through VI show the JES direct expansion, the Landsat estimates and the final USDA estimates. The relative efficiencies of the Landsat estimates are mostly in the range from 1.2 to 2.0 for the major crops of winter wheat, corn and soybeans. The relative efficiencies for crops with fewer hectares such as cotton and rice are considerably better. The level of some of the estimates for cotton and rice, however, differ considerably from other data sources used to make the official estimate. Part of the variability in the relative efficiencies for the major crops can be explained by the amount of Landsat coverage available to do each estimate. Figure 1 shows three graphs comparing the percent of each crop covered by Landsat data with the relative efficiency obtained. If the trend apparent in these graphs can be extended, one would expect that the best we could do is relative efficiencies of about 2.5. These results, although promising, are not as good as originally expected. However the continued personnel limitation and the increasing respondent burden being placed on our farm sector may make our Landsat estimator one of few techniques feasible for improving crop statistics in the U.S.

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Table I: States and Crops for Which Landsat Area Estimates Have Been Made

State	Years in Project	Area Estimates Produced for:	Number of Landsat Scenes Needed:
Kansas	1980, '81, '82, '83, '84	winter wheat	16
Iowa	1980, '81, '82, '83, '84	corn, soybeans	12
Oklahoma*	1981, '82, '83, '84	winter wheat	7
Missouri*	1981, 1/, '83, '84	winter wheat, corn, soybeans, cotton, rice	12
Colorado*	1982, '83, '84	winter wheat	14
Illinois	1982, '83, '84	corn, soybeans	10
Arkansas*	1983, '84	soybeans, rice, cotton	5
TOTAL			66

* major producing areas

Table II: Area Estimates for Winter Wheat Harvested by State and Year

	JES Direct Expansion		Landsat Regression			
State/Year	Estimate	Standard Error	Estimate	Standard Error	Relative Efficiency	USDA Estimate
	(1,000 hectares)		(1,000 hectares)			(1,000 hectares)
Kansas						
1980	5,214	162	5,051	136	1.3	4,856
1981	5,452	158	5,298	104	2.3	4,897
1982	5,677	167	5,611	120	1.9	5,301
1983	4,652	153	4,477	124	1.5	4,371
Oklahoma						
1981	2,612	117	2,483	101	1.4	2,590
1982	2,914	119	2,660	90	1.8	2,792
1983	1,725	85	1,688	74	1.3	1,740
Colorado						
1982	1,276	91	1,132	49	3.4	1,178
1983	1,193	115	1,110	81	2.0	1,214
Missouri						
1983	830	66	866	49	1.9	749

Table III: Area Estimates for Corn by State and Year

State/Year	JES Direct Expansion Estimate	JES Direct Expansion Standard Error	Landsat Regression Estimate	Landsat Regression Standard Error	Relative Efficiency	USDA Estimate
	(1,000 hectares)		(1,000 hectares)			(1,000 hectares)
Iowa						
1980	5,735	115	5,801	93	1.9	5,666
1981	5,828	128	5,820	103	1.6	5,828
1982	5,601	118	5,568	113	1.1	5,565
1983	3,708	111	3,666	81	1.8	3,683
Missouri						
1981	870	75	775	51	2.2	850
1982 1/	-	-	-	-	-	-
1983	758	60	629	45	1.8	688
Illinois						
1982	4,809	115	4,677	106	1.2	4,735
1983	3,482	113	3,380	102	1.2	3,318

Table IV: Area Estimates for Soybeans by State and Year

State/Year	JES Direct Expansion Estimate	JES Direct Expansion Standard Error	Landsat Regression Estimate	Landsat Regression Standard Error	Relative Efficiency	USDA Estimate
	(1,000 hectares)		(1,000 hectares)			(1,000 hectares)
Iowa						
1980	3,395	112	3,290	96	1.5	3,359
1981	3,260	104	3,275	82	1.6	3,278
1982	3,539	106	3,433	99	1.2	3,428
1983	3,155	98	3,200	88	1.3	3,238
Missouri						
1981	2,306	115	1,964	86	2.1	2,072
1982 1/	-	-	-	-	-	-
1983	2,275	124	2,008	97	1.6	2,104
Illinois						
1982	3,866	120	3,767	109	1.2	3,743
1983	3,696	107	3,669	99	1.2	3,602
Arkansas						
1983	1,661	78	1,565	70	1.3	1,578

Table V: Area Estimates for Rice by State and Year

	JES Direct Expansion		Landsat Regression			
State/Year	Estimate	Standard Error	Estimate	Standard Error	Relative Efficiency	USDA Estimate
	(1,000 hectares)		(1,000 hectares)			(1,000 hectares)
Missouri						
1981	47	20	31	10	6.8	31
1982[1/]	-	-	-	-	-	-
1983	51	21	46	10	3.9	25
Arkansas						
1983	419	48	376	32	2.2	374

Table VI: Area Estimates for Cotton by State and Year

	JES Direct Expansion		Landsat Regression			
State/Year	Estimate	Standard Error	Estimate	Standard Error	Relative Efficiency	USDA Estimate
	(1,000 hectares)		(1,000 hectares)			(1,000 hectares)
Missouri						
1983	26	15	30	4	11.1	44
Arkansas						
1983	144	33	103[2/]	19	2.9	138

[1/] No Landsat estimates were made for Missouri during 1982 due to insufficient Landsat coverage.

[2/] Arkansas had a lot of cotton that was planted and abandoned prior to the satellite overpass. This area was not included in the Landsat regression estimate.

Figure 1: Plot of Percent of Each Crop Covered by Landsat Data Versus the Relative Efficiency of the Landsat Estimate.