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## TWO PHASE SAMPLING FOR WHEAT ACREAGE ESTIMATION

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### ABSTRACT

A two phase Landsat-based sample allocation and wheat proportion estimation method was developed. This technique employs manual, Landsat full frame-based wheat or cultivated land proportion estimates from a large number of segments comprising a first sample phase to optimally allocate a smaller phase two sample of computer or manually processed segments. Application to the Kansas Southwest CRD for 1974 produced a wheat acreage estimate for that CRD within 2.42 percent of the USDA SRS-based estimate using a lower CRD inventory budget than for a simulated reference LACIE system. Factor of 2 or greater cost or precision improvements relative to the reference system were obtained.

### I. INTRODUCTION

One of the most important aspects controlling the success of any inventory system is the sampling/aggregation plan utilized. Substantial differences in final estimate precision, bias, and cost can occur depending on which sample design is selected. Moreover, the number of parameters (e.g. different crop acreages or yields) that can be estimated and the reporting level at which they are available are similarly affected by the design.

The advent of timely and relatively inexpensive remote sensing data has fostered new inventory sample design options and improved estimate performance possibilities. While progress has been made in this regard through the Large Area Crop Inventory Experiment (LACIE) and through smaller projects, current inventory performance capability falls significantly short of its present potential.

### II. STUDY OBJECTIVE

In order to provide a relatively simple demonstration of crop inventory performance possibilities presently unexploited, a two phase Landsat-based sample allocation and wheat proportion estimation method was developed in this study\*. A \*Work supported by NASA Contract No. NAS9-14565. A more detailed description of this study is given in Thomas and Hay.<sup>2</sup>

simulated second year LACIE inventory system was used as a base for performance (precision, cost) comparison.

The two phase technique employs manual, Landsat full frame-based wheat or cultivated land proportion estimates from a large number of segments comprising a first sample phase to optimally allocate a smaller phase two sample of computer or manually processed segments. Proportion estimates from each phase are then linked by regression or probability proportional to estimated size (ppes) estimators to provide wheat proportion estimates and standard errors by reporting unit.

### III. SAMPLING AND MEASUREMENT METHODS

#### A. Information Requirements and Performance Goals

The information target for the inventory was defined to be wheat acreage sown (1973-74) expressed as a proportion of total land area for county and by U.S. Department of Agriculture (USDA) Crop Reporting District (CRD). Counties and CRD's were defined on a "pseudo" basis meaning that their boundaries were slightly modified so as to avoid splitting inventory sample segments.

Inventory precision control was set to achieve a wheat acreage estimate within five percent of the corresponding USDA estimate, 95 times out of 100 at the Crop Reporting District level. Budget and inventory throughput rate constraints were selected to be similar to those of the reference LACIE year two system.

Two Kansas CRD's were chosen to demonstrate the Landsat two phase sample technique in the winter wheat region. The first of these, the Kansas, Southwest CRD (11,865 mi<sup>2</sup>) occupies a predominantly semi-arid to sub-humid environment. The dominant small grain-related crop rotation in this water-limited area is summer fallow, wheat and sorghum. To provide a contrasting wheat distribution and appearance situation, the moister and more humid Central Crop Reporting District (8,968 mi<sup>2</sup>) was selected as the second Kansas inventory test area. Here moisture is no longer the dominant limiting agent and double cropping sequences often result. Field size is generally smaller, wheat density lower, and noncultivated range-grassland interfringes more extensively with cultivated areas within the Central CRD.

Inventory data was purposely limited to that available in the LACIE counterpart; namely Landsat full frame color infrared transparencies (not real-time), Landsat digital data for a small sample of five mile by six mile on-a-side segments, and ancillary crop calendar and cropping practice information. A more tailor-made domestic inventory system, not considered here, might also include aircraft and ground data for estimate and measurement calibration purposes.

Table 1 summarizes the inventory information goals and constraints.

## B. Sample Design Specification

A stratified double sampling (i.e. two phase) design was selected to demonstrate the capability of remote sensing-aided systems to meet wheat proportion information requirements within the CRD performance constraints just described.

This design takes advantage of the relationship between a more expensive to measure variable Y (e.g. computer-based wheat proportion) and a corresponding less expensive to measure variable X (e.g. a rapid analyst estimate of sample segment wheat proportion). A relatively large first phase sample of observations on X may be used to efficiently allocate a much smaller sample of observations on Y. Similarly, the small sample of information on Y can be used to calibrate (to Y accuracy standards) the area-wide information on X. If the correlation between X and Y is sufficiently large, significant reductions in estimate (e.g. wheat proportion) variance and second phase (e.g. computer segment) sample size can result when compared with single phase sampling on Y alone.

Figure 1 illustrates the two phase sampling concept as applied to the wheat proportion estimation problem. The top layer in the figure was defined to represent a CRD-wide phase 1 sample frame composed of standard 5 x 6 mile (30 mi<sup>2</sup>) sample segments. A "data sandwich" consisting of several previous-to-crop-year Landsat transparencies was associated with the phase 1 sample frame. These color infrared transparencies were used by an image analyst to produce rapid and inexpensive wheat proportion estimates (variable X) for all sample segments\*.

The resulting sample phase 1 proportion data were then used to minimize final crop estimate variance by stratifying the segment population into crop (in this case wheat or, alternatively, cultivated land) density strata. Thus, after tabulating a list of phase 1 data, a small phase 2 sample can be allocated within the phase 1 strata with either equal or variable probability. Stratified probability proportional to estimated size (of phase 1 wheat proportion) allocation was used to select sample phase 2 segments in this study. More accurate (Y variable) wheat proportion estimates were then made for each phase 2 segment selected by using multitemporal manual or machine-aided classification methods as illustrated by the lower layer in Figure 1.

## C. Determination of Optimal Phase 2 Sample Size

The optimal second phase sample size, n, designed to minimize estimate variance for specified survey budget levels was determined via regression based optimal sampling rate formulas. These are presented and discussed in detail in Thomas and \*Since all phase 1 units are sampled, the sample design applied here becomes regression sampling. However, the more general technique developed in this study can be applied when sampling less than the population size at phase 1.

Hay.<sup>5</sup> Optimal phase 2 sample size for each wheat density stratum is a function of the relative cost and correlation between phase 1 and phase 2 sample segment proportion measurements as well as the actual sample segment variability represented by the variance of Y. The latter quantity was estimated by the variance obtained from phase 2 sample segment wheat proportion data. For purposes of sample size determination, correlation between phase 1 and phase 2 proportion estimates was assumed to be 0.8 on the basis of preliminary tests.

Based on a detailed cost analysis<sup>5</sup> it was determined that the cost ratio for unitemporal machine processing at phase 2 to analyst estimation at phase 1 was 170:1. If multirate manual classification of a small point sample was used instead at phase 2 then the cost ratio became 17:1.

A simulated LACIE system sample size was determined in order to define the total survey budgets available for the Kansas Southwest and Central CRD's crop year 1972-73 USDA statistics were used to give the proportion of wheat average sown, harvested, and produced in each CRD relative to the U.S. total.<sup>2</sup> Under an early LACIE assumption that 636 sample segments would be allocated to U.S. wheat regions, the total expected number of sample segments allocated to both CRD's was determined for each allocation factor.<sup>6</sup> Cost per unitemporally processed computer segment was then multiplied times the sample size required under the acreage sown allocation assumption to give total available CRD survey budget. This budget represented that theoretically available to the reference LACIE system.

Given the crop reporting district budgets, phase 1 to 2 correlations and cost\* ratios, and estimated phase 2 variances, optimal phase 2 sample sizes for the two phase sample with regression estimation were calculated. These are presented in Table 2. Sample selection was defined to be with replacement.

For purposes of this study, only pps phase 2 sample unit selection was used within wheat density strata. The sample sizes required for pps estimation were assumed to be the same as those calculated for regression. This initial assumption was considered to be conservative in that several important areas in all three test sites experienced significant variability in the parameter of interest (e.g. wheat proportion or crop proportion). Hence pps second phase sample unit selection might be expected to give slightly lower variance per stratum than equal probability regression sampling.

## D. Specification of Measurement Procedures

Wheat or cultivated land percent estimates were obtained for phase 1 sample units by the first of \*In order to be conservative relative to two phase sample system performance, a phase 2 to phase 1 ratio of 150:1 was assumed.

two image analysis procedures developed in this study. The first image interpretation procedure allowed quick (approximately three minutes per segment including rest time) proportion estimates to be made from a base date Landsat full frame transparency. The base date was selected from a recent crop year date that gave maximum contrast between wheat versus other crop types. In the two Kansas CRD's examined, this base date occurred at or shortly after harvest. At this time, wheat fields appeared very white relative to all other cover categories.

When confusion situations were identified by reference to ancillary data concerning crop calendar and cropping practices as well as multirate interpretation of Landsat imagery, an additional one and rarely two dates of color infrared full frame data was referenced by the image analyst. Grain sorghum fields, not easily separable from wheat on the base date, represented an example of such a situation. Land use/soils association stratification on Landsat full frame data was found to provide a convenient means of coding circumstances in which wheat versus other confusion might occur.

A second image interpretation procedure served to provide phase 2 wheat proportion estimates. This technique was chosen to represent the best Landsat-based wheat proportion measurement capability available for phase 2 sample segments. Earlier tests had shown that this multitemporal image interpretation approach resulted in more accurate proportions than did corresponding unitemporal machine-aided classification. Ideally multitemporal machine processing should give results at least comparative to the manual method, and for this reason the machine cost figures were used for phase 2 sample size determination.\*

The phase 2 wheat mensuration procedure was to employ a systematic sample of 48 points over enlargements of phase 2 sample segments obtained from full frame transparencies. Enlargements were to CX120 "latern slide" size representing a five to six times scale increase relative to the original 1:1,000,000 scale. Dates chosen for inclusion in this analysis included a representative for each image biophase for the 1973-74 crop year having the least cloud cover, least noise, and most contrast between cover classes.

Wheat versus other classification were recorded on an acetate sheet covering a record photo for the given sample segment. In order to maximize wheat identification accuracy (correctly identifying wheat as wheat) and minimize commission error (classifying a sample point as wheat when it was not), other major non-wheat cover types and confusion crops were identified when possible. This additional identification task was designed

\*Original unitemporal machine processing costs were retained as opposed to substituting higher multitemporal costs. Again this assumption is conservative relative to two phase sample system performance.

to ensure a conscientious consideration of wheat alternatives by the photointerpreter.

#### E. Specification of Proportion Estimators

Two estimators were considered: stratified regression and stratified probability proportional to estimated size (ppes).<sup>1,3,4</sup> Generally the linear regression estimator is used when the relationship between X (phase 1 proportion) and Y (phase 2 proportion) can potentially move far from the origin and when the variance of Y about the regression line ( $\sigma_e^2$ ) remains approximately constant over the range of X. In this situation it is known as the best linearly unbiased estimate (BLUE). When the relationship between X and Y is thought to pass close to the origin and  $\sigma_e^2$  increases proportionally to X then ppes estimators are termed BLUE. This latter situation may occur especially in areas with high wheat density variability. In addition, ppes allocation may be used to drive second phase sample unit selection towards a greater proportion of "higher value" areas and still maintain unbiased estimation. For example, it may be desired to force computer segment selection to units tending to have higher wheat density or higher wheat variety spectral class mixture representation in order to maximize signature extension success.

#### IV. SYSTEM EVALUATION: COST-EFFECTIVENESS ANALYSIS

A portion of the analysis involved a precision versus cost performance comparison between the double sampling system described in this study and the reference LACIE sampling system. This analysis was done to demonstrate the relative amount of improvement to be expected with inclusion of the full frame Landsat data in the system. The form of cost-effectiveness analysis used is known as a "system comparison study". It helps a decision-maker answer questions about how to achieve a given set of objectives at the least cost, or conversely, how to obtain the most effectiveness from a given set of resources.

Figure 2 illustrates this comparative cost-effectiveness framework by showing the effect of technological progress on the cost-capability "frontier" of an existing production system. The frontier  $F_0F_0$  shows the maximum capability that can be expected from the present system at a given level of budget. A system producing on the frontier is defined as "cost-effective" because a decrease in cost is not possible without a decrease in capability. A technological advance would now beneficially alter this relationship: the cost-efficient frontier would be pushed out to some new set of points,  $F_1F_1$ . A point  $P_0$  on the old frontier  $F_0F_0$  in the shaded area of Figure 2 would now represent an inefficient pattern of production. A set of points in the shaded area of Figure 2 would represent an improved return, with cost-effective points now lying on  $F_1F_1$  between  $P_1$  and  $P_2$ . The effect of technological progress thus "ranges" between equivalent capability at a lower budget ( $P_1$ )

and greater capability within the same budgetary constraints ( $P_2$ ).

#### V. RESULTS AND DISCUSSION

##### A. CRD and County Wheat Proportion Estimates:

Application of the two phase design to the Kansas Southwest CRD for 1974 produced a wheat acreage estimate for that CRD within 2.42 percent of the USDA SRS-based 1974 estimate using a lower CRD inventory budget than for the assumed referenced LACIE system.

Table 3 presents the results for regression and probability proportioned to size (ppes) estimation for the Southwest CRD. Recall that both estimates are based on the same ppes draw of phase 2 sample segments. Consequently a comparison of the increased estimate precision available with ppes versus random within stratum selection could not be made aside from that resulting from the formulas themselves. The regression estimator was used in a predictive manner to produce county estimates (see Table 4). County regression estimates for the Southwest CRD show a greater range of departure from their corresponding USDA-based values than the CRD level estimates. This situation is expected when sample allocation is optimized for the CRD as opposed to county level. Differences range from -6.66 percent in Stanton county to a low of 0.25 percent in Finney county to a 9.54 percent over-estimate in Ford county. The average difference, sign considered, was 0.18 percent (not statistically significant with the paired t-test). The average absolute difference, sign ignored, was 2.93 percent also found not to be statistically significant with the paired t-test.

A disadvantage of the ppes estimator was that estimates could not be made on a county basis. This circumstance resulted from the fact that sample allocation was based on achieving performance criteria at the CRD level without phase two sampling constraints at the county level. Hence phase two sample segments, necessary for use in the ppes estimator, were not selected for all counties. If desired, however, an unstratified ppes estimator could be used for counties or groups of counties having two or more phase two segments.

The performance of both the regression and ppes estimators in the Kansas Central CRD was below that obtained in the Southwest CRD. The regression estimate fell 3.50 percent absolute below the USDA-based proportion estimate while the ppes estimate was found to be 6.09 percent low. These same departure percentages represent 10.94 and 19.04 percent of the USDA-based estimate, respectively. Resulting estimate standard errors were 1.67 times higher for regression and 1.53 times higher for ppes in the Central as opposed to the Southwest CRD.

The less satisfactory performance in the Central Crop Report District resulted from a poor correlation between phase 1 and phase 2 proportion estimates. This low correlation was in turn

traced to the fact that a significant amount of wheat had been plowed-down in some sample segments on the original phase 1 base date transparency. A test was run to determine if an earlier base date would produce correlations obtained (.8) in the Southwest CRD. This test was successful and suggested that inventory performance levels comparable to those achieved in Southwest should have been obtainable in the Central CRD.

Use of correct base date transparencies for phase 1 wheat estimation resulted in phase 1 to phase 2 correlations of .82 and .79 for the Southwest and Central CRD's respectively. These correlations were achieved when strata were pooled. Within stratum correlations varied from .54 to .83. The generally lower stratum-specific correlations suggest that some strata should be grouped or phase 2 sample sizes increased somewhat so as to allow a more accurate representation of the stratum phase 1 to phase 2 relation.

Interestingly, phase 1 cultivated and proportion estimates gave a phase 1 to phase 2 (wheat) correlation of .89 in the Southwest CRD. The corresponding value for the Central District, however, dropped to .68. Dominance of the wheat crop in Southwest CRD may explain the former result, while the more complex multicrop patterns in the Central may be responsible for the latter result. In any event, the importance of inexpensive phase 1 cultivated land estimates, easily obtained in most agricultural situations, should not be overlooked as an inventory performance improvement option.

##### B. Cost-Effectiveness Comparison

The cost-effectiveness framework outlined earlier was used to compare the relative precision and cost performance of (1) the reference LACIE sampling system with stratification based on historical agricultural wheat area statistics, (2) the two phase sample procedure with machine-aided wheat classification at the second phase, and (3) the two phase sample procedure with multi-temporal manual processing at the second phase. Figure 3 illustrates the results of this analysis.

Cost ratio, correlation, and phase 2 variance data obtained for the Kansas Southwest CRD was used to construct the Figure. The LACIE reference system was defined to be a stratified random sample with phase 2 sample allocation to wheat density strata proportional to area. This reference system was defined to represent as closely as possible the LACIE second year procedure. Stratification on historical county wheat data was assumed to give a 4 to 5 times reduction in variance relative to unstratified random sampling. The total CRD survey budget determined earlier for the LACIE reference system was defined as the 100 percent inventory level.

Comparison of points  $P_0$  and  $P_2$  in Figure 3 indicates that the two phase sample with computer processing at phase 2 should give greater than a

two fold increase in precision relative to the reference LACIE system. Alternatively, the same LACIE reference system standard error at point  $P_0$  should be obtainable with less than one half to one fifth the reference system cost by using the two phase sample approach. This cost relationship can be seen by projecting\* the curve containing  $P_a$  to the level of  $P_0$ .

Similar comparison of  $P_0$  with  $P_b$  indicates a greater than 10 fold increase in precision relative to the LACIE reference system may be achievable with the two phase sample using manual wheat classification at phase 2.

Comparison of  $P_a$  and  $P_b$  shows a four fold increase in precision when two phase sampling with manual as opposed to machine-aided wheat classification is employed. A similar reduction in cost is indicated.

It should be emphasized that these results are limited to the Kansas data set examined and the particular sample design assumptions made. The authors submit that the important information here is not the exact cost or precision improvement values, but rather the relative performance relationship between the two phase and single phase (reference) sample system.

#### VI. CONCLUSIONS

The sampling and measurement methods described in this study are of practical utility in many agriculture inventory situations. Optimum allocation of sample units to control precision of acreage estimation is a common sampling concern. The spatial information provided on the full-frame Landsat imagery can, as demonstrated in this study, be used to cost-effectively stratify a population of segments so as to minimize final estimate variance. For the Kansas test areas examined in this study, it appears that remote-sensing-aided inventory systems can perform with high precision and accuracy at the Crop Reporting District level.

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\*Using the shape relationship of the curve containing  $P_a$ . The shape relationships are approximately equivalent.

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TABLE 1:

INVENTORY DESIGN GOALS AND CONSTRAINTS

- TEST LOCATION: Kansas Winter Wheat Region
- INFORMATION TO BE OBTAINED
  - Phase 1 wheat proportion or cultivated land proportion for all sample segments
  - Pseudo county and CRD wheat proportion estimates, variances, costs, and biases resulting from a two phase sample
- PERFORMANCE CRITERIA
  - Precision: Within 5% of the USDA CRD estimate 90% of time
  - Cost: Less than or equal to current LACIE system
  - Bias: Minimal
  - Timeliness: Meet current LACIE objectives
- AVAILABLE DATA TYPES
  - LANDSAT full frame, LACIE digital segment data, ancillary data
- OUTPUT PRODUCE FORMAT
  - Wheat proportion estimates in tabular form

TABLE 2:

OPTIMAL PHASE 2 SAMPLE SIZES FOR THE KANSAS CRDs EXAMINED

	WHEAT DENSITY STRATUM		
	0 - <10%	10 - <25%	25 - Max %
Southwest CRD			
Phase 1 size/Phase 2 size	68/2	175/7	140/7
Central CRD			
Phase 1 size/Phase 2 size	176/8	117/8	6/0

- ASSUMPTIONS: (1) Phase 2 to Phase 1 cost ratio of 150:1  
 (2) Total CRD survey budget of 2700 cost units  
 (3) Phase 1 to Phase 2 correlation of 0.8  
 (4) All Phase 1 sample units measured (i.e.  $N' = N$ )

TABLE 3:

## RESULTING TWO PHASE KANSAS SOUTHWEST CRD WHEAT PROPORTION ESTIMATES

(ACREAGE SOWN 1973 - 1974)

USDA-Based Estimate	Two Phase Regression			Two Phase PPES		
	Estimate	Std. Error	R.D. USDA VS. Two Phase	Estimate	Std. Error	R.D. USDA VS. Two Phase
27.63%	28.31%	1.68%	2.42%	28.30%	0.40%	2.42%

R.D. =  $\frac{\text{SAMPLE ESTIMATE} - \text{USDA ESTIMATE}}{\text{USDA Estimate}} \times 100$

TABLE 4. COUNTY TWO PHASE RESULTS FOR THE KANSAS SOUTHWEST CRD (1973 - 1974)

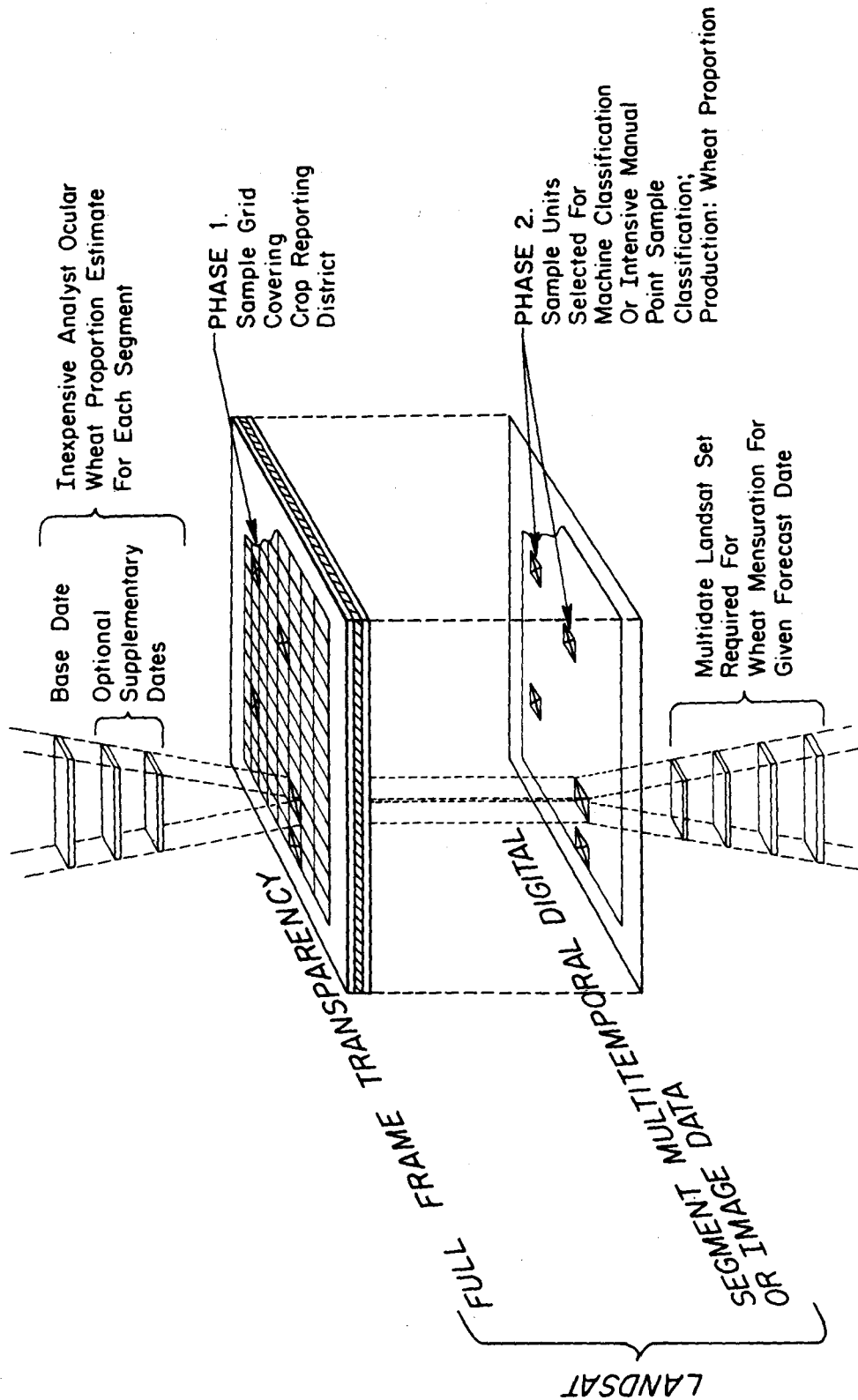
COUNTY	WHEAT PROPORTION ESTIMATE DIFFERENCE	
	(Two Phase - USDA Based)	
Hamilton	-1.95%	
Kearny	-5.95%	
Finney	0.25%	
Hodgeman	5.33%	
Stanton	-6.66%	
Grant	0.27%	
Haskell	-0.91%	
Gray	2.08%	
Ford	9.54%	
Morton	-0.74%	
Stevens	-3.48%	
Seward	-0.19%	
Meade	1.74%	
Clark	2.56%	

Ave. Difference sign considered = 0.18%

Ave. Difference sign ignored = 2.93%



Figure 1: TWO PHASE SAMPLE FRAME FOR WHEAT ACREAGE ESTIMATION



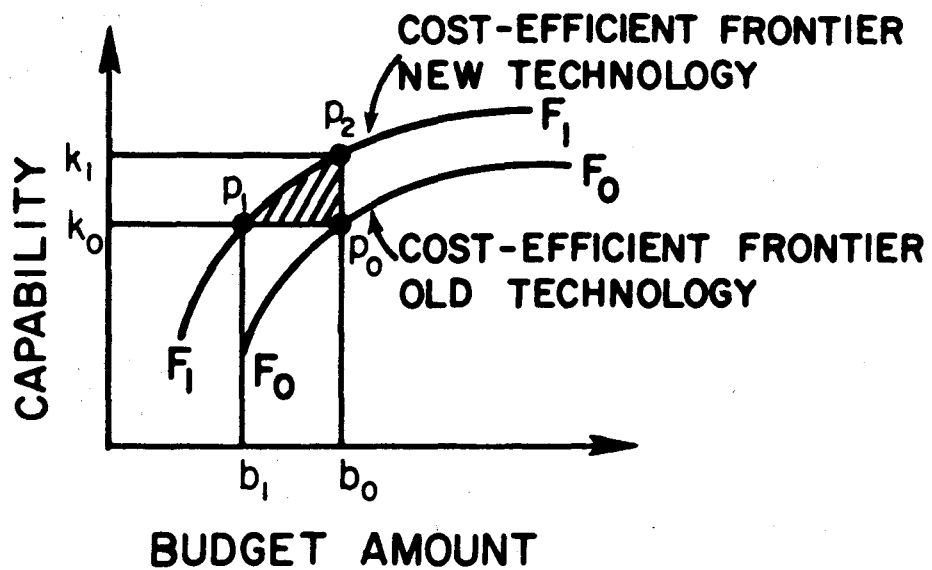
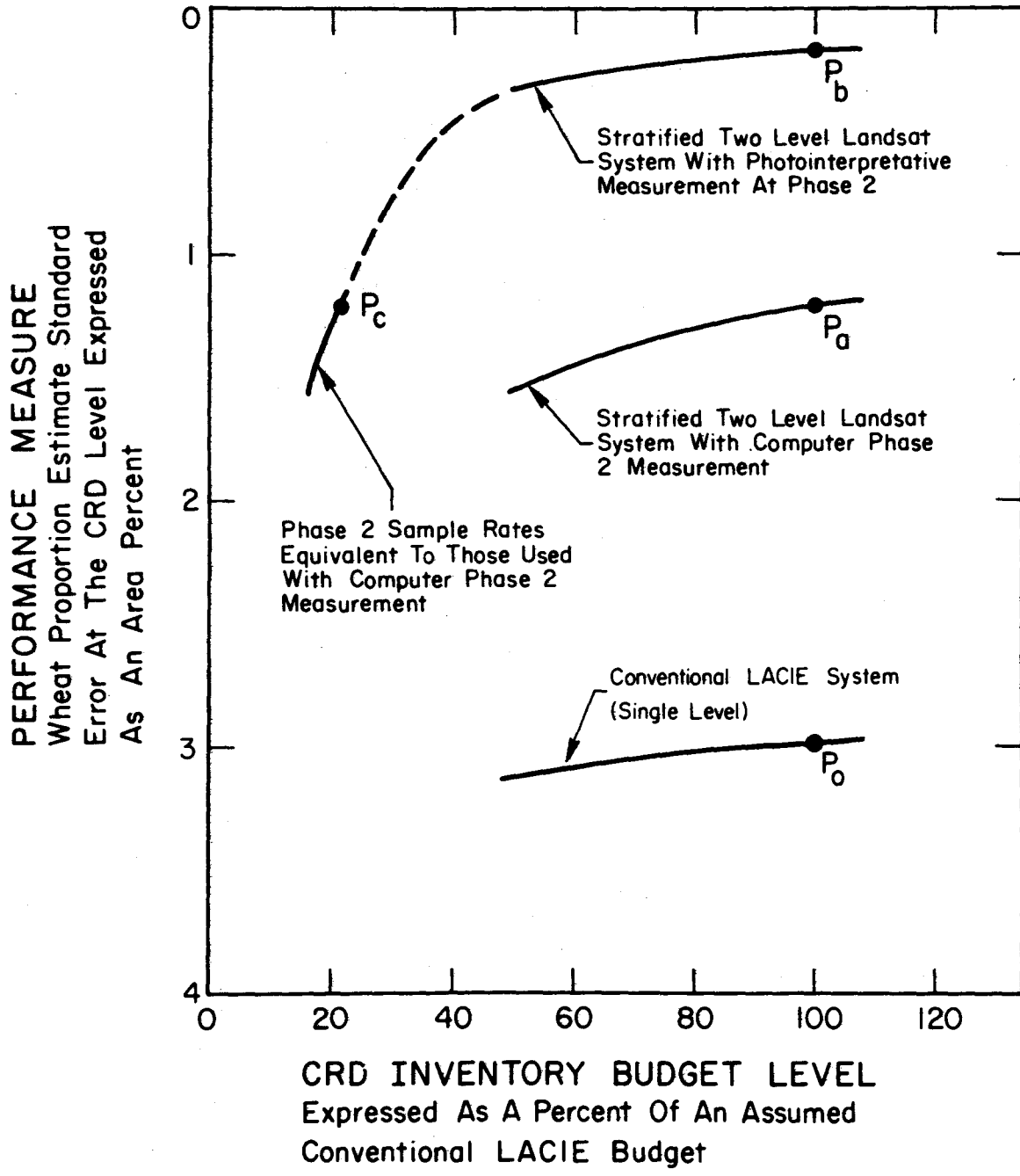


Figure 2: EFFECT OF A TECHNOLOGICAL ADVANCE OF A COST-CAPABILITY PRODUCTION FRONTIER

Figure 3: COST-CAPABILITY COMPARISON OF TWO LEVEL VERSUS SINGLE LEVEL LANDSAT SAMPLE ALLOCATION/ESTIMATION SYSTEMS



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Ms. Hay holds an A.B. Degree in Geography (June 1967) from the University of California, Berkeley and has completed all course work toward a M.A. in Geology at the University of California. For the past nine years Ms. Hay has been engaged in remote sensing research with the Remote Sensing Research Program, University of California. She has worked with Apollo, Skylab, Landsat, and high altitude aircraft data with regard to geologic resource, and agricultural and wildland vegetational resources. In recent years Ms. Hay has concentrated on the utilization of Landsat data in crop inventory systems and is currently Project Manager for the RSRP LACIE contract.