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An Overview of the Large Area Crop Inventory Experiment and the Outlook for a Satellite Crop Inventory

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AN OVERVIEW OF LACIE AND THE
OUTLOOK FOR SATELLITE
CROP INVENTORY

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ABSTRACT

The purpose of the Large Area Crop Inventory Experiment (LACIE) was to assimilate remote sensing technology into a "proof of concept" system for estimating wheat production and demonstrating the technical and cost feasibility of satellite remote sensing for agricultural monitoring.

During the 40 months from late 1974 through 1977, LACIE expanded from localized acreage testing to global-scale monitoring of both acreage and yield.

LACIE advanced, in a major way, the application of aerospace remote sensing and weather effects modeling for crop inventory. Further, it has established the applicability of this technology to global wheat-production estimation.

On the basis of the LACIE experience, the technological prospects for crop inventory over the next few years are encouraging. However, improvements in the effectiveness and availability of the technology are needed for the potential of agricultural remote sensing to be realized.

This paper describes the LACIE background and experience and comments on the prospects for future crop inventory systems utilizing spacecraft technology remote sensing technology and computer technology on a global scale.

INTRODUCTION

The Agro-Economic Situation

Agricultural production is highly dynamic and depends on complicated interactions of prices, weather, soils, and technology.

Wheat, the most important internationally traded crop is particularly subject to these dynamics. It is planted, harvested, and grown throughout the year in various regions of the world. Much of it is grown in semi-arid, marginal climates. It is cultivated with technology ranging from very primitive to advanced. Thus, production is subject to extreme variations. The world's wheat supply has fluctuated from the critical deficiencies of the 1972, 1974 years to the apparent oversupplies of the current period. Both of these conditions have had severe economic impact.

Leaders of most industrial and developing nations acknowledge that global agricultural planning is a minimum requirement in assuring adequate food supplies at an equitable price. It follows that this planning requires timely and accurate global crop forecasts and that such forecasts entail a global agricultural monitoring system.

Experiment Overview

The basis for LACIE was established in 1960 by the Agricultural Board of the National Research Council. By late 1962, experiments to examine the feasibility of multispectral remote sensing for agricultural crop monitoring were designed. An organized research program was established by the United States Department of Agriculture (USDA) and the National Aeronautics and Space Administration (NASA) in 1965. The program progressed from successful computer recognition of wheat using multispectral measurements collected with aircraft in 1966 to development and testing of a satellite technique by 1972.

The design and initiation of LACIE in 1973-1974 followed directly from feasibility investigations conducted with the Earth Resources Technology Satellite (ERTS). (The ERTS was renamed Land Satellite 1 [Landsat 1]. The second and third earth resources satellites Landsats 2 and 3 are now in orbit.)

LACIE, a joint program between NASA, USDA, and NOAA, was designed to test the use of remote sensing to estimate wheat production over important producing regions of the world. Three major goals were established:

1. An accuracy goal that the at-harvest estimates should be within 10 percent of the true estimate at the national level 90 percent of the time.

2. A timeliness goal to establish the feasibility of acquiring and analyzing Landsat data within a 15-day interval.

3. An additional performance goal was to determine how early in the crop year accurate estimates could be produced. Estimates were to be made with repeatable and objective procedures.

The experiment was conducted in three phases. In Phase I, the technology to estimate the proportion of regions planted to wheat was implemented and tested in the U.S. Great Plains (USGP). Similarly, a technique to estimate the yield from specific areas was developed and tested. In Phase II, the technology as modified during Phase I was further tested over expanded geographic regions, the USGP again, Canada, and two indicator regions in the U.S.S.R. In Phase III, the modified technology was tested and evaluated over a still wider range of geographic conditions including all of the wheat-growing region of the U.S.S.R. Further, exploratory analyses were conducted for Australia, China, India, Brazil, and Argentina to gain experience with conditions in these areas. Figure 1 shows the areas studied in LACIE.

The major elements of LACIE were (1) a quasi-operational element to acquire and analyze Landsat and meteorological data to make experimental estimates of production; (2) an independent element to test and evaluate alternative approaches as required to meet the performance goals of the experiment; and (3) an element to research and develop alternative approaches.

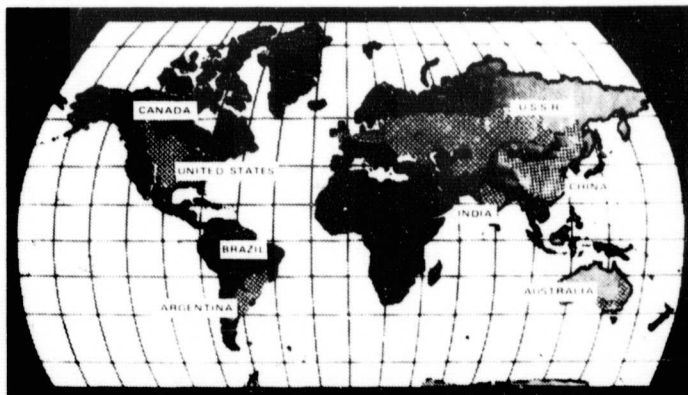


Figure 1.- Wheat producing areas considered in LACIE.

The major components of the quasi-operational element of the experiment include the Landsat and its acquisition and preprocessing subsystems; the World Meteorological Organization (WMO) weather reporting system; the NOAA development and operational facilities in Washington, D.C., and Columbia, Missouri; and the analysis, compilation, and evaluation activities by personnel from USDA, NASA, and NOAA at the NASA Johnson Space Center (JSC) in Houston, Texas. The experiment also drew significantly on the expertise of university and industrial research personnel.

THE LACIE TECHNICAL APPROACH

LACIE estimated production of wheat on a region-by-region basis. Area estimates were derived by classification and mensuration of Landsat multispectral scanner (MSS) data. 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 the sampling and aggregation strategy. It efficiently allocated segments to be imaged by Landsat

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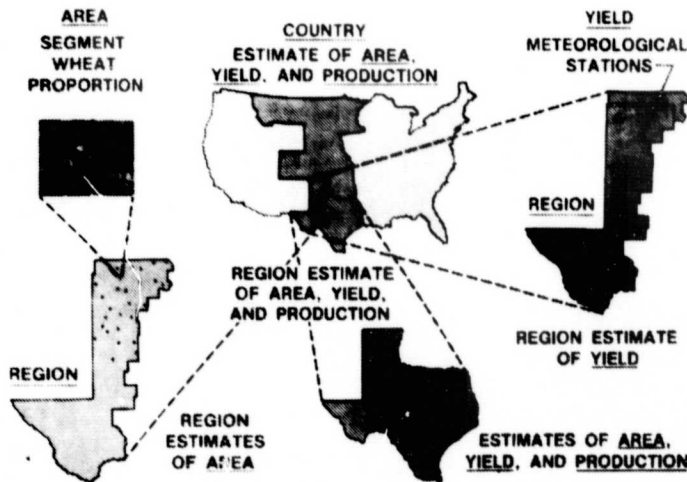


Figure 2.- Sampling and aggregation strategy for production estimation.

and analyzed for wheat proportion. It defined the strata boundaries for the wheat yield models, and formulated the upward expansion (aggregation) model for the area and yield estimates to regional and country estimates of production (fig. 2). These aggregations resulted in experimental commodity reports of wheat area, yield and production. These reports were then submitted 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.

Landsat Data Acquisition

The sampling strategy defined the locations of the segments (5 x 6 n.m.) over which Landsat data were acquired each 18 days during the crop season (fig. 3). Data were normally transmitted to ground receiving stations at Maryland, Alaska, or California either in real-time or by use of the on-board tape recorders. However, other ground stations were also 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 were 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.

Analysis for Area Estimation

The analysis of the Landsat data was performed at the JSC (fig. 4) where procedures were designed and personnel were trained to perform a 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 (fig. 5). The assembled Landsat data products included full-frame color IR

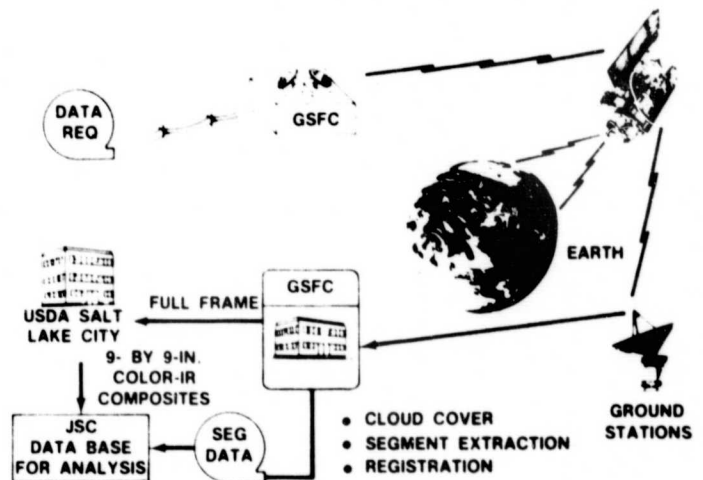


Figure 3.- Landsat data acquisition for area estimation

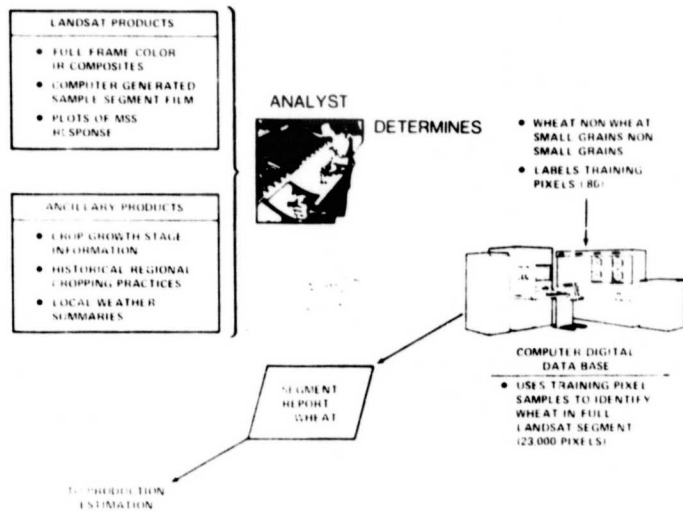


Figure 4.- LACIE analysis for wheat area determination.

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 (pixels) as being

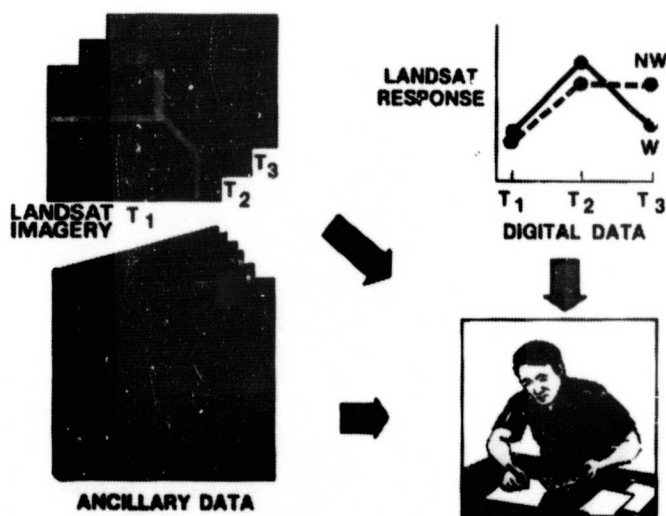


Figure 5.- Data used in analyst labeling.

either wheat or non-wheat or small grains or non-small grains. This labeling was strongly based on the variability 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 (22,932 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.

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, D.C., 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 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, (fig. 6).

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 percent of the total area using the Landsat 5 x 6 nautical mile sampling segments. Confidence limits on the area, yield, and production estimates were also estimated.

Accuracy Assessment

The LACIE accuracy assessment effort (fig. 9) 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

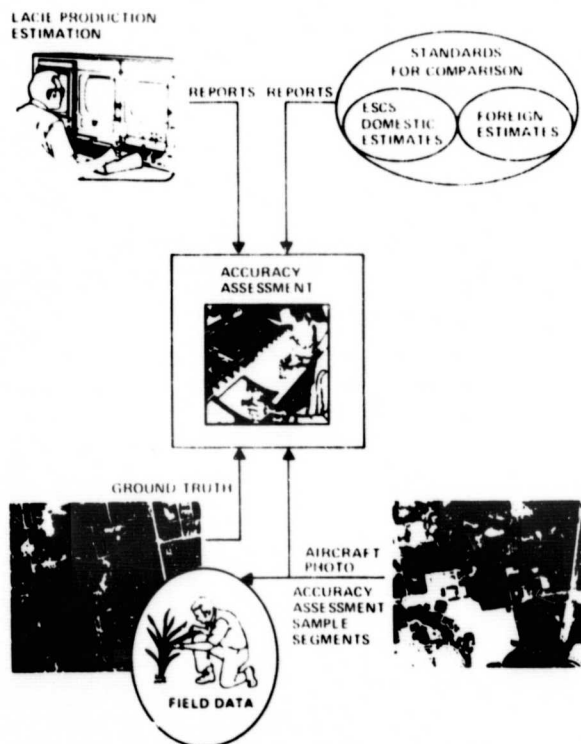


Figure 9.- LACIE accuracy assessment.

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 (fig. 10). This field level data was acquired during Phases 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 10.- Accuracy assessment comparison levels.

RESULTS

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 U.S.S.R. spring wheat shortfall. This

was well before more definitive information was released by the U.S.S.R.

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 percent 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.

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 U.S.S.R. results could be within 3 percent in August, about 1-1/2 months prior to harvest.

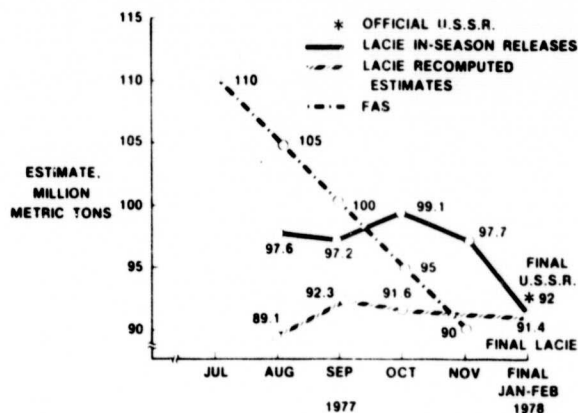


Figure 11.- Phase III U.S.S.R. wheat production.

The accurate performance of the LACIE estimate in the U.S.S.R. 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 (of ESCS). The LACIE estimates marginally met the accuracy goal at harvest and even achieved this 1-1/2 to 2 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

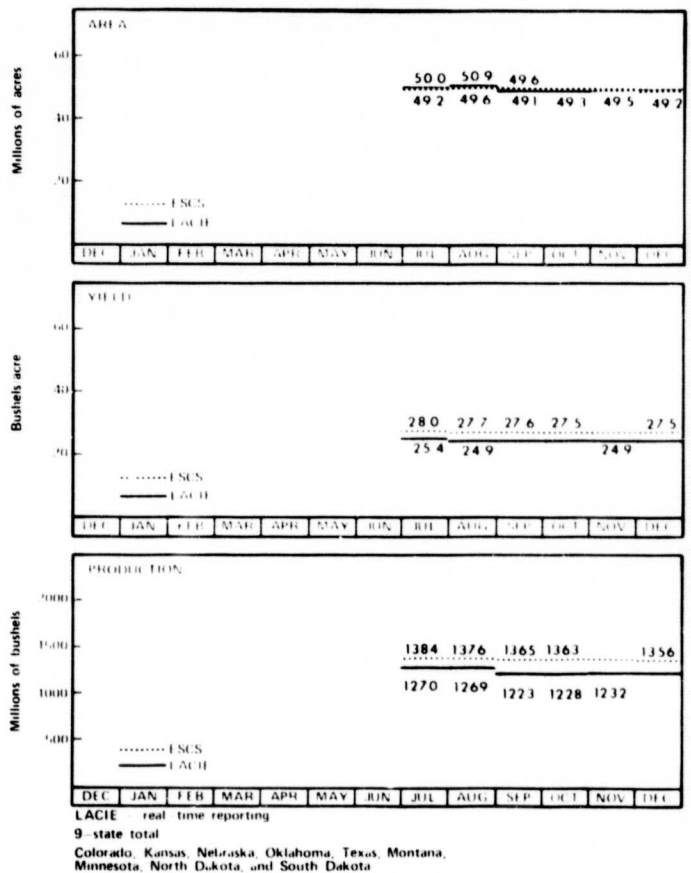


Figure 12.- USGP Phase III results.

planned 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 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 U.S.S.R. spring wheat regions, these models did perform adequately in a departure from normal which, while not extreme, was of great importance to the United States and other countries. The Phase III results for production, area and yield in the "yardstick" winter wheat region of the United States generally support the results achieved in the U.S.S.R.

The results in the strip/fallow areas of spring wheat regions of the United States 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 percent under as compared to the 10.7 percent underage experienced in Phase I and the 14 percent 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 U.S.S.R. are taken into consideration, the yardstick results are supportive of what was observed in the U.S.S.R. 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 accuracy goal would have been exceeded

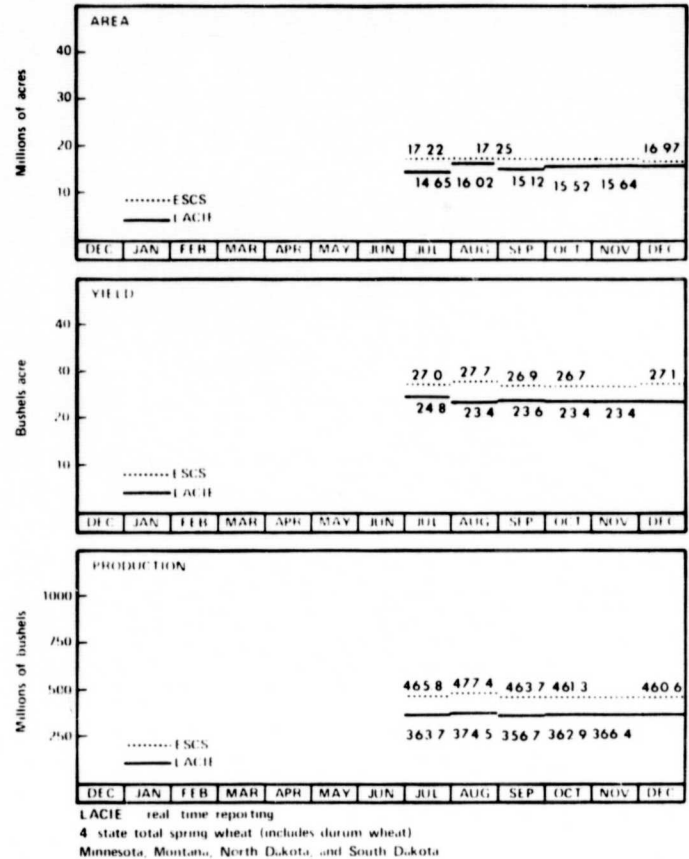


Figure 13.- U.S. spring wheat results.

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

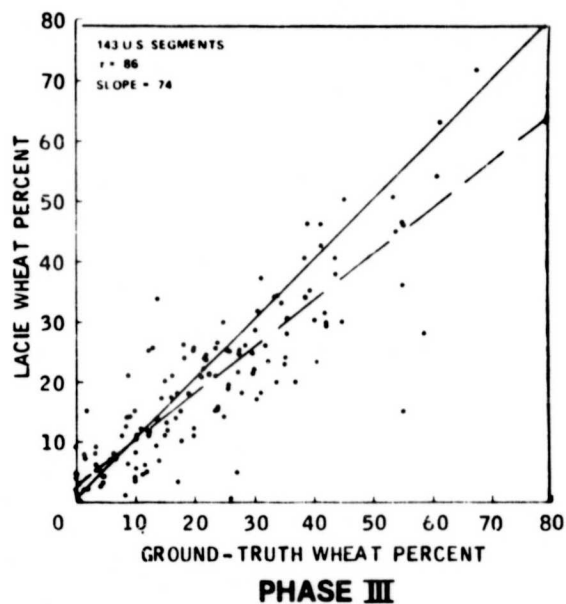
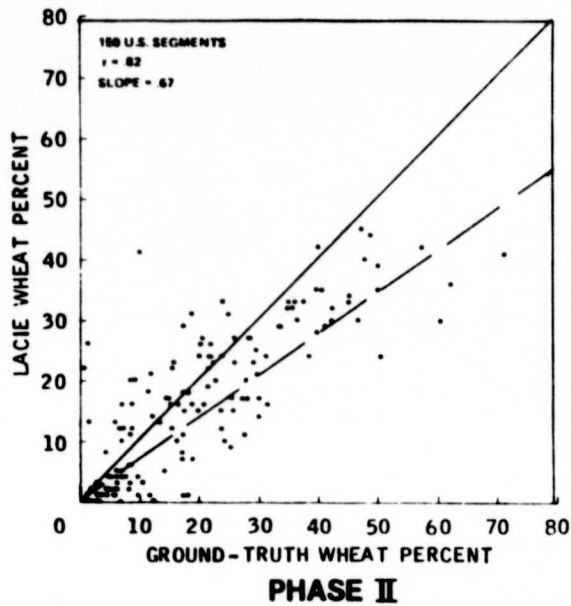


Figure 14.- Accuracy of LACIE area estimates.

estimates derived from Landsat using the Phase III procedures and supports the improved aggregated results previously described for the total region.

MAJOR LACIE FINDINGS

The most important LACIE finding was that the technology worked very well in estimating wheat production in important geographic regions. LACIE produced an accurate estimate of the U.S.S.R. spring wheat shortfall in August 1977, and 2 years of study in both spring and winter wheat regions of the U.S.S.R. resulted in estimates that supported the experiment performance goals. The confidence in this success was reinforced by the accuracy of the production estimates in the U.S. hard red winter wheat region during 3 years of study. Exploratory investigations made in other countries show that the current technology may be applicable to some countries (Australia, Argentina, and possibly Brazil) but may require improvement in others (China and India).

A major goal of LACIE was to identify the technological issues related to wheat-production estimation and to provide a better understanding of the significance of these issues. LACIE did provide, as called for in the experiment design, an identification of technology issues that, when resolved, could significantly improve the technology for wheat inventory. In addition, specific approaches for the resolution of many of these issues have been identified.

A significant result of the experiment was the development of an improved scientific base on which production estimation studies for other crops could be pursued. An accomplishment of LACIE was the development of methodologies for sampling, for computer-aided spectral discrimination, for yield modeling, and for accuracy assessment. These methodologies provide a basis for studying other crops. The parameters involved in estimating production for other crops are far more complex. The task will not be easy, but the technology base produced in LACIE will provide a sound starting point.

The LACIE was the first demonstration of the operational potential of using satellite spectral and weather data for global crop production estimation, and the experiment demonstrated that a system could be engineered to provide timely production estimates. The self-imposed LACIE practice of deferring the release of production estimates until 120 days after report generation was simply to ensure that experimental results from LACIE would not be confused with official estimates.

The LACIE effort resulted in many technological improvements in the application of satellite and weather data: global sampling using the Landsat data, a production estimation technology using area and yield components, an area estimation technology of acceptable accuracy accomplished *without* the use of ground data, and crop yield estimation technology of acceptable accuracy. Further, the execution of LACIE resulted in several significant lessons about the planning, management, and implementation of crop-monitoring technology development programs. The major lessons were that

1. Research, development, and evaluation require several years of testing with large data sets over extensive geographic regions to verify technological issues resulting from the wide range of variability of the contributory factors.

2. A comprehensive accuracy assessment effort is vital, and considerable ground data for the regions under investigation are essential to the understanding of the experimental results and to the identification and correction of deficiencies in the technology.

3. A research and development program involving diverse scientific disciplines focused on technical issues arising from a project similar to LACIE stimulates more applied research activity and provides an improved and common understanding in the supporting research and industrial community.

4. The periodic use of a peer review, in which critical issues on methodology and results are subjected to the scrutiny of independent reviewers, provides essential feedback.

IMPROVEMENTS NEEDED IN THE TECHNOLOGY

There were, of course, shortcomings in the technology tested in LACIE. There were issues which were not resolved during the experiment. They must be resolved to expand the usability of LACIE technology for wheat inventory in other important geographic regions. The application of the technology during LACIE was less successful in Canada than in the United States or the U.S.S.R. The causes are reasonably well understood. Because of crop planting practices (i.e., strip farming) the effective field size is typically close to the present satellite resolution limits (fig. 15). Also, Canadian spring wheat is grown in proximity to other crops which are spectrally similar. More recent work on spring wheat in the U.S. Great Plains indicates that these problems can be overcome.

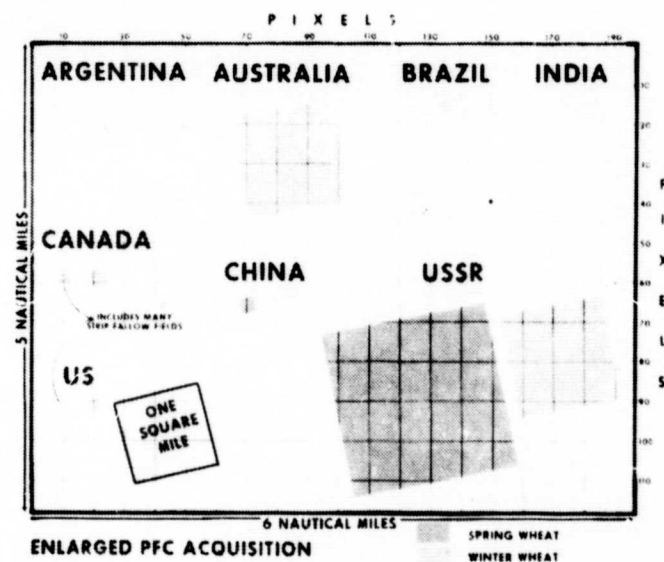


Figure 15.- Average field sizes for LACIE countries.

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Other difficulties arose in crop years that showed extreme departures from normal; the result was estimation errors in both yield and area estimation. In some cases, historical data with which to build the data bases for the yield models were poor to non-existent. To overcome these problems, improvements in sensor resolution, area estimation technology, and yield models will be required. Although these issues are far better understood because of LACIE, the usefulness of the current LACIE total system inventory technology will be limited to areas with moderately large fields and adequate historical data until these issues are resolved.

AVAILABILITY OF THE TECHNOLOGY

At this stage of technology development, there is a logical question about whether the present capability is generally available. Until Landsat-D is launched, it could be available to the U.S. Government or to other governments with access to Landsat ground stations covering their own country. Because of the tape-recorder limitations of the current Landsat spacecraft system, reliable and timely availability of the data for all potential users cannot be guaranteed. Although the weather data are routinely available through the World Meteorological Organization for input to yield models, the nonavailability of Landsat data on either a temporal or geographical basis would have significant impact on local or regional production estimates. LACIE has clearly demonstrated the important interrelationship of yield and acreage (in local agrophysical regions) in estimating production before aggregation to obtain regional or national crop production estimates. The nonavailability of adequate historical data on some crops in certain areas of the world would also limit the use of current yield models.

Although the total technology may not be available, parts of it are currently being used by the U.S. Federal Government.

Examples are the efforts to use early warning indicators of wheat production changes and test use for augmenting U.S. domestic local statistics by the USDA. In addition, several private and commercial firms are using portions of the technology for the United States and other nations, notably weather-driven yield models and assessments of weather episodic effects. Because of limitations on the availability of timely Landsat data as mentioned previously, acreage estimation technology is only being used in a research and development (R&D) environment and as a tool to train future commercial and government users. As to the more general availability of the LACIE technology, one must look from a practical viewpoint to the Landsat-D time frame. The current plans for that spacecraft include a multispectral scanner and rely on the incorporation of the Tracking and Data Relay Satellite System (TDRSS) into the data transmission loop to overcome the current tape-recorder limitations. Also, by the time of the Landsat-D launch, improved distribution systems will be available for more timely dissemination of the Landsat data.

The evolution of the Landsat-LACIE program has an analog in the environmental satellite program. A comparison between the time phasing of these two programs is shown in figure 16. As can be noted, the environmental satellite program really started with the launch of TIROS-1 in 1960. In its early stages, this program had problems very similar to those of Landsat. A new source of raw data, completely different from any source previously available, was provided to users. New models and analysis procedures had to be developed and tested, first on a limited basis and then on an operational scale, before the users could incorporate the new data into their decision models. In the early stages, analysis techniques and distribution systems were rudimentary and the applications were simple. As the program developed, various stages of operational systems and subsystems were developed, evaluated, and implemented.

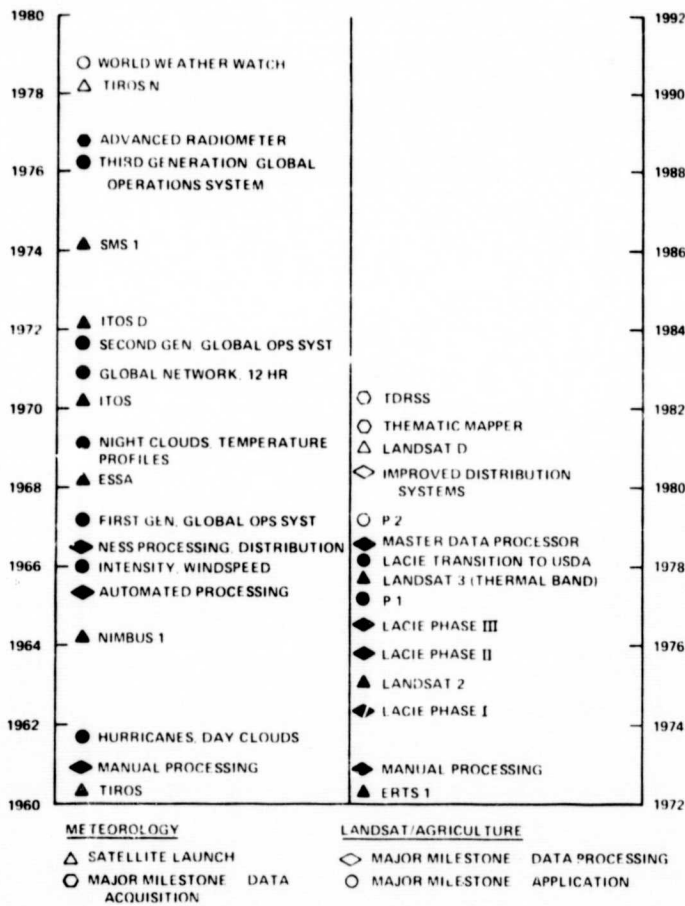


Figure 16.- Remote sensing applications in major space programs.

Now, some 19 years later, NOAA is looking toward the establishment of a world weather-reporting system. Assuming a similar time scale for Earth resources agricultural applications and working from the launch of Landsat-1 in 1972, one can look forward to a global agricultural information system in the late 1980's or early 1990's, if national priorities allow the needed support. Figure 16 also shows a lack of planned Landsat-type components beyond the early 1980's. However, one can easily correlate the feasibility of developing the necessary Landsat data acquisition, transmission, and distribution technology with that accomplished by the environmental satellite program within a similar time frame.

This issue is not solely technical but also includes policy and institutional considerations. Current legislative and executive matters must be resolved to enable the application of the technology to meet its potential.

LACIE has identified several technical issues and shortcomings that need to be addressed. Problems in need of special attention in the future include the following.

1. Yield models that are based on daily or weekly rather than monthly averages of temperature and precipitation and that closely simulate critical biological functions of the plant and its interactions with the external environment must be formulated to provide a yield response of greater fidelity to a wider range of conditions than present models.

2. Analysis techniques are needed to deal more effectively with the spatial information in Landsat data and to improve area estimation accuracies in regions having a high percentage of fields with sizes near the resolution limit of Landsat. Additionally, the anticipated improvements in area estimation resulting from the increased resolution of Landsat-D and spatial resolution requirements for future Landsats must be investigated.

3. Landsat coverage at more frequent intervals than every 18 days may be needed, as well as the addition of spectral channels to identify vegetation stress more reliably and to differentiate crops of interest from confusion vegetation more reliably. Also, the additional spectral channels of Landsat-D must be evaluated together with definition of recommended spectral channels for future Landsats.

4. A special challenge is assessment of crop production in tropical regions. Crop varieties tend to be significantly different and crop growing conditions tend to depart radically from those experienced in the temperate zones.

5. The effects of cloud cover as it prevents the acquisition of usable Landsat data at critical periods in the crop season need

to be better quantified, particularly in more humid environments, such as the U.S. Corn Belt.

6. The trade-offs between the need to shorten the time between data acquisition, analysis, and reporting and the costs of obtaining such shortened response need to be evaluated. While considerable improvements can be made, considerable costs may be required to obtain them.

With development of solutions to these specific technical issues, testing over other significant geographic regions will be required. It can be safely assumed that this technology will not evolve automatically but that it needs to be purposely pursued. It will require a substantial commitment to a research, development, and evaluation program covering the full range of variability present in the important growing regions of the globe. The LACIE experience has shown that it requires a positive dedication on the part of the involved parties to this type of experimentation to gain the desired results.

CONCLUSIONS

In summary, based on working through the many successes and the shortcomings of LACIE, it can be stated with confidence that

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

2. 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.

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

4. With suitable effort, this technology can now advance rapidly and could be in widespread use in the late 1980's.