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ILLINOIS CROP-ACREAGE ESTIMATION EXPERIMENT*

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ABSTRACT

This paper describes remote-sensing data analysis research conducted collaboratively during the last year by personnel of the Center for Advanced Computation (CAC) of the University of Illinois at Urbana-Champaign and the Statistical Reporting Service (SRS) of the U. S. Department of Agriculture. The research reported has been undertaken by CAC and SRS to assess the practicalities of existing high-volume earth observations data acquisition, processing, and communication technologies such as LANDSAT, the ILLIAC IV parallel computer, and the ARPA Network as mechanisms for improving the accuracy of USDA annual estimates of agricultural crop acreages for geographic regions corresponding to U. S. states.

INTRODUCTION

Throughout this research, our basic approach has been to seek an integration of ILLIAC IV^{1,2} and ARPA Network^{3,4} software systems developed previously at CAC for more cost-efficient machine interpretation of LANDSAT data^{5,6} with geographic information systems implemented explicitly for interactive digitizing, storage, and retrieval of large quantities of crop-acreage information collected routinely by SRS in the course of the extensive field surveys associated with its ongoing agricultural production estimation methodology. Our primary goal has been to determine the extent to which SRS ground survey samples may be employed successfully as ground-truth information for calibrating ILLIAC IV procedures for classification of LANDSAT multispectral scanner (MSS) imagery for regions corresponding to U. S. states.

For this exploratory application of machine processing of LANDSAT data, the state of Illinois was selected as the basic study area. All ground-

truth information was acquired during the Illinois 1975 growing season by SRS acting in collaboration with the Illinois Cooperative Crop Reporting Service. Digital data tapes for all 1975 late-summer, cloud-free LANDSAT imagery over Illinois were made available to the project by NASA's Office of Earth Observations Programs acting in cooperation with NASA's Ames Research Center.

In this paper we describe the overall methodology adopted for this investigation of the practicalities of LANDSAT imagery analysis for USDA crop-acreage estimation purposes and report research findings to date. We describe the general strategy pursued in developing a comprehensive LANDSAT imagery analysis system of the scale required for monitoring agricultural crop acreages over a geographic region of the scale of the state of Illinois. For a region corresponding to ten (10) western Illinois counties (a subset of the 102 counties of Illinois), we present preliminary crop-acreage estimation results derived from ILLIAC IV - ARPA Network analysis of LANDSAT data. Assuming the practicality of similar analyses for LANDSAT imagery covering the entire state, we discuss a procedure for evaluating statistically the information to be gained by estimating state crop-acreage totals from LANDSAT imagery classification results where SRS sample survey data are used as ground-truth information for classification training as opposed to estimating state crop-acreage totals directly from SRS survey data alone.

GROUND DATA COLLECTION, STORAGE, AND RETRIEVAL

In support of this research project, all crop-acreage information collected by SRS within the state of Illinois in the course of its 1975 crop and livestock surveys was retained and re-formatted for use as ground-truth information for calibration of LANDSAT imagery analysis systems. These data contain complete descriptions of all agricultural and non-agricultural fields, i.e., areas of homogeneous land cover, for all ownership tracts within each of 300 area segments of the SRS national survey sample that fall within the state of Illinois.

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In accordance with SRS survey procedures, these 300 area segments had been selected earlier with respect to strict statistical sampling criteria and hence, while allocated heavily to agricultural terrains, may be considered randomly distributed throughout all land in the state. Each area segment corresponds to a geographic area of approximately one square mile. Each segment typically contains multiple ownership tracts with numerous fields ranging in size from several-acre farmsteads, ponds, and forested areas to several-hundred-acre agricultural fields.

Following standard SRS survey practices, throughout the summer of 1975 ASCS aerial photographs (at a scale of 8" = 1 mile) were taken by survey enumerators to the location of each segment and used for delineation of all current field boundaries. Field boundaries for all tracts of all segments were monitored continually throughout the summer in conjunction with June, July, August, and September surveys conducted by SRS personnel. Field boundary changes from month to month were recorded using a color-coded marking system.

All crop-acreage data recorded by field enumerators on ASCS photos and interview forms were re-checked independently for consistency by personnel of the central offices of the Illinois Cooperative Crop Reporting Service in Springfield. All crop-acreage data contained on survey forms were put into machine readable format. Output from this process consisted of a computer tape for which individual records represent crop-acreage information for all fields of all tracts in all segments for each of the four surveys conducted throughout the summer.

As still another source of ground-truth information, low-altitude infrared photography (at a scale of approximately 5" = 1 mile) was obtained commercially for a subsample of 202 area segments. This current aerial photography provided directly an accurate, high-resolution picture of the agricultural crops and land uses actually existing in late summer for the 202 segments covered. Hence, it was possible to check the degree of accuracy with which 1975 field boundaries had been delineated on the older ASCS photos. For those segments for which summer 1975 photography had been obtained, field boundaries (and changes) were re-drawn directly on the current photography making reference both to data recorded by survey enumerators on ASCS photos and to features visible directly in the current infrared photos themselves. This task was also done in Springfield by SRS personnel. A quantitative evaluation of the relative advantages for LANDSAT imagery classification objectives of this current photography and the older ASCS photography is currently being conducted by SRS.

To make all crop-acreage data thus compiled convenient for LANDSAT imagery analysis purposes, all field, tract, and segment boundaries recorded on a complete set of area segment photos (202 current infrareds and 98 ASCS photos) are presently being digitized jointly by personnel of CAC in Illinois and personnel of SRS in Washington. This

task is being accomplished using graphics data tablet digitizing equipment connected via the ARPA Network to interactive DEC PDP-10 computers at Bolt, Beranek and Newman (BBN) in Boston. Data tablet digitizers at CAC are connected directly to the ARPA Network through CAC's own ANTS (ARPA Network Terminal System) computer facilities. SRS digitizing equipment has been linked to BBN computer systems via dial-up telephone line connection to ARPA Network node facilities at the National Bureau of Standards in Gaithersburg, Maryland and at Fort Belvoir, Virginia.

All agricultural field boundary digitizing is being accomplished using an interactive DEC PDP-10 data tablet software system developed at CAC explicitly for take-off of SRS crop-acreage data recorded on aerial photos. This interactive data tablet software package was implemented as an extension of the EDITOR system -- a general PDP-10 LANDSAT imagery analysis system developed previously at CAC as an interactive ARPA Network interface to LANDSAT image interpretation procedures available on the ILLIAC IV computer at NASA's Ames Research Center.⁶

These additional procedures added to the EDITOR system for digitizing SRS crop-acreage data also include provisions for on-line geographic registration of all field boundaries digitized with respect to USGS quadrangle map coordinates. This task is done simply by mounting simultaneously both photo and quad map on the active surface of the data tablet (36" x 48") and digitizing points of geographic correspondence visible within both the photo and quad map.

After digitization and geographic registration of all segment, tract, and field boundaries delineated on any one photo, an areal-network mask is determined by the software system for the segment digitized. This segment network mask is stored as a DEC-10 disk file in terms of a list of network nodes and links representing respectively digitized field corners and boundaries.

Immediately following digitization and registration of all crop-acreage data on any photo, two line plotter displays are produced using a drum plotter at CAC to provide a hard-copy record of the segment mask thus created. One of these displays is plotted at the exact scale of the photo itself and hence, by overlaying photo and plot, the correctness of all digitized boundaries may be conveniently checked. The other display is plotted at the scale and cartographic projection of the USGS quad map and by overlaying this plot and quad map the accuracy of geographic registration may be verified. (See Figures 1-2.)

LANDSAT IMAGERY SELECTION AND PREPROCESSING

All LANDSAT imagery collected over Illinois during the summer of 1975 was acquired from NASA in the form of 70 mm film transparencies and evaluated by SRS and CAC with regard to project objectives. Assuming ideal meteorological conditions, only

eleven (11) frames of LANDSAT imagery are required for complete coverage of the entire state. Given prevailing conditions, however, a total of sixteen (16) frames of imagery acquired between the dates of 16 July and 7 September was deemed necessary to obtain cloud-free coverage of all of the 102 counties within Illinois. Digital data tapes and positive film imagery (both at 1:1,000,000 and 1:500,000) were obtained for each of these sixteen (16) scenes.

Since one of the goals of our project is to obtain crop-acreage estimates for the entire state of Illinois, and since counties represent smaller geographic units more convenient for estimation of state-wide crop-acreages in terms of regional sub-totals, it was decided to preprocess and re-format all LANDSAT imagery acquired from NASA into a set of image files such that each of the 102 counties of Illinois was contained wholly and cloud-free within at least one image file. To accomplish this objective, the following strategy has been adopted.

Despite the vertical overlap of approximately fifteen (15) miles between successive LANDSAT frames of the same orbit, in many cases individual counties falling on north and south frame boundaries are not wholly contained in any one frame. Hence, in numerous instances it is necessary to compile pseudo-frames of LANDSAT digital imagery by concatenating data records of a top portion of one frame to data records of a bottom portion of another frame of the same orbit. Such pseudo-frames are to be compiled wherever they are necessary to achieve continuous cloud-free imagery for a particular county.

Due to the size of counties in Illinois, the horizontal overlap of approximately fifty miles between frames of successive orbits is sufficient to insure that no county fails to lie wholly within the swath of at least one orbit. Thus fortuitously, the considerably more difficult problem of splicing LANDSAT imagery horizontally across orbits does not arise.

Having obtained a complete set of image files (LANDSAT frames and pseudo-frames) such that each county is completely contained in cloud-free fashion within at least one image file, the complete set of 102 counties is to be subdivided among non-overlapping subsets of contiguous counties, one group of counties per each image file. These groups of counties are to be designated for project purposes as LANDSAT imagery analysis districts. All subsequent data management and machine processing of LANDSAT data is then to be structured in terms of the geographic regions corresponding to these analysis districts. Inspection of the imagery available suggests that for 1975 Illinois LANDSAT imagery only fourteen (14) such analysis districts -- ranging in size from as few as two or three counties to as many as a dozen -- are required to provide integral-county, cloud-free LANDSAT coverage for the entire state.

Once a comprehensive set of analysis districts has been established and their corresponding

LANDSAT image files created, the digital image data for each district is being geometrically corrected and geographically registered to USGS topo maps existing for the state. This task is being performed using an image skew transformation procedure developed at CAC for efficient de-skewing and rotation of LANDSAT digital data to map orientation⁸ in conjunction with other systems developed at CAC for precision geographic registration of LANDSAT imagery.⁹

Finally, all image files are being geographically registered to the SRS ground-truth data available (and hence simultaneously also to the USGS map control already associated with all ground-truth). This step is being accomplished in the following manner.

First, with respect to digital image calibration information available, all SRS area segments are located approximately in terms of digital image file row and column coordinates. Gray-scale displays for windows of LANDSAT data known to contain all SRS area segments are produced using a conventional line printer and over-printing techniques. Then digitized SRS segment masks (described above) are again plotted this time at the exact scale of the line-printer LANDSAT imagery displays. Following manual overlay and visual correlation of line-printer and plotter displays on a light table, overlay positions of maximum geographic correspondence between LANDSAT image pixels and SRS segment masks are recorded. (See Figures 3-4.)

LANDSAT DATA ANALYSIS SYSTEMS

As the SRS ground-truth data is digitized and LANDSAT imagery preprocessed for each analysis district, LANDSAT data is being analyzed collaboratively by SRS and CAC using a common set of computer facilities available via the ARPA Network. For small-scale analyses of SRS area segment data the EDITOR software system at BBN is used. For specific large-scale LANDSAT image analysis functions, the ILLIAC IV at NASA's Ames Research Center is employed also via the ARPA Network but addressed conveniently through the EDITOR system at BBN.

All ILLIAC IV - ARPA Network image analysis systems implemented to date have been designed and developed in close collaboration with personnel of the Laboratory for Applications of Remote Sensing (LARS) of Purdue University. Hence all software procedures implemented specifically for machine interpretation of LANDSAT data follow closely multispectral image interpretation methods researched previously at LARS.^{10,11}

Specifically, ILLIAC IV procedures are now operational for both multivariate cluster analysis and maximum-likelihood statistical classification of LANDSAT image samples. The speed of the ILLIAC IV with respect to these two image interpretation procedures has proven to be generally two orders of magnitude faster than execution times observed for the same processing tasks using the IBM 360/67 computer at LARS.⁵

Such LANDSAT imagery interpretation capabilities available via ILLIAC IV batch processing, together with the availability for classifier training operations of the interactive image processing software of the EDITOR system, suggest that operational crop-acreage monitoring via digital processing of orbital remote-sensing imagery may indeed be practical. Our project has been undertaken to assess more exactly the potentialities existing in this area. In the next section, we present preliminary results of one LANDSAT imagery analysis experiment using SRS data available for a single analysis district consisting of ten (10) counties in western Illinois.

EVALUATION PROCEDURE

Of central importance to our experiment is the evaluation of the extent to which regional crop-acreage estimates may be improved by estimation with respect to LANDSAT imagery classification methods as opposed to estimation directly from SRS survey data alone. Statistical regression techniques may be used to obtain estimates of the total acreage of each crop type for each analysis district.¹² Following estimation of crop-acreages for all analysis districts separately, state-wide acreage estimates for each crop may easily be obtained by simply summing individual district estimates. Such estimates may be determined both with and without use of LANDSAT classification results and a measure of the value of the LANDSAT data may be computed.

Following ILLIAC IV classification of all LANDSAT pixels contained within the counties making up a particular analysis district, classification results for each crop type will be aggregated to obtain individual totals for all segments sampled within the district. Also, acreage totals for each crop type will be determined for the entire analysis district itself.

An estimator of the total acreage for a particular crop in a particular analysis district and its sampling error may then be computed as follows. The total acreage may be estimated as

$$\hat{Y}_i = N_i \hat{\bar{y}}_i = N_i (\bar{y}_i - \hat{B}_i (\bar{x}_i - \bar{X}_i))$$

and the variance for a large sample of segments is:

$$V(\hat{Y}_i) = N_i^2 V(\bar{y}_i) (1 - r_i^2) \left(\frac{n_i - 1}{n_i - 2} \right)$$

For the individual analysis districts, the normal approximation for small samples is used, that is

$$V(\hat{Y}_i) \text{ for large samples multiplied by } \left(1 + \frac{1}{n_i - 3} \right).$$

Where $N_i \hat{\bar{y}}_i$ = total acres of the crop within all area segments contained within the i^{th} analysis district

N_i = total number of all segments contained

within the i^{th} analysis district (known from sampling frame)

$\hat{\bar{y}}_i$ = a regression estimate of the average number of acres of the crop per area segment for the i^{th} district

n_i = the number of area segments sampled in the i^{th} district

\bar{y}_i = average number of acres of the crop reported per area segment for all n_i area segments sampled in the i^{th} district

\bar{x}_i = average number of pixels classified into the crop per area segment for all n_i area segments sampled in the i^{th} district

\bar{X}_i = average number of pixels classified into the crop per segment over all possible segments for the i^{th} district

\hat{B}_i = the regression coefficient between y_{ij} and x_{ij} based on the n_i area segments sampled in the i^{th} district

y_{ij} = number of acres of the crop enumerated for the j^{th} segment sampled in the i^{th} district

x_{ij} = number of pixels classified into the crop for the j^{th} segment sampled in the i^{th} district

$$V(\bar{y}_i) = \frac{\sum_{j=1}^{n_i} y_{ij}^2 - \frac{(\sum_{j=1}^{n_i} y_{ij})^2}{n_i}}{n_i (n_i - 1)}$$

r_i^2 = correlation coefficient squared between y_{ij} and x_{ij} for the i^{th} district

The formulas given are appropriate for a simple random sample within each analysis district. However, the SRS surveys are stratified by land use categories which require that item totals, sums of squares, and sums of cross products be weighted and combined in order to obtain the equivalent of a simple random sample over the entire analysis district.

An estimate of the total state-wide acreage for each crop may be obtained by making use of the additive property of the estimator and its sampling error over all districts. The estimators are

$$\hat{Y} = \sum_{i=1}^f \hat{Y}_i$$

$$V(\hat{Y}) = \sum_{i=1}^f V(\hat{Y}_i)$$

A measure of the gain in relative efficiency of estimation of state-wide acreage obtained by using machine-interpreted LANDSAT data may be computed

$$RE = \frac{\sum_{i=1}^f N_i^2 V(\bar{y}_i)}{\sum_{i=1}^f N_i^2 V(\bar{y}_i) (1 - r_i^2) \left(\frac{n_i - 1}{n_i - 3} \right)}$$

where the value of RE is expected to be greater than 1.0. A value of RE less than 1.0 would indicate that information had been lost through use of LANDSAT data. A value of 5.0 would indicate the regression estimator using LANDSAT classification results is equivalent to increasing the number of area segments by five times if costs of acquiring the LANDSAT data are equal to the costs of collecting the area segment data. For the single analysis district analyzed, the information gain or loss is:

$$\frac{1}{(1 - r_h^2)} \cdot \frac{n_h - 3}{n_h - 1}$$

where n_h is the number of area segments sampled.

These values for the first analysis district are shown in the last column of table 5.

To date limited results are available for only one analysis district of 10 counties in western Illinois. A maximum likelihood quadratic classifier using the prior probabilities for 10 land cover categories was used for classifying each pixel into one of the 10 categories for the entire analysis district. The prior probabilities were calculated from the ground enumerated data in the 10 counties.

Table 1. Prior Probabilities for Land Cover Categories

Crop or land use	Prior probabilities (Survey land use July 27, 1975)
Corn	.3282 (.3097*)
Soybeans	.1602 (.2297*)
Permanent pasture	.1392
Dense woods	.0935
Alfalfa hay	.0180
Other hay	.0467
Wheat stubble	.0101
Crop pasture	.0118
Water (farm ponds & lakes)	.0074
Wasteland (no agri. prod.)	.1148
Other crops & land uses	.0701
(Training data not available):	

* Based on 1974 crop year data from Illinois Assessor Census

A sample of fields was selected from the segments falling in the LANDSAT image. The acres in each crop or land use type was "expanded" to correct for varying probabilities of selecting segments. Then a sample of fields was selected independently for each crop so that each acre (or pixel) had an equal chance of being selected for cover types with 80 or more fields. That is, the probability of a field being selected was proportional to its expanded acres. The selection was made from a listing of fields ordered by segment numbers to help insure that fields would be spread over the entire LANDSAT image. The number of fields selected for calculating mean vectors and covariance matrices are given in tables 2 and 3.

Table 2. Number of Sample Fields by Cover Type

Crop or cover type	Number of fields	Acres/field	Total pixels	Nonborder pixels
Corn	425	23.3	9026	5604
Soybeans	215	22.5	4502	2712
Perm. pasture	163	19.7	2780	1289
Dense woods	144	16.8	2147	784
Hay	83	11.8	1069	477
Wasteland	274	8.7	2087	920
Alfalfa	40	11.0	423	183
Wheat stubble	27	11.2	259	86
Water	17	12.1	190	73
Crop pasture	21	13.3	280	119

Table 3. Number of Training Fields by Cover Type

Crop or cover type	Number of fields	Nonborder pixels
Corn	50	1648
Soybeans	50	1107
Perm. pasture	25	297
Dense woods	40	453
Hay	16	153
Wasteland	8	492
Alfalfa	40	183
Wheat stubble	27	86
Water	17	73
Crop pasture	21	119

The pixels for all the selected fields were combined and treated as one large field for analysis purposes; however, only the nonborder pixels were used in calculating the mean vector and covariance matrix. (It is planned to investigate the use of all fields and all pixels in developing mean vectors and covariance matrices as well as using equal prior probabilities in the classification.)

The estimates and their errors are based on the 33 segments falling in the 10 western Illinois counties comprising the first analysis district corresponding to LANDSAT image ID#2194-16042 of August 4, 1975. The estimates are shown in table 4 and their sampling errors squared in table 5 for eight agricultural land use categories. The window containing the 10 counties included 4,887,960

pixels and required less than 80 seconds for classification on the ILLIAC IV.

Table 4. Estimates of Agricultural Cover Types

Crop or cover type	Reported : acres : July 27	Regression : estimate	Pixel count : x 1.114
	--- (000 acres) ---		
Corn	1286	1390	2105
Soybeans	631	701	610
Perm. pasture	533	434	678
Hay	179	154	104
Alfalfa	69	71	14
Wheat stubble	39	39	0.3
Water	28	32	10
Crop pasture	45	45	0

Table 5. Variances of Estimates of Agricultural Cover Types for 10-County Analysis District

Crop or cover type	Variance : reported : (10 ⁶ acres ²)	Variance : regression : estimate : (10 ⁶ acres ²)	Information gain or loss : (1) ÷ (2)
	(1)	(2)	(3)
Corn	17202	2459	7.00
Soybeans	5880	847	6.94
Perm. pasture	4489	1096	4.09
Hay	630	376	1.67
Alfalfa	155	135	1.14
Wheat stubble	66	70	.94
Water	30	11	2.71
Crop pasture	88	94	.94

SUMMARY

The four dimensional distributions by cover types exhibited considerable overlap except for water. In general, the distributions were unimodal or where several modes were present, one mode was much higher than the other. Soybeans had two distinct modes (one major and one minor), but no factor could be isolated as a basis for grouping fields into two categories. Based on the principal component analysis, bands 6 and 7 (IR) explain practically all the variation for most cover types, but for several cover types bands 4 and 5 (visible) were equally important. The quality of the data for band 7 appeared to be superior to the other bands which had discontinuities or gaps in the data values.

The LANDSAT data for major crops or cover types (i.e., large acreages) showed significant improvements can be expected in the estimates, but minor cover types showed little improvement or even loss of information unless their distributions were reasonably separated (i.e., in the measurement space) from the distributions of the major cover types.

These results for the first LANDSAT image are quite encouraging. Assuming LANDSAT digital tapes and near real-time processing of the ground and classification data, acreage estimates of spring planted crops could have been significantly improved for the area of this LANDSAT image by September 1. The authors believe that similar results can probably be achieved in other areas if the same conditions can be met; namely:

- (1) excellent quality, cloud-free LANDSAT imagery
- (2) good geographic registration of ground segments to LANDSAT imagery
- (3) mean vector and covariance matrices for each crop for each LANDSAT frame (i.e., localized classifiers)
- (4) prior probabilities for each LANDSAT frame (i.e., localized priors)
- (5) sufficient ground data for each crop for classifier training
- (6) an adequate number of ground segments for each LANDSAT frame to compute the regression and correlation coefficients for each crop.

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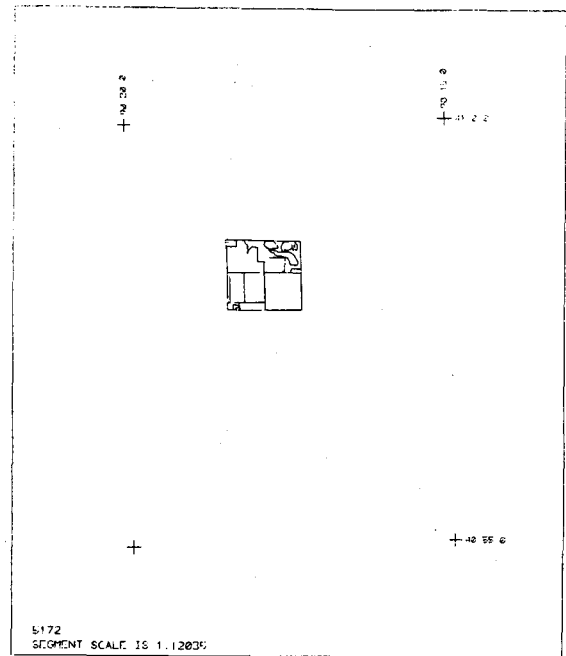


Figure 2. Example Area Segment Mask Plotted at Scale of USGS 15' Quad and Showing 5' Quad Ticks.

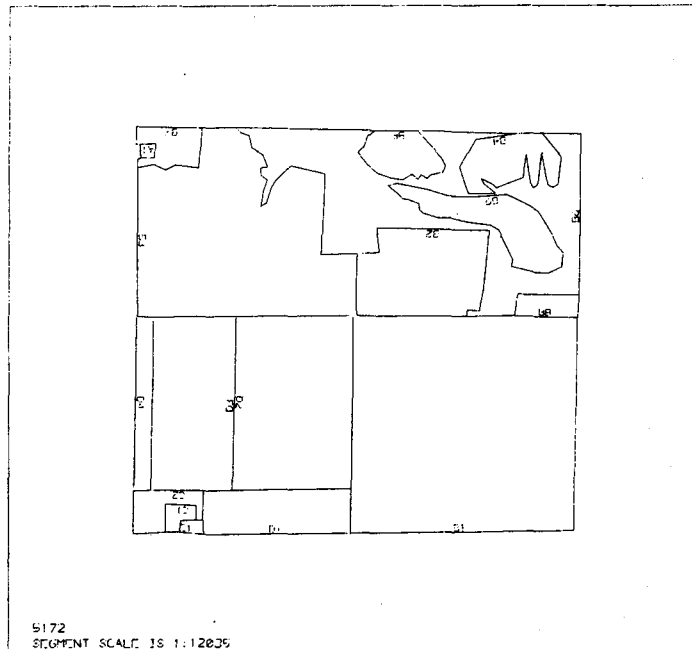


Figure 1. Example USDA/SRS Area Segment Mask Plotted at Scale of Photo Digitized. (Shown reduced here.)

