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The Large Area Crop Inventory Experiment - Methodology for Area, Yield and Production Estimation, Results and Perspective

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By R. Bryan Erb

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geographic pattern of weather and other growing conditions.

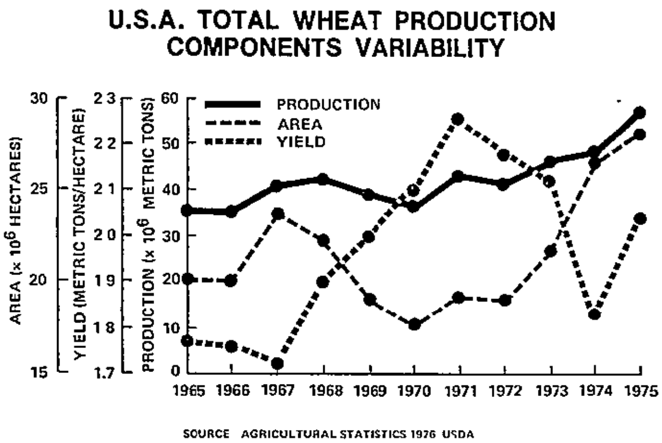

Figure 1.— Variability in Area, Yield, and Production in the U.S.A.

1.4 The Background of LACIE

The roots for LACIE were intentionally and carefully established in 1960 by the Agricultural Board of the National Research Council in the U.S. when experiments were conceived to examine the feasibility of using multispectral remote sensing for agricultural crop monitoring. An organized research program was established in 1965 by the U.S. Department of Agriculture (USDA) and the National Aeronautics and Space Administration (NASA). This program led, in an orderly fashion, from the first successful computer recognition of wheat in 1966 using multispectral measurements collected with aircraft to follow-on development and testing of satellite capability in 1972. The success of several feasibility investigations in 1972-73 (Erb, 1974) conducted with the Earth Resources Technology Satellite, then known as ERTS 1 and later renamed Landsat 1, led to the design and initiation of LACIE in 1973-74. LACIE was a logical next step in the chain of research and development activities and was designed to test on a regional or national basis the technology developed over the previous decade, and to establish the technical feasibility of a global agricultural monitoring system.

1.5 The Roles of the Agencies Participating in LACIE

Each of the three agencies of the U.S. Government (the National Aeronautics and Space Administration (NASA), the U.S. Department of Agriculture (USDA) and the National Oceanic and Atmospheric Administration (NOAA) of the U.S. Department of Commerce) that conducted LACIE brought particular expertise to the experiment. NASA was responsible for the overall technical design and management of the experiment, for the acquisition of Landsat data for the area analysis and for all data handling and logistics. NOAA was responsible for the development and operation of the yield models and weather summaries and for the acquisition and handling of meteorological data. The USDA was responsible for acquisition of historical agricultural data, for the acquisition of current-year ground data for accuracy assessment and for the compilation of the production reports. There was substantial involvement of a number of research establishments at universities and in industry and the major support contractor for NASA, the Lockheed Electronics Company, was responsible for much of the implementation of the experiment.

2. THE DESIGN OF THE EXPERIMENT

LACIE was initiated in 1974 to demonstrate the forerunner of an operational global wheat monitoring system. The experiment objectives were:

o To demonstrate an economically important application of repetitive multispectral remote sensing from space.

o To test the capability of the Landsat together with climatological, meteorological and conventional data sources to estimate the production of an important world crop - wheat.

o Commencing in 1975, validate technology which could provide timely estimates of crop (wheat) production.

Performance goals, based on both an analysis of the capabilities of existing conventional survey systems and a projection of future needs, were established for the experiment to be utilized as evaluation criteria. These included:

o An accuracy goal for estimates at harvest to be within ±10% of true country production 90% of the time (referred to as the 90/90 criterion). An additional goal was to establish the accuracy of these estimates (made on a monthly basis from early season through harvest period) prior to harvest.

o A timeliness goal to demonstrate that the Landsat data could be reduced to acreage information within 14 days after acquisition in an operational environment.

o All estimates to be based on objective and repeatable procedures and not adjusted within the experiment utilizing outside information sources.

The LACIE was focused on monitoring production in selected, major wheat-producing regions of the world. The experiment extended over three global crop seasons and was designed for expansion up to eight regions (Figure 2). The early phases of the experiment concentrated primarily on a "yardstick" wheat-growing region of the U.S., the nine-state, wheat region in the U.S. Great Plains (USGP), where current information relative to wheat production and the components of production were available to permit quantitative evaluation of the technology. As the experiment progressed, a combination of programmatic policy decisions, availability of resources, and the LACIE experimental design permitted an orderly expansion of the initial scope to include the monitoring of wheat production in two additional major producing regions, (Canada and the USSR). This expansion included exploratory studies for monitoring wheat production in five other major-producing regions (India, Peoples Republic of China, Australia, Argentina and Brazil). In addition, at the end of Phase I, key USDA management decisions resulted in the incorporation of a USDA-User System within the USDA-LACIE effort.

The experiment extended over three overlapping global crop seasons, each of which was considered an experiment phase. Phase I of LACIE, global crop year 1974-75, focused on the integration and implementation of technology components into a system to estimate the proportion of wheat in selected study segments within the major producing regions, and the development and feasibility testing of yield and production estimation systems. An end-of-season report for area estimates of wheat/small grains in the U.S. Great Plains was generated.

In Phase II, global crop year 1975-76, the technology, as modified during Phase I, was evaluated for monitoring wheat production for the U.S. Great Plains and Canada, and "indicator regions" in the USSR. Monthly reports of area, yield, and production of wheat for these three major-producing regions were generated. A substantial level of effort was expended to identify significant problem areas and to incorporate recommended technology components into the LACIE analysis systems for use during Phase III.

During Phase III, global crop year 1976-77, new technology, developed during Phase II, was implemented and evaluated for monitoring wheat production for the U.S. Great Plains and the USSR. Monthly reports of

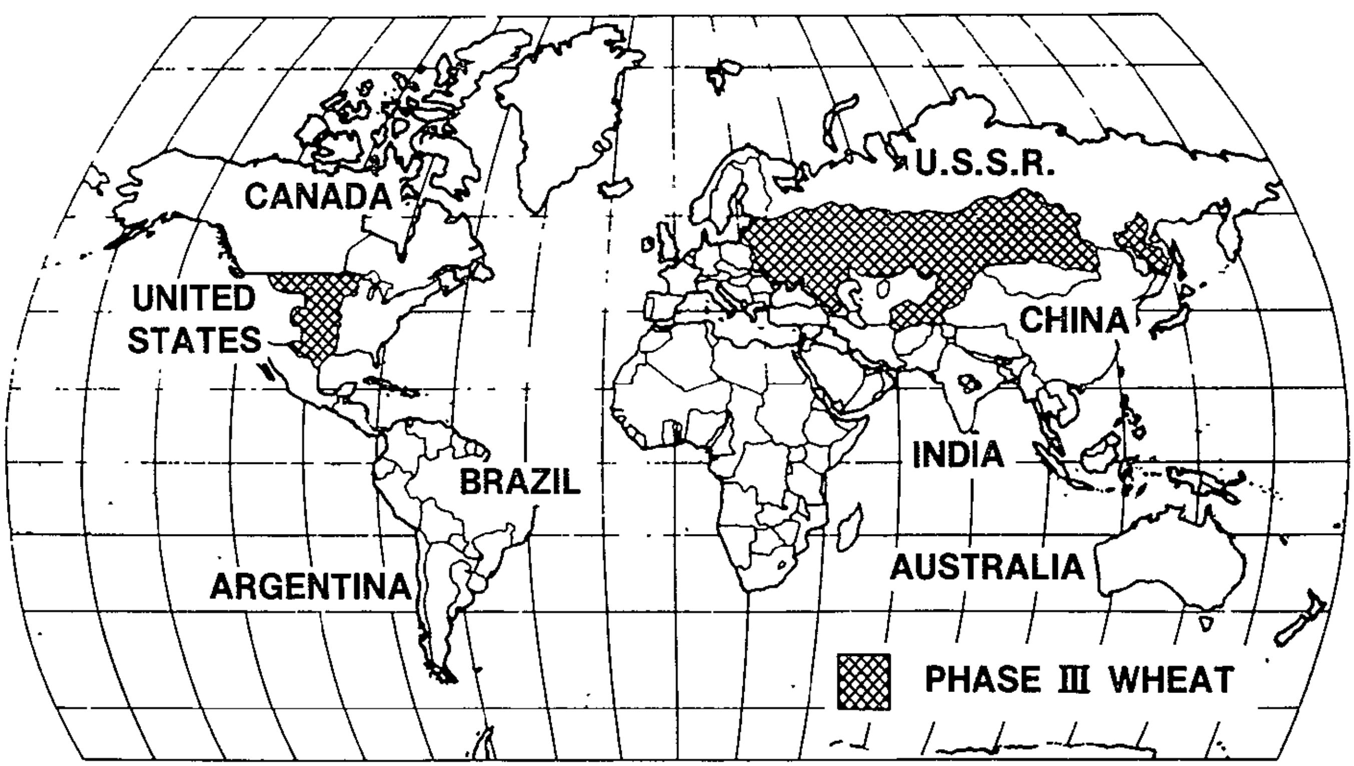

Figure 2.— LACIE Study Areas.

area, yield, and production estimates of wheat for these major producing regions were generated.

3. THE LACIE TECHNICAL APPROACH

The technical approach (Figure 3) to the LACIE was to estimate production of wheat on a region-by-region basis where production is the product of area and yield. Area was derived by classification and mensuration of Landsat multispectral scanner (MSS) data and yield estimates were obtained from statistical regression models which relate wheat yield to local meteorological conditions, notably precipitation and temperature. The integrating factor for the area and yield estimates was a sampling and aggregation strategy which efficiently allocated sample segments (5x6 nautical mile) to be acquired by Landsat and analyzed for wheat percentage, defined the strata boundaries for the wheat yield models, and formulated the upward expansion (aggregation) of the area and yield estimates to regional and country estimates of production. These aggregations resulted in experimental commodity reports of wheat area, yield and production for user evaluation and accuracy assessment. The performance evaluations provided the mechanism both for verifying where the LACIE technology was performing adequately and for isolating and identifying problems.

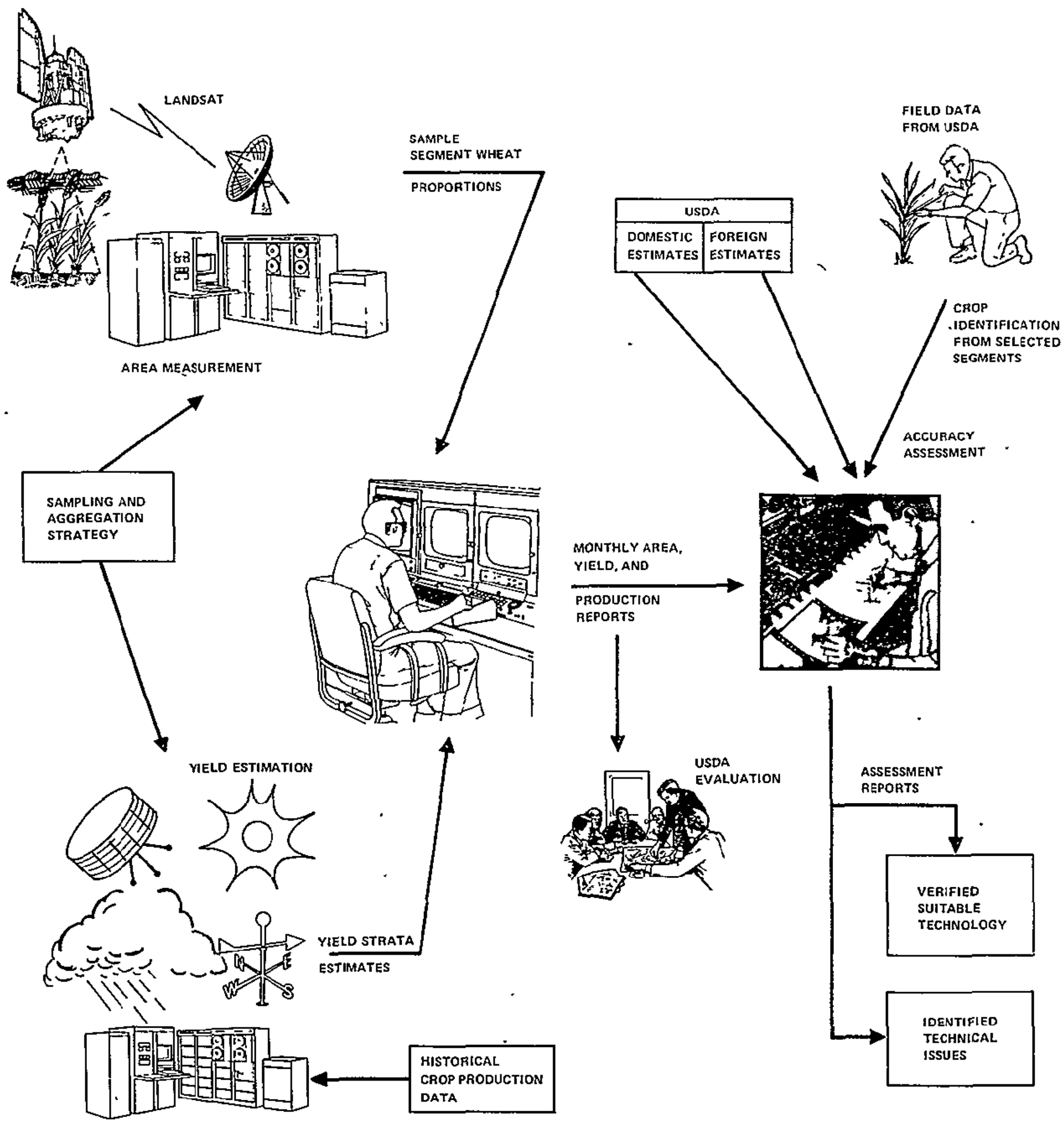

Figure 3.— LACIE Technical Approach.

3.1 Landsat Data Acquisition

The initiation of Landsat data acquisition (Figure 4) is at the Johnson Space Center (JSC) where the sampling strategy defined the locations of the segments to be acquired. The Landsat acquisition information was transmitted via existing Apollo communication lines to the Goddard Space Flight Center (GSFC) which commanded the Landsat for multispectral scanner acquisition each 18 days during the crop season. Data was, for the majority of LACIE, transmitted to ground receiving stations at Maryland, Alaska, or California either in real-time or by use of the on-board tape recorders. During the latter parts of LACIE, ground stations in Italy and Pakistan were utilized to conserve the on-board recorders. Data from the ground stations were shipped to the GSFC where the Landsat preprocessing was performed. The data was screened for cloud cover, registered to previous acquisitions, and the sample segment data extracted and transmitted in digital computer compatible format to JSC where it was entered into an electronic data base. In addition, electronically regenerated full-frame (100 n.m. x 100 n.m.) film in 70mm black-and-white format for each MSS band was shipped to the USDA Aerial Photography Field Office in Salt Lake City which converted it to 9-inch color infrared (IR) film composites and shipped them to JSC. The 9-inch composites were prepared four times per crop season.

3.2 Analysis for Area Estimation

The analysis of the Landsat data was performed at the JSC (Figure 5) where procedures were designed and personnel were trained to perform computer-oriented crop identification and mensuration without the availability of ground truth. The analysis was basically a four-step process. In the first step, the Landsat and ancillary data was prepared and assembled so that a trained analyst could perform crop identification. The assembled Landsat data products included full-frame color IR film, segment level color IR film products, and graphical plots of MSS response. Ancillary data included historical agronomic practices, crop growth stage information based on historical data and current year weather and summaries of the meteorological conditions for the current crop year. The second step was the labeling by the analyst, based on established procedures of a small percentage of the segment data elements

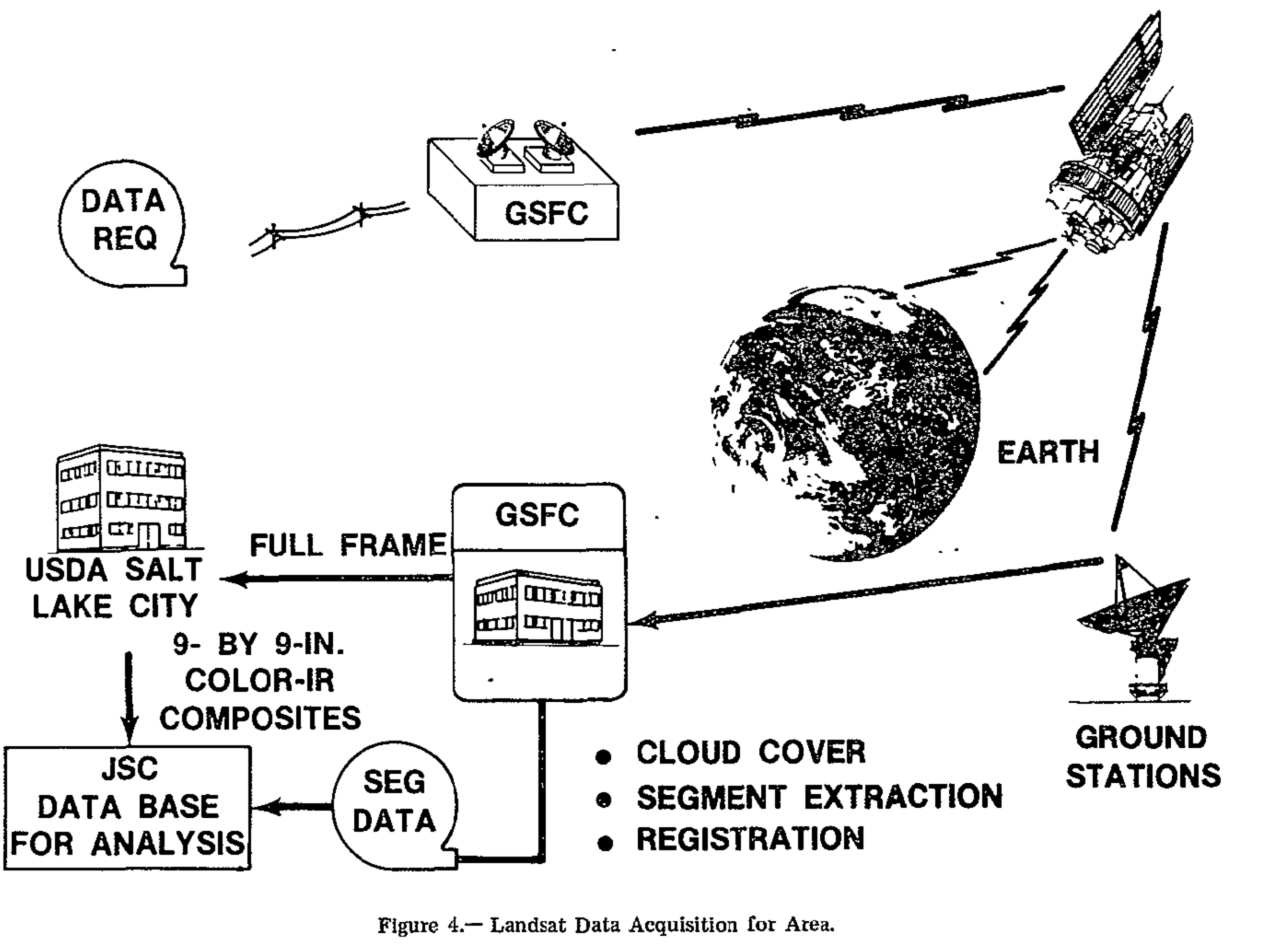

Figure 4.— Landsat Data Acquisition for Area.

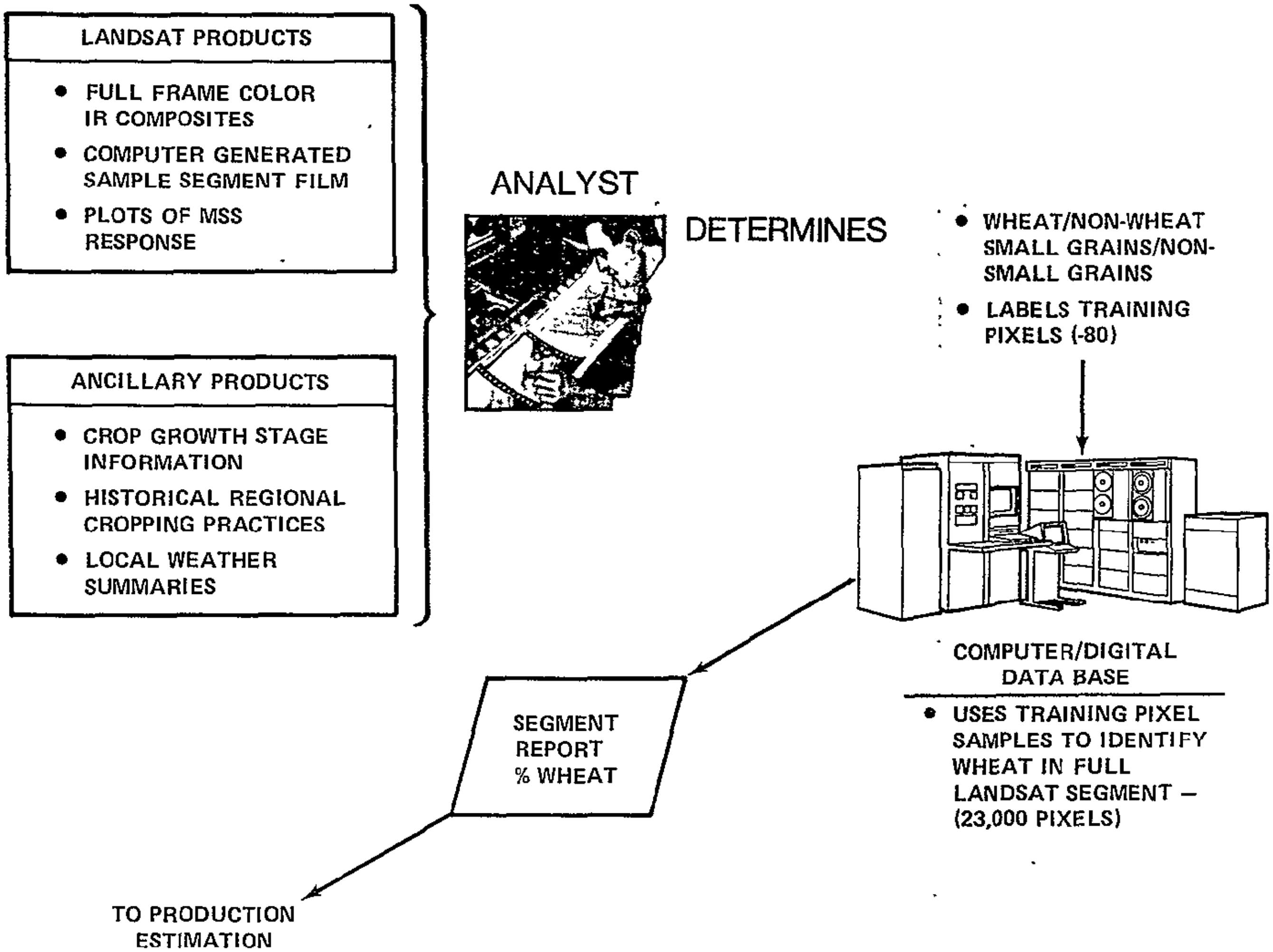

Figure 5.— LACIE Analysis for Wheat Area Determination.

(pixels) as being either wheat or non-wheat or small grains or non-small grains. This labeling was strongly based on the variability (Figure 6) in the multitemporal (over time) crop appearance of ground cover types afforded by the sequential Landsat coverage. In the third step, the analyst labels were used in a computer to train a multivariate pattern recognition algorithm to identify wheat or non-wheat for all the data elements (approximately 23,000 pixels) of the Landsat segment, and to tabulate the results as a percentage of wheat for the segment. The final step was the evaluation by the analyst of the result as acceptable before submitting the result for wheat production estimation. It should be noted that early attempts by the analysts to discriminate between wheat and other small grains such as barley were not generally successful and labeling was primarily either small grains or non-small grains. Historically derived ratios were then applied to the resultant segment level estimates of small grains to estimate wheat. A procedure for analyst discrimination between spring small grains based on subtle differences in crop growth stages was tested in North Dakota during LACIE Phase III and shows promise.

3.3 Meteorological Data Acquisition

The overall implementation and operation of the applications involving meteorological data were under the direction of NOAA's Center for Climatic and Environmental Assessment (CCEA). This included global meteorological data acquisition for use in wheat yield models, in wheat growth stage models (crop calendars), and in the weather summaries used by the area estimation analysts. In Washington, DC, weather data was routinely acquired through the World Meteorological Organization's (WMO) Global Telecommunications System and was augmented by foreign data from the U.S. Air Force's Environmental Technical Applications Center (ETAC) and domestic data from the National Weather Service (NWS), the Federal Aviation

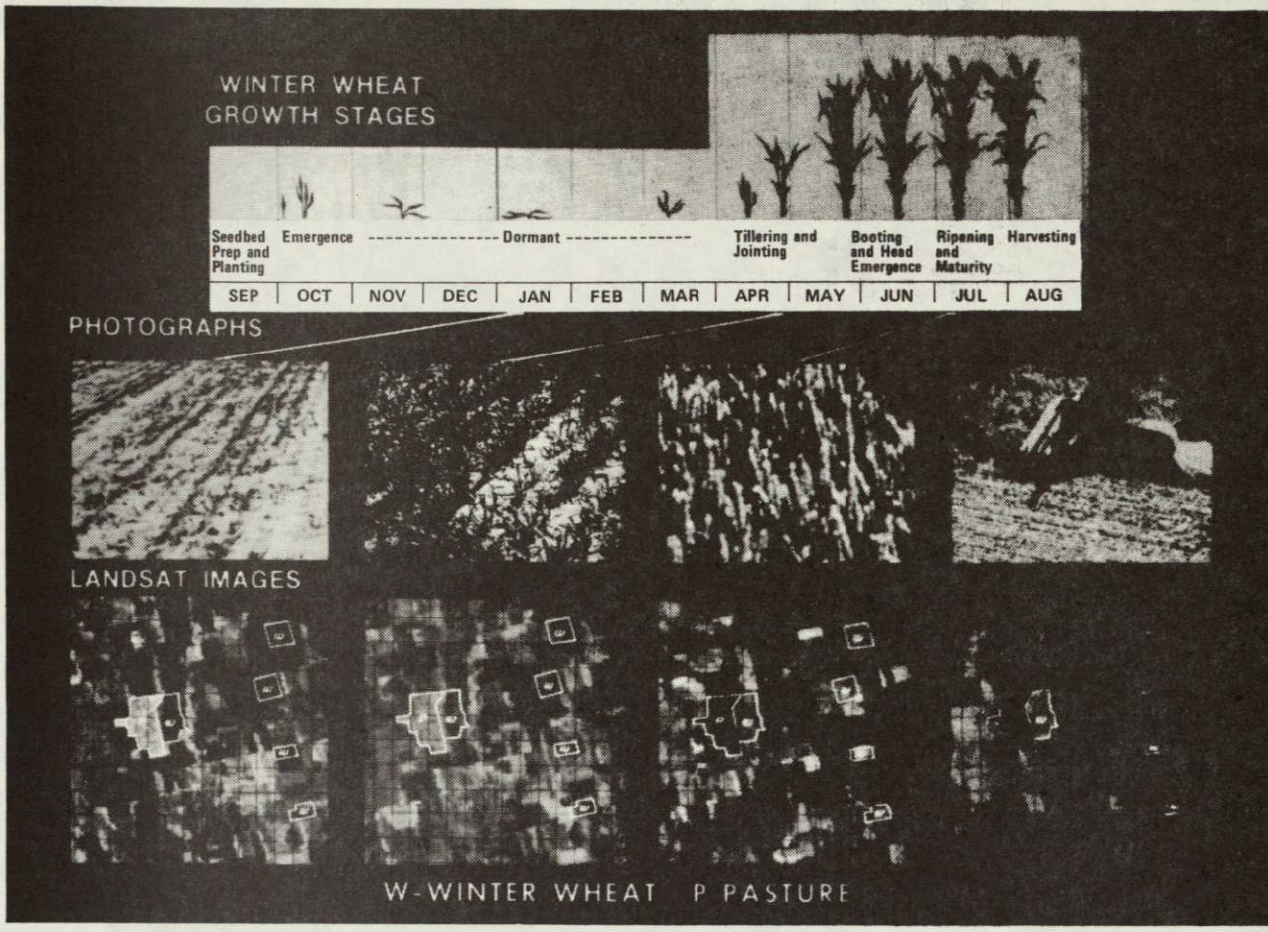

Figure 6.— Variability in the Appearance of Wheat.

Agency (FAA), and by imagery of cloud cover and type acquired by the National Environmental Satellite Service. Preprocessing of this data for the project was assisted through the NOAA Center for Experimental Design and Data Analysis. This primarily involved preparation of temperature and precipitation at individual meteorological stations and representative values over the yield model strata. This data was transmitted to the computers of the National Meteorological Center (NMC) in Suitland, Maryland, (Figure 7).

3.4 Yield Estimation

The wheat yield models utilized in LACIE were statistical regression models based upon recorded historical wheat yields and weather. These regression models forecast wheat yield for fairly broad geographic regions (yield strata) using calendar monthly values of average temperature and cumulative precipitation over the strata, thereby providing monthly updated yield estimates during the growing season. Figure 8 illustrates the factors which influence wheat yields. Along with the required meteorological data, the yield models for each of the model strata were stored on the NMC computers. Operation of the yield models was under the control of the NOAA-CCEA Modeling Division at Columbia Missouri, (Figure 7). After the yield estimates were generated, they were transmitted to the NASA-JSC for input to the wheat production estimation.

3.5 Crop Calendar Models

Models which estimated the current year's growth stage for wheat utilizing meteorological data as input were also implemented on the NMC computers and under the operational control of the NOAA, Columbia, MO, personnel. These models utilized daily values of meteorological data and were run on a biweekly basis for selected meteorological stations in the regions of interest. At JSC, the crop calendar model results were input to a program which interpolated to define a wheat growth stage at the location of the sample segments at the times of Landsat acquisition for utilization by the analysts performing the crop identification and labeling.

3.6 Production Estimation

The wheat production estimation process (Figure 9) involves the upward expansion (aggregation) of the segment level wheat percentages to the yield strata regions where the aggregated area estimates and yield model estimates were multiplied to provide estimates of production. Estimates of production for larger regions are the sum of the appropriate strata level production estimates. The statistical sampling approaches on which the production estimation procedure was designed allow country level production accuracies to be within a few percent while requiring analysis of only 2 to 5% of the total area using the Landsat 5x6 nautical mile sampling segments. Confidence limits on the area, yield, and production estimates were also estimated.

3.7 Accuracy Assessment

The LACIE accuracy assessment effort (Figure 10) was designed to determine the accuracy of the LACIE area, yield, and production results. This assessment was performed both at the large area level (i.e., state, region, country) and at the detailed level (i.e., segment, yield model and lower) in order to isolate problem areas and identify factors to be addressed for potential resolution. Although comparison to USDA and foreign country estimates were made, the primary assessments were made over the USGP "yardstick" region where reliable USDA estimates are available at the state and higher levels, and where collection programs provided information down to the field level for detailed evaluations. This field level data was acquired during Phase II and III for accuracy assessment sample segments representing approximately one-third of the total USGP sample segments. Field data for some selected Canadian segments were also provided. From accuracy assessment results, LACIE was able to identify the sources of error and prioritize issues for further research, as well as to verify procedures and approaches used.

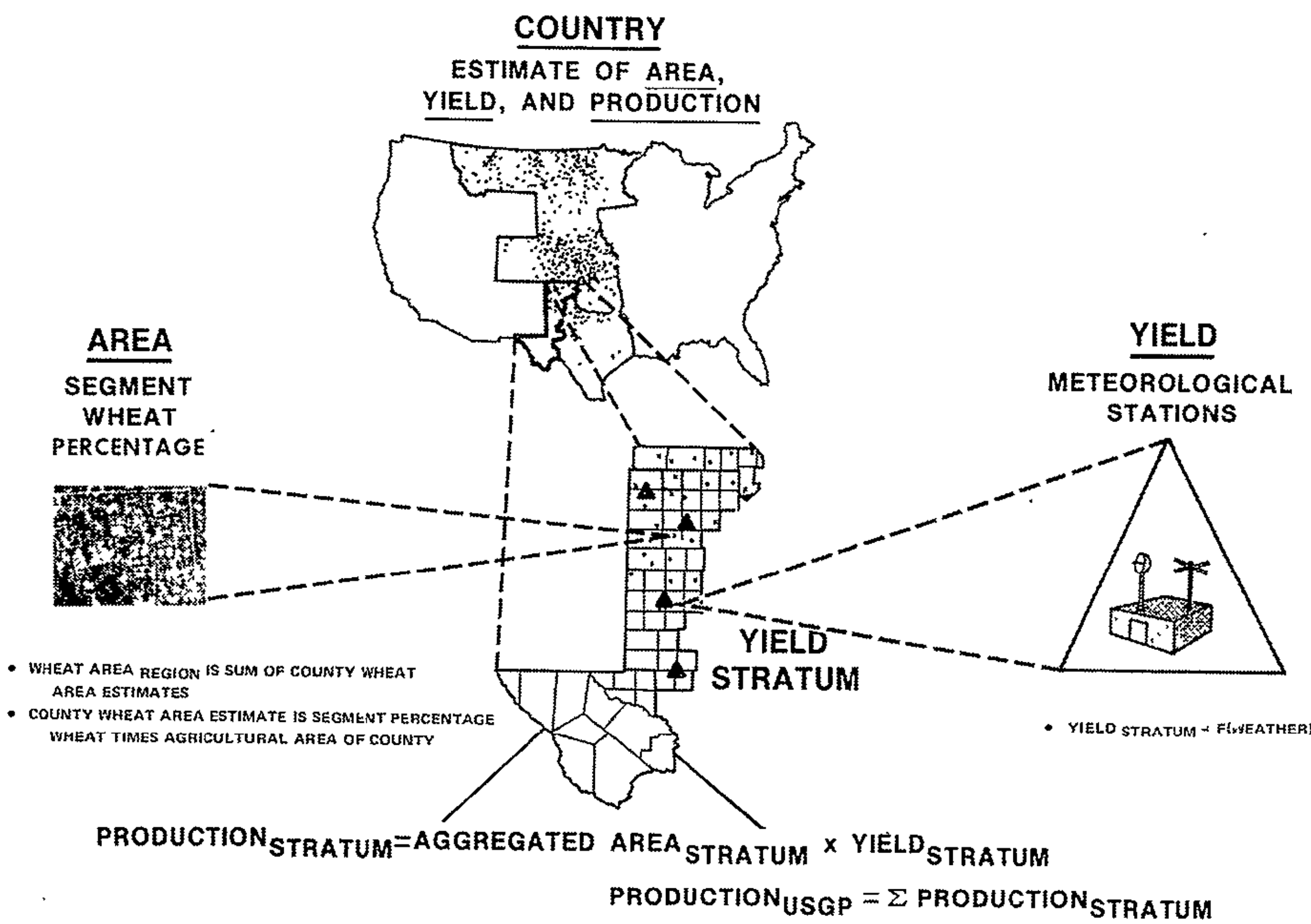

Figure 9.— Production Estimation Procedures

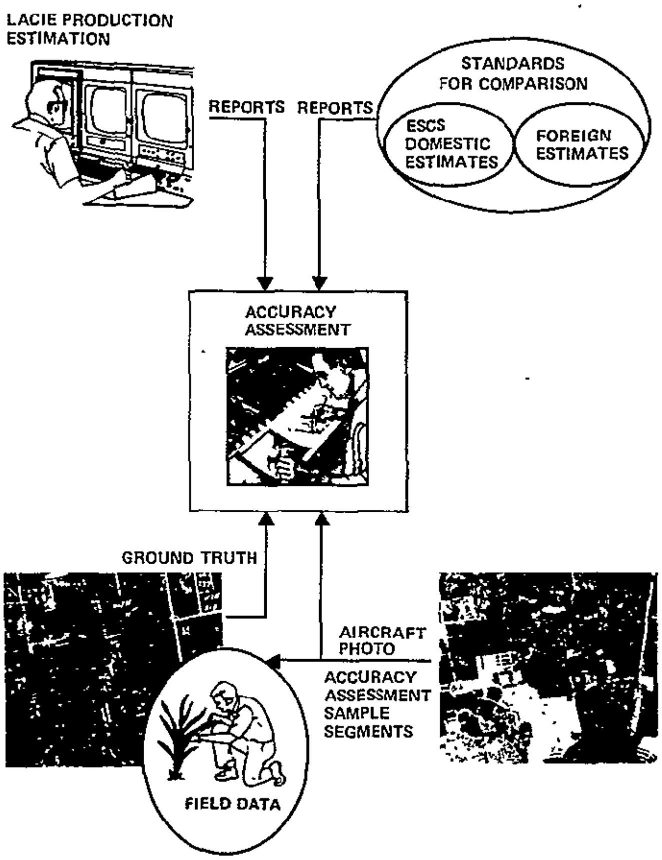

Figure 10.— LACIE Accuracy Assessment.

4. RESULTS

4.1 Accuracy of the Estimates

The experiment established that the technology developed for LACIE met the performance goals for wheat production inventory in important cases. Notably LACIE produced, in August 1977, what proved to be an accurate indication of the USSR spring wheat shortfall. This was well before more definitive information was released by the USSR.

The 1977 Soviet final production estimate released in January 1978 was 92 million metric tons and the LACIE final estimate was 91.4 million metric tons, a difference within 1% as shown in Figure 11. Additionally, two crop years of study in both spring and winter wheat regions of the Soviet Union resulted in estimates that support the experiment performance goals. Compared to historical information, this LACIE achievement represents a significant advance in acquiring an accurate and timely wheat production estimate in an area of great significance.

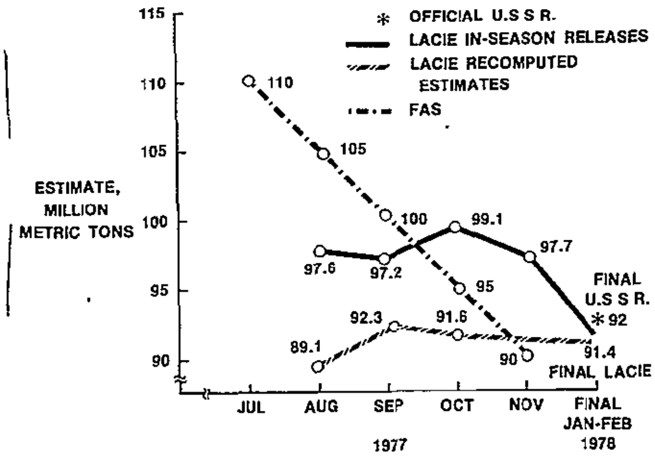

Figure 11.— Phase III USSR Wheat Production.

For comparison, Figure 11 shows USDA projections and LACIE initial and recomputed results. The recomputation involved a simulation of what the LACIE results could have been in a truly operational situation with timely (30 day delay) analyses. These results are extremely encouraging, indicating that USSR results could be within 3% in August, about one and one half months prior to harvest.

The accurate performance of the LACIE estimate in the USSR situation was validated by more intensive evaluation in the U.S. yardstick area. Phase III results in this region support a conclusion that the technical modifications incorporated into the experiment had indeed led to significant improvement from previous Phase II technology in the results from the analysis of Landsat data. The production estimates for the region are compared throughout the season to the "true value" as represented by the USDA Statistical Reporting Service. The LACIE estimates marginally met the 90/90 accuracy goal at harvest and even achieved this one and one half to two months prior to harvest. The results of the area and yield components for the region are shown in Figure 12. It can be noted that, on the average, the acreage estimates were quite good while the yield forecasts tended to be under those of the Statistical Reporting Service. The models were developed with data for the 45 years prior to each of the test years and, when tested on 10 years of historic data, were supportive of the 90/90 accuracy goal. An analysis of the yield model behavior indicates that they generally perform adequately if no significant changes in trend occur and if the average weather conditions for a region are not drastically different from the historic data used in their

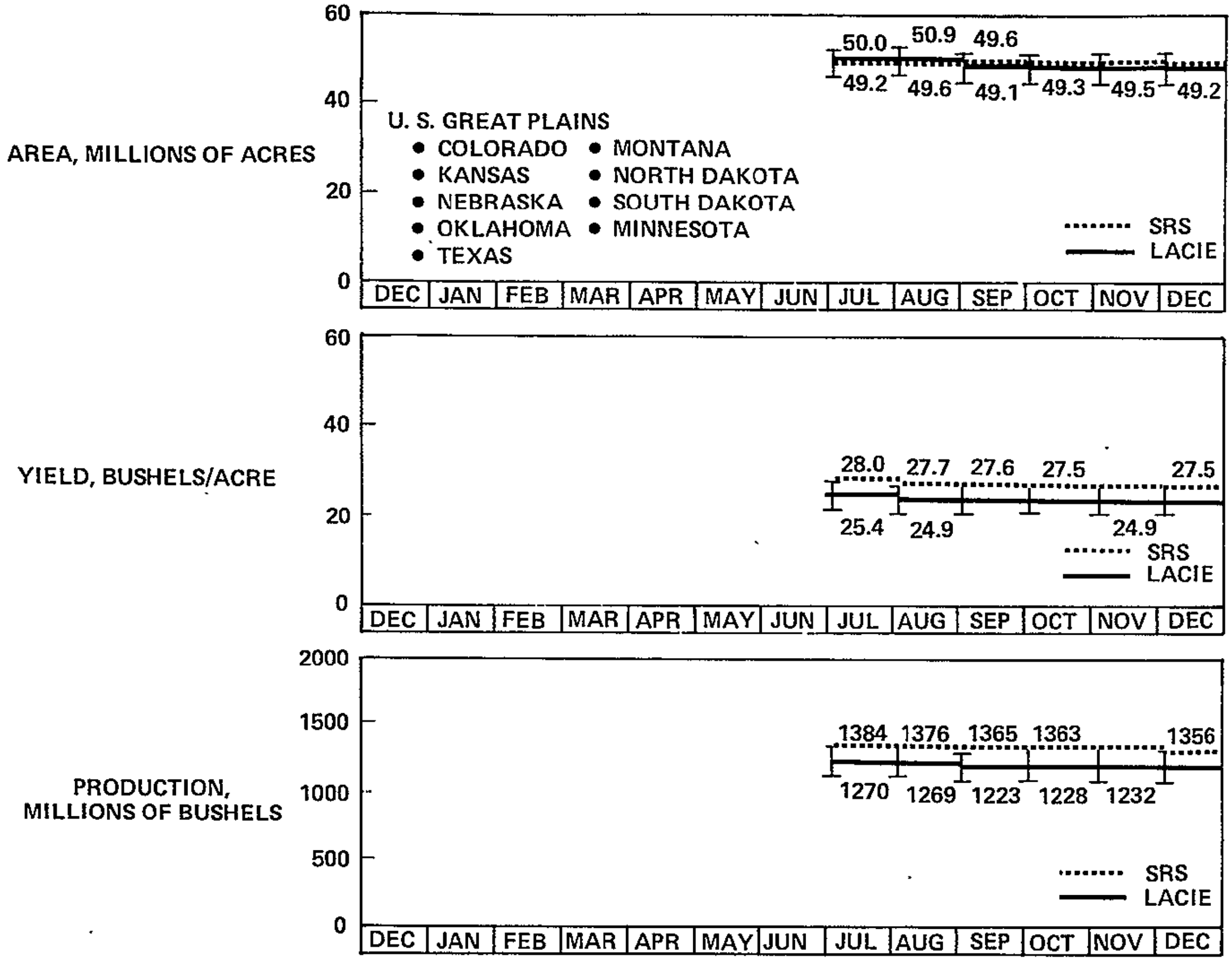

Figure 12.— Monthly Comparisons of LACIE and SRS Estimates, U.S. Great Plains, Phase III.

development. Where extreme departures from normal weather do occur, the models tend to respond in the right direction but do not capture the extent of the excursion. However, as could be seen in the Phase III USSR spring wheat regions these models did perform adequately in a departure from normal which, while not extreme, was of great importance to the U.S. and other countries. The Phase III results for production, area and yield in the "yardstick" winter wheat region of the U.S. generally support the results achieved in the USSR.

The results in the strip/fallow areas of spring wheat regions of the U.S. exhibited a tendency to underestimate the spring small grains. Econometric ratio models, developed in Phase II and used to estimate the spring wheat from the LACIE estimates of small grains, worked well for the region. As indicated above, the yield models tended to underestimate the expected values of the yields at harvest. The area estimates were less than 1% under as compared to the 10.7% underage experienced in Phase I and the 14% underage of Phase II. Figure 13 displays the results for Phase III spring wheat. If the major differences between the spring wheat regions of the yardstick area and the USSR are taken into consideration, the yardstick results are supportive of what was observed in the USSR results in Phases II and III. That is there is nothing inherently difficult about spring wheat and it can be estimated accurately under the right conditions.

In general, if the yield models had performed as they did in Phases I and II, and on the average in the 10 year test, the 90/90 accuracy goal would have been exceeded in the yardstick region. It is also concluded that in regions where the minimum field dimension tends to be similar to the Landsat spatial resolution, the estimates tend to be low. More recent results are indicating that spring wheat can be differentiated from spring barley during the wheat soft dough stage.

Considerably more research will be required to accomplish this reliably. However, LACIE investigators are optimistic that with Landsat D considerable improvement will be possible in these more difficult regions.

As an example of the progress achieved in obtaining improved wheat estimates, Figure 14 compares the LACIE segment wheat proportion estimates with ground truth for Phases II and III. This data indicates a significant improvement in the proportion estimates derived from Landsat using the Phase III procedures and supports the improved aggregated results previously described for the total region.

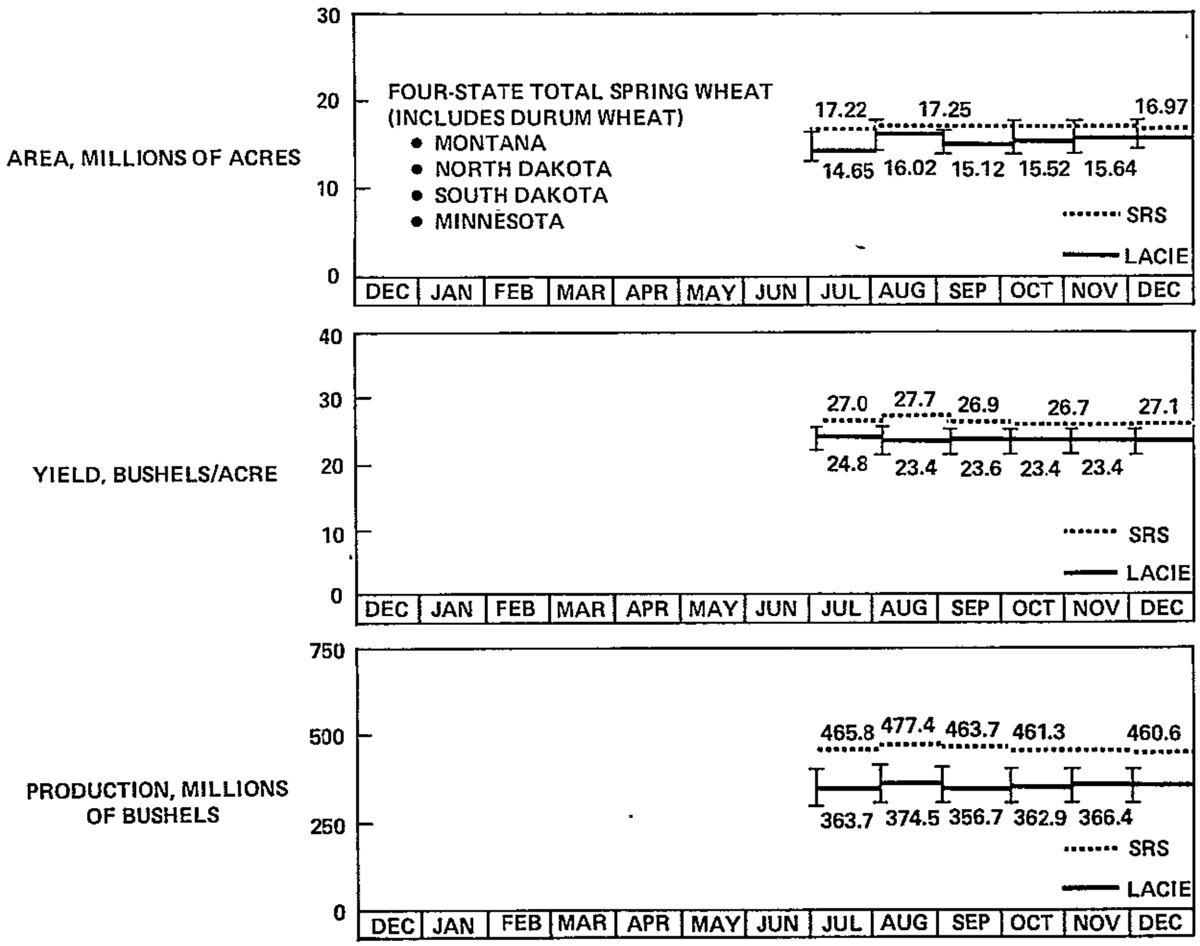

Figure 13.— Monthly Comparisons of LACIE and SRS Estimates, U.S. Spring Wheat, Phase III.

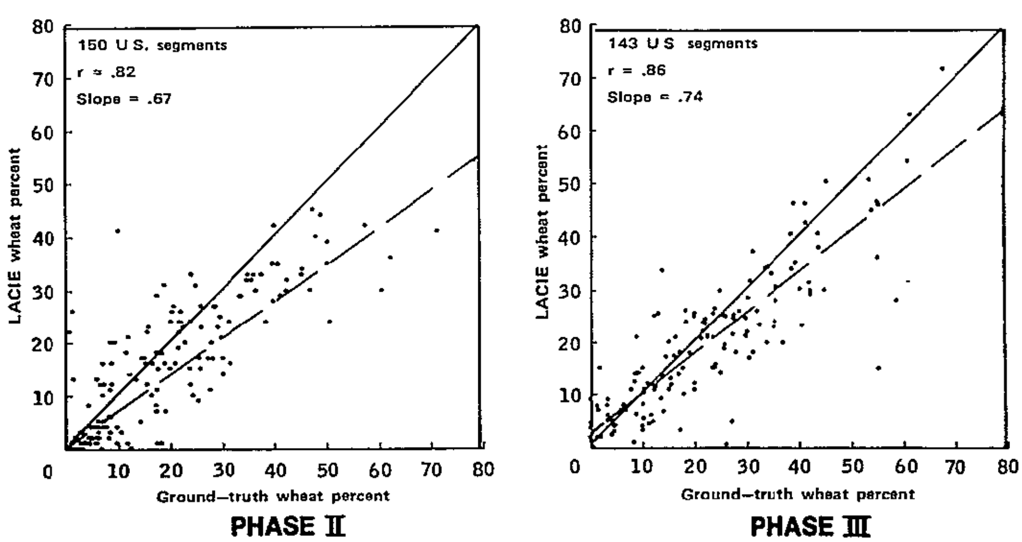

Figure 14.— Comparison at Phase II and Phase III U.S. Estimates with Ground Truth.

4.2 Transfer of the Technology

A decision was made by USDA early in 1976 to initiate an additional activity to develop a data analysis system to transfer and exploit the emerging LACIE technology for USDA use. This prototype was approved in January of 1976 to serve as the vehicle for the transfer of technology from applied research to an application test within USDA.

The goal of this activity was to develop the basic analytical capabilities, hardware and software to support the testing and evaluation for USDA use of the technology developed during LACIE. This USDA-led effort within the LACIE involved the active participation by NASA and NOAA in providing assistance in the transfer of technology from LACIE to the USDA user system.

5. CONCLUSIONS AND OUTLOOK

LACIE was a carefully conducted experiment designed to research, develop, apply and evaluate a technology to monitor wheat production in important regions throughout the world. LACIE utilized quantitative multispectral data collected by Landsat in concert with current weather data and historical information. The experiment exploited high-speed digital computer processing of data and mathematical models to extract information in a timely and objective manner.

The totality of results from the three crop years of focused experimentation strongly indicated that:

- o The current technology can successfully monitor wheat production in regions having similar characteristics to those of the USSR wheat areas and the U.S. hard red winter wheat area.

- o With additional applied research, significant improvements in capabilities to monitor wheat in these and other important production regions can be expected in the near future.

- o The remote sensing and weather-effects modeling approach followed in LACIE is generally applicable to other major crops and producing regions of the world.

Note: Between the delivery of these lectures at the Ispra Advanced Seminar on Applications of Remote Sensing in Agriculture and Hydrology in November/December 1977, and the preparation of this paper for publication, some additional analysis of results was conducted and, in January of 1978, the official USSR production figures were released. Accordingly, these final Phase III results were included for the sake of completeness. Further, extensive documentation of the experiment was accomplished and papers thereon presented at a LACIE Symposium. References to the symposium documentation are included for the reader who may wish more detail.

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