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UPDATE ON A SYSTEM FOR LARGE AREA CROP INVENTORY FROM REMOTELY SENSED DATA

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ABSTRACT

This paper presents an update on the state of the art in large area crop inventory from Landsat multispectral image data. In particular, it describes progress with and improvement to the estimation system developed during the Large Area Crop Inventory Experiment (1975-77) and its follow-on Transition Year project (1978-79). Both were jointly sponsored projects of the National Aeronautics and Space Administration, the U.S. Department of Agriculture, and the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce. The improved large area estimation technology is a product of and research tool for the current joint venture of these three agencies in conjunction with the Agency for International Development of the U.S. Department of State and the U.S. Department of the Interior, known as the Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing program. Several candidate technologies under development as possible improvements to the system are also presented.

I. INTRODUCTION

During the Large Area Crop Inventory Experiment (LACIE), a state-of-the-art technology for the inventory of crops using satellite data was developed and tested over a period of 3 years (1975-77). The resulting product was a method for determining the total wheat production in a given region by looking at only a subset of its area. All information on target-year wheat acreage was obtained through Landsat imagery for a statistical sample of 5- by 6-nautical-mile segments, the basic areal units for acreage estimation, selected from the region of interest. The estimation of wheat acreage for large subareas enclosed within the region of interest was accomplished by aggregation of the wheat area estimates for the sampled segments from that area. The complete documentation for the sampling design, frame construction, and estimation equation development is presented in the Proceedings of the LACIE Symposium.[1] The follow-on LACIE Transition Year (LACIE-TY) efforts (1978-79) produced a significantly improved estimation system by switching from a sampling design which employed a stratification based entirely on political subdivisions (e.g., counties and states) to one with the lowest level stratification based on agricultural and meteorological characteristics of the region.[2]

Since the advent of the Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) program in 1980, a refined large area aggregation component has been implemented and tested in the project's fiscal year 1981 U.S./Canada Spring Small Grains Pilot Experiment (FY81 SSG Pilot). This document presents an overview of the current state of the art in AgRISTARS aggregation technology, including pertinent results from the FY81 SSG Pilot in section II. In addition, several candidate technologies for improving aggregation capabilities are reviewed in section III.

II. AgRISTARS BASELINE AGGREGATION TECHNOLOGY

A. THE TWO-PHASE AGGREGATION SYSTEM APPROACH

From the beginning, the philosophy of the large area crop inventory system has been to estimate crop area based on a stratified sample of segments selected from the region of interest. Consequently, a two-stage clustered-sample approach to aggregation has been required because it may happen that not every stratum is represented in the sample of segments with Landsat imagery suitable for crop area estimation. Hence, to date, the aggregation component for large area estimation systems operates via a protocol similar to the following:

1. Allocate the sample segments to the region of interest according to a stratified design. Not every stratum need be represented in the sample.

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2. Produce a crop proportion estimate for each sample segment with suitable Landsat imagery available.

3. Aggregate the segment crop proportion estimates to obtain large area crop estimates in two stages:

Stage 1 - For each stratum containing one or more sample segments with usable crop area estimates, produce an aggregated estimate of the crop area for the whole stratum. Also, calculate a measure of the statistical variability of the stratum-level estimate produced.

Stage 2 - For each stratum not represented in the sample of segments with usable crop area estimates, identify one or more strata for which stratum-level estimates from stage 1 are similar in some respect to the unrepresented stratum and use these estimates to infer an estimate for the unrepresented stratum. An estimate of variance is also determined in each case.

Once each stratum has an estimate of crop area (and variance), the estimate of area for the entire large region (or any sizable subregion) is found by summing the individual stratum-level estimates. A similar procedure yields an estimate of the variance of the crop area estimate for the corresponding region.

B. DESCRIPTION OF THE BASELINE AGGREGATION PROCEDURE

Baseline Sample Design. The aggregation component of the AgRISTARS aggregation procedure is amenable to any stratified sampling design. However, experience with the procedure to date has been limited to data allocated according to the LACIE and LACIE-TY sampling designs. The LACIE-TY design, which was the assumed design for all segment data aggregated during the FY81 SSG Pilot, is a stratified random sampling design. Allocation of the fixed-size sample of segments to strata was proportional to the harvested wheat acreage in each stratum for a predetermined base year as reported by a Government agency.

Proportion Estimates. The baseline aggregation component accepts as inputs crop proportion estimates for the sample segments. The current approach requires segment-level estimates of crop to be based solely on Landsat imagery and generally known regional cropping information (e.g., crop calendars and planting dates). Several technologies appropriate for use in producing such estimates are currently available for use.[3-6] The choice of a procedure in a specific instance depends on the region and each crop of interest. The proportion estimates could be based on any number of sources, however, including meteorological satellite (metsat) imagery, high-altitude aerial photography, or ground observation data.

Baseline Aggregation Component. The baseline aggregation component is, as indicated above, a two-stage procedure involving aggregation to the stratum level first and then aggregation to higher levels as required. A technical description of the procedure is presented in the literature.[1,7] A description of the general flow of the procedure follows.

The Stage 1 (Stratum-Level) Aggregation Subcomponent. While the stratum-level aggregation subcomponent will vary in specific items, depending on the exact sampling design realized, the concept is generic. The following is a description of the stratum-level subcomponent employed in the FY81 SSG Pilot:

1. For each stratum with one or more usable segment proportion estimates for the target crop year, treat the observed estimates as a realization of a simple random sample from the stratum, computing the sample mean and variance. For any strata represented by fewer than eight sample segments, form a pooled estimate of variance by associating the under-represented strata with similar nearby strata. The necessary extent of the association varies from one application to the next.

2. Convert the stratum-level estimates of crop proportion mean and variance to the appropriate units of area for each stratum.

Note: At this point, there may be some strata with no estimate of crop area.

The Stage 2 Aggregation Subcomponent. For the purposes of description, we refer to the "zone" as the level of subdivision directly above the stratum. The first purpose of the second aggregation stage is to produce a stratum-level estimate of crop area for those strata not represented by sample segments. This activity is accomplished by associating each unrepresented stratum with one or more strata for which both similar cropping histories and stratum-level mean and variance estimates from stage 1 are available. If such an association is impossible (or unreasonable), large area estimation is not attempted. The estimate of crop area for an unrepresented stratum, say u, may be denoted generically by the weighted average:

$$A_u = \sum_{i=1}^{m} W_{ui} A_i$$

where

A_u = the estimate of crop area for the unsampled stratum u

A_i = the estimate of crop area for stratum i, as determined in stage 1

W_{ui} = a weight determined by the historical behavior of stratum i relative to stratum u, as indicated by stratum-level Government statistics on crop area for two or more past crop years

m = the number of strata represented by the sample segments

(This notation assumes that the strata represented by sample data are numbered i = 1, 2, ···, m and that the unrepresented strata are numbered u = m + 1, m + 2, ····.) The estimate of variance in the estimate of crop area for stratum u, V_u, is

$$V_u = \sum_{i=1}^{m} W_{ui}^2 V_i$$

where

V_i = the variance estimate for stratum i (from stage 1)

The estimates of crop area and variance for the zone and higher levels are found by summing, respectively, the area and variance estimates for all strata lying within the zone or region.

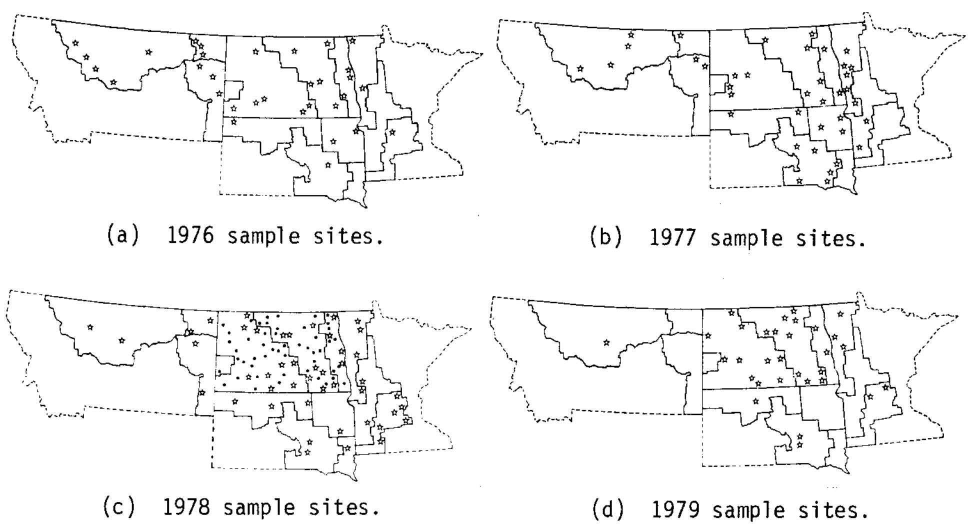
During the LACIE project, the weights (W_{ui}'s) were chosen to be ratios of historical crop (wheat) areas for a single predetermined "ratioing" year, with the summation extending only over those strata deemed similar to stratum u by the scientist performing the aggregation. For the technique employed in the current implementation, known as the Grouped Optimal Aggregation Technique (GOAT), the weights are determined based on a multiyear data base of Government cropping statistics so that the estimate of area variance at the region level is minimized. Also, the aggregator need not supply stratum association information and/or restrictions unless he chooses to do so.

C. EXPERIENCE IN THE FY81 SSG PILOT

The technology described above underwent initial testing in the FY81 SSG Pilot. The aggregation test-bed was the spring small grains region of the United States, principally North Dakota, but including parts of Minnesota, Montana, and South Dakota also. Archived (Landsat) segment imagery from the crop years 1976-79 was made available for processing by each of three spring small grains segment crop proportion estimation procedures. For Minnesota, Montana, and South Dakota, only imagery corresponding to LACIE ground truth segments was processed. (Note: A ground truth segment is any sample segment for which the actual crop area has been ascertained by a ground observer.) For North Dakota, imagery for all LACIE-TY crop year 1978 sample segments was processed, whereas only imagery corresponding to ground truth sites was processed for crop years 1976, 1977, and 1979.

The three spring small grains proportion estimation procedures, denoted in the following as SSG3B, SSG3C, and SSG4, were all developed using subsets of the archived Landsat data described above but none had undergone a large-scale test prior to the pilot experiment.

<u>Description of Test-Bed</u>. Figure 1 shows the locations of the candidate segment sites available for processing for each of the four test years. Those sites with available ground truth data are indicated by a star; non-ground truth sites, by a dot. The delineation of the region into strata, known as agrophysical units (APU's), is also noted.



(a) 1976 sample sites.

(b) 1977 sample sites.

(c) 1978 sample sites.

(d) 1979 sample sites.

Figure 1. Sample sites considered for processing in FY81 SSG Pilot.

Table 1 gives a summary of the number of segments yielding usable crop proportion estimates for each procedure/crop year combination.

Table 1. Segments Yielding Usable Crop Proportions.

Procedure	Number of crop proportion estimates			
	1976	1977	1978	1979
SSG3B	24	32	62	17
SSG3C	17	24	56	11
SSG4	31	31	68	27
Candidates	32	40	71	31

In the following, it is assumed that for each combination of procedure, crop year, and stratum the sample of segments with usable crop proportion estimates is a simple random sample of the segments within the stratum.

North Dakota Aggregations. During the LACIE project, the allocation of sample segment sites to specific areas was accomplished using an algorithm designed to assure a specified overall experiment error rate.[1] The performance requirement, known as the "90-90 criterion," was that the procedure estimate the crop (wheat) production for a region to within 10 percent of the true value 90 percent of the time. Of those sites selected for use in aggregation, approximately 10 percent were designated as ground truth sites.

In the FY81 SSG Pilot, the only region-year combination whose full LACIE segment allocation was submitted for processing was North Dakota/1978. The results of the aggregations for this single state-year combination, along with the information (where available) for the corresponding LACIE-TY aggregation results, are presented in table 2. The performances are expressed as percentages of the published [U.S. Department of Agriculture (USDA)] Government estimate of the spring small grains acres harvested in North Dakota during 1978.

Table 2 also presents independent estimates of the components of relative error for each procedure. The components and their descriptions are as follows:

1. Ratioing - The area estimation error that arises from the estimation of the weighting constants (W_{ui}'s).

2. Sampling - The area estimation error that arises from the realization of a particular random sample of segments from the superpopulation of all random samples of given size. This factor is sometimes referred to as the random error.

3. Classification - The area estimation error that arises from the failure of the segment proportion estimates to be equal to their corresponding ground truth values.

The estimates of the sampling and classification components of error are conditional on the estimated weights. That is, the numbers produced do not reflect "pure" estimates of sampling and classification bias but reflect interactions between the respective effects and use of slightly erroneous weights. These breakdowns were accomplished by making use of the ground truth information. The basic approach used has been documented; however, specific procedural changes in estimation details required appropriate modifications to the technique described by Zullo.[3] The following observations are appropriate:

1. The sampling and classification components are the largest contributors to relative error.

Table 2. Results of 1978 Aggregations for North Dakota. Entries are expressed as percentages of the USDA spring small grains area estimate of 13,120,000 acres.

Procedure	Relative area estimate	Coefficient of variation	Observed relative error	Independent estimates of components of relative error				Number of segments used
				Total	Ratioing	Sampling	Classification	
SSG3B	103.45	4.44	3.45	3.83	-2.67	4.38	2.12	62
SSG3C	106.91	4.26	6.91	8.44	-2.35	3.52	7.27	56
SSG4	90.79	4.61	-9.21	-0.74	-1.08	12.84	-12.50	68
LACIE-TY	92.59	4.32	-7.41					76

2. The procedurally induced ratioing component tends to be relatively small and, in these examples, counteracts some of the error attributable to other sources.

3. The estimator of relative variability, coefficient of variation (CV), is very stable for the cases considered. The implication is that the varying uncertainty in the estimates is due primarily to sample-size fluctuations rather than to differences in proportion estimation procedure performances. This conclusion is further strenghtened since the observed estimated CV's vary monotonically with sample size.

Four-State Aggregations. In order to ascertain the general level of performance that could be expected from the aggregation system at a regional level, aggregations were also performed for the entire four-state U.S. spring small grains region. The overall performance was expected to be inferior to that published for the LACIE and LACIE-TY aggregations because of the large differences in sample sizes of the respective experiments. Also, in order to maintain a constant sampling rate across the entire four-state region, only ground truth segments were included in the four-state aggregations. Since the true segment proportions are known for all candidate segments, the four-state aggregations were also performed using the ground truth data for each year as input.

The results of the four-state aggregations are presented in table 3, again with each entry expressed as a percentage of the USDA standard for its corresponding year. The following observations are appropriate:

1. The ground truth proportion aggregation results all correspond closely to the USDA estimates for their respective years. In each case, the observed relative error is, in fact, a bias due to the chance nonrepresentativeness of the sample actually observed and the procedure-selected ratios used in aggregation. Since the total sample size is small, the large sampling bias components in the 1977 and 1979 aggregations are not surprising. The ratioing bias component, though moderate in size, varies considerably from year to year. In every case, the estimates for the two bias sources are of opposite sign and, hence, compensating in nature.

2. As in the one-state aggregations, the proportion estimation component of relative bias detected in aggregations of SSG3B, SSG3C, and SSG4 results tends to be the largest single source of error. There are, however, several notable exceptions: SSG3C/1977, SSG4/1977, SSG3C/1979, and SSG4/1979.

3. For any given year, the estimated CV's of the various procedures vary monotonically and inversely with sample size, indicating the major differences in the variances of the procedures are due to sampling rather than to differences in proportion estimation procedure performance.

Table 3. Preliminary Results of the FY81 SSG Pilot — Four-State Aggregation. Each entry is expressed as a percentage of the USDA estimate of spring small grains area in the appropriate year.

Year / USDA area estimate	Segment estimation processing	Area estimate	Coefficient of variation	Relative error	Components of relative error			Number of segments
					Ratioing	Sampling	Classification	
1976	GT	103.86	5.80	3.86	4.01	-0.15	0.00	32
	SSG3B	121.59	7.80	21.59	4.85	0.83	15.90	24
27,575,400 acres	SSG3C	116.10	8.23	16.10	3.55	0.11	12.44	17
	SSG4	77.13	6.02	-22.87	3.67	-0.94	-25.60	31
1977	GT	104.43	5.02	4.43	-3.56	7.98	0.00	40
	SSG3B	106.25	6.41	6.25	-5.22	3.70	7.77	32
27,579,400 acres	SSG3C	101.10	8.29	1.10	-5.51	3.26	3.35	24
	SSG4	104.54	6.07	4.54	-3.12	9.39	-1.73	31
1978	GT	99.33	5.50	-0.67	-1.22	0.56	0.00	46
	SSG3B	94.34	6.56	-5.66	-0.86	-1.23	-3.56	38
26,183,400 acres	SSG3C	96.41	5.90	-3.59	-1.23	-1.03	-1.32	36
	SSG4	95.17	6.51	-4.83	-1.50	2.63	-5.95	42
1979	GT	105.21	7.55	5.21	-2.75	7.95	0.00	31
	SSG3B	124.98	13.76	24.98	-2.52	2.69	24.81	17
24,268,700 acres	SSG3C	99.74	23.18	-0.26	-0.75	-11.11	11.60	11
	SSG4	115.19	7.86	15.19	-2.08	14.62	2.65	27

Summary of Experience With AgRISTARS Baseline Aggregation Procedure. The implications of the above results for the AgRISTARS baseline aggregation system are twofold. The first is that the system tends to produce large area crop estimates that reflect the magnitude and direction of biases in the input data. The obvious implication is that unbiased inputs result in the most nearly unbiased outputs. However, even a perfectly unbiased sample of exact segment proportions would still result in a slightly biased large area estimate because of variations in the historical data used to form ratioing coefficients and groups. Secondly, with segment proportion estimates of the caliber available from SSG3C, SSG3B, and SSG4, the primary factor in determining the large area estimation variance is the number of segments used in estimation. However, since the analysis of these results is continuing as an FY82 AgRISTARS effort, the interpretation rendered here must be considered preliminary.

III. RECENT IMPROVEMENTS AND FUTURE RESEARCH DIRECTIONS

A. THE MULTIYEAR MODEL

Recently, an improved technique for the stratum-level phase of aggregation has been developed and will be tested as a part of the AgRISTARS FY82 U.S./Canada Spring Small Grains Pilot Experiment. The procedure, known as the multiyear model, is a general methodology for estimating a stratum-level crop acreage proportion for a specified season (growth stage) in a target year from the estimated crop acreage proportion for sample segments from within the stratum. Sample segment data for several crop years and seasons (growth stages) may be used in conjunction with those for the target year and season. The methodology is an application of estimation from a mixed analysis-of-variance model. A detailed technical description of the procedure is available.[8,9]

The concept of the multiyear model is as follows. In estimating the crop area for a stratum in each of two or more years, some of the sample segments may be used in both (two or more) years - either by accident or by design; hence, the estimates from the samples are not strictly independent unless the crop content for an individual segment exhibits no year-to-year correlation. Informal studies conducted by the authors indicate that, in the U.S. spring small grains region, the year-to-year Pearson product moment correlations of Landsat segment crop proportions are in the range $\rho = 0.2$ to $\rho = 0.7$.

For observed correlations at the upper end of this range, the concept should be useful in producing an estimate of the stratum crop area with a lower variance than the estimate that would be obtained by considering only the segment proportions for the target year.

To date, success with the model in conjunction with archived LACIE segment proportion estimates has been mixed - primarily because of the sporadic pattern of year-to-year sample segment recurrence. However, Sielken and Ghur[10] have conducted extensive simulations with the technique which indicate that the method can be very effective if the experimenter can control the amount, duration, and location of year-to-year sample segment overlap.

B. THE PARTIAL RESPONSE MODEL

One of the major goals in the AgRISTARS program is to extend the technology for single-crop large area estimation (i.e., wheat, during LACIE) to handle aggregations in an environment with more than one crop of interest. Although the AgRISTARS baseline aggregation technology can easily be applied to the segment proportion estimate for each crop separately, current multiple crop proportion estimation technology sometimes produces crop-group proportion estimates rather than individual-crop proportion estimates for some segments. For example, a procedure developed at the Environmental Research Institute of Michigan (ERIM) for segment proportion estimation in the corn and soybean agricultural regions in the United States[6] usually produces separate estimates of the corn and soybean proportions in a segment. In some circumstances, however, the procedure results in only a summer crop proportion estimate (i.e., an estimate of the total proportion of segment area planted in either corn or soybeans). Another multicrop proportion estimation procedure under development by the AgRISTARS Inventory Technology Development project[11] may sometimes produce a corn proportion estimate but neither a soybean proportion estimate nor a summer crop estimate.

In order to avoid having to exclude segments with these kinds of partial response from large area aggregations, work is underway to develop a method for extracting all possible useful information from the segments exhibiting only partial response.

An approach currently under development at Texas A&M University attacks the problem at the stratum level during phase 1 of the aggregation strategy. The technique, known as the partial response model, treats the true stratum-level crop proportions as the unknown parameters of a multinomial distribution, with the individual-crop and crop-group proportion estimates for each segment comprising estimates of the true corresponding stratum-level individual-crop and crop-group parameters. For example, let

Π_c = the proportion of corn within the stratum

Π_s = the proportion of soybeans within the stratum

$\Pi_o = 1 - \Pi_c - \Pi_s$ = the proportion of "other" (i.e., nonsummer crop) within the stratum

For a segment with individual estimates for corn ($\hat{p}_c$) and soybean ($\hat{p}_s$) proportions, $\hat{p}_c$ estimates Π_c and $\hat{p}_s$ estimates Π_s.

For a segment with only a summer crop proportion estimate, say $\hat{p}_{sc}$, $\hat{p}_{sc}$ estimates $\Pi_s + \Pi_c = 1 - \Pi_o$. This model together with the assumption of segment-to-segment independence allows the multinomial parameters to be estimated via the maximum likelihood estimation technique. The estimation is easy and direct in the three-parameter case, yielding an intuitively appealing closed-form estimator for each individual crop.[12] The case of four or more parameters yields no closed-form solution; however, theoretically, this situation should pose no problem because numerical techniques for nonlinear-constrained optimization can be employed to determine the parameter estimates. To date, this technique has not been employed in a large-scale experiment, but it is scheduled to be tested during the FY82 Corn and Soybeans Pilot Experiment.

C. CHANGE ESTIMATION

Very early in LACIE, it was noted that it is sometimes possible to estimate the change in crop area within a stratum from one year to the next with considerably higher accuracy than the crop area for a year can be estimated directly from segment data. This fact has led to a major effort aimed at identifying the conditions under which such savings are possible and optimal methods for actually producing an estimate of change. Ideas for the direct implementation of these concepts within the segment-based estimation/aggregation framework are currently in the infancy of their development but are all related - at least distantly - to extensions or simplifications of the multiyear model described earlier.

Also, because the real impetus behind change estimation research is to reduce the number of segments required to support an aggregation with a specified accuracy, attention has recently focused on the possibility of adopting a sample area larger than the 5- by 6-nautical-mile LACIE segment as the basic sampling unit. The application of this concept is, of course, not restricted to the change estimation setting.

IV. SUMMARY AND CONCLUSIONS

This paper has presented a discussion on the state of the art in large area crop inventory from Landsat segment data. In particular, results from the FY81 SSG Pilot show that the AgRISTARS baseline aggregation technology produces both accurate and efficient estimates, provided the input segment data fairly represent the actual segment crop proportions. Finally, several promising extensions and refinements to the baseline procedure have been described briefly - specifically, the multiyear model, the partial response model, and change estimation.

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AUTHOR BIOGRAPHICAL DATA

Thomas C. Baker, Jr. Currently, he is involved in the design, development, and integration of statistical sampling techniques in support of remote-sensing-based technology for the estimation of the amount of change in crop area for a target region over time. Other recent activity includes the development of extensions to a multiyear aggregation technique. Areas of specialization include statistical computing, stochastic mathematical programming, and simulation. He received a B.S. in mathematics from Abilene Christian University in 1974 and an M.S. and Ph. D. in statistics from Texas A&M University in 1975 and 1978, respectively.

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