

CHAPTER 8

The LACIE Experiment in Satellite Aided Monitoring of Global Crop Production

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ABSTRACT

The Large Area Crop Inventory Experiment (LACIE) demonstrated that improved accuracy in USDA predictions of wheat production can be achieved for the US Great Plains by the use of satellite imagery. LACIE experimenters also used their technique to predict with great accuracy the size of the 1977 Soviet wheat crop six weeks prior to harvest. This paper discusses the experiment as a potential model for other programmes designed to measure globally other terrestrial plant communities by remote sensing from satellites.

8.1 INTRODUCTION

The Large Area Crop Inventory Experiment (LACIE) was carried out by the National Aeronautics and Space Administration (NASA), the US Department of Agriculture (USDA) and the National Oceanic and Atmospheric Administration (NOAA). The objective was to develop and test a method for estimating production of wheat worldwide. The experiment was intended:

- (1) To demonstrate an economically important use of repetitive, multispectral, remote sensing from space;
- (2) To test the capability of the LANDSAT, together with climatological, meteorological and conventional data sources, to estimate in advance the size of an important world food crop;
- (3) To validate techniques that can provide timely estimates of crop production.

The basic approach used in the experiment was to combine estimates of the land area planted in wheat with estimates of yield per unit area. Estimates of area were derived from LANDSAT data on selected segments of land, estimates of yield were obtained from models which relied on weather data from the World Meteorological Organization. The experiment included

computer processing of data and the use of mathematical models to obtain information in a timely manner.

In August 1977 the experiment produced what later proved to be an accurate estimate of the shortfall in the Soviet spring wheat crop. This observation was well before definitive information about the crop was released by the USSR. In addition, analysis of spring and winter wheat production in the Soviet Union during two other crop years resulted in estimates that supported the experiment's goals for performance. The success of the LACIE experiment was reinforced by accurate estimates of production in the US winter wheat region for three crop years.

The experiment was less successful in predicting Canadian wheat production, but the reasons are well understood. They were that effective field size in Canada was often very close to the resolution limits of the LANDSAT, and that spring wheat is difficult to distinguish from certain other crops.

LACIE resulted in the development of a technique for estimating overall wheat production on the basis of area and yield estimates, a technique of acceptable accuracy for estimating crop area without the use of ground data, and a technique of acceptable accuracy for estimating crop yields.

Refinements of the procedures for analysing LANDSAT data can further improve the satellite's accuracy in identifying land area planted in wheat. Yield models may be improved by utilizing LANDSAT data together with weather data to better define the crop's response to natural conditions. Models that estimate the crop's stage of development can also be improved to provide data that will help to distinguish wheat from similar crops (such as barley) and thus also lead to improved forecasts.

LACIE was a timely response to an identified national need and to a specific need. It was the culmination of more than a decade of research and development, it assembled a special array of people and equipment, and it was rigorously tested on a large scale. LACIE's encouraging results have led to further efforts to determine the requirements of the USDA and other users and to extend the capability to other important questions.

The experiment was initiated in 1974 to assimilate remote sensing by satellite and its associated communications techniques into an experimental system and to use that system to make production estimates of important crops. Wheat was selected for the experiment both because of its economic importance and because it would fit well with the evolution of space technology. Wheat is grown on huge areas of the United States and the Soviet Union as well as on smaller plots in India and China. It is grown in some part of the world on every day of the year. As well as being one of the least complex crops from an agricultural standpoint, wheat was also one of the crops most amenable to remote sensing. It seemed likely that techniques developed to predict wheat production more accurately might be adaptable to other crops.

Agricultural production is highly variable, since it is dependent on the

complicated interactions of weather, soils, technology, and other factors. The agricultural outlook can and usually does change as these ingredients are altered, either by natural forces or as a result of human decisions.

To forecast agricultural production accurately, it is vital to associate the correct weather with the actual crop area being affected. When the effects of the weather are so severe as to remove an area from agricultural production, the area must be correctly measured. Therefore, an agricultural information system must monitor not only the total area harvested but also the proportion of the area rendered worthless from an agricultural standpoint by weather extremes.

8.1.1 The Background of LACIE

In 1960 the Agricultural Board of the National Research Council recommended the formation of a committee to investigate the potential ability of aerial surveys to monitor agricultural conditions over large geographic areas. An interdisciplinary group of scientists was then selected to serve on the Committee on Remote Sensing for Agricultural Purposes, and by late 1962 the Committee had designed experiments to examine the feasibility of using multispectral remote sensing to monitor crop production. This step was followed in 1965 by the establishment of an organized research programme, by the USDA and NASA. The programme led, from the creation of the first multispectral scanner and computer recognition of wheat from multispectral measurements collected by aircraft in 1966, to (1) the identification of the spectral bands and other design characteristics of the first Earth Resources Technology Satellite (ERTS) in 1967; (2) a simulation of ERTS data from the SO-65 multispectral photographic data taken by Apollo IX in 1969; (3) the successful launching of ERTS in 1972 and (4) feasibility investigations in 1972 and 1973 which demonstrated the potential ability of the ERTS system to monitor important crops.

Investigations into the relationships between weather and crop yield have been an agricultural research interest of long standing. The availability of high-speed computers and worldwide weather data in recent decades has allowed much more extensive statistical analysis of those relationships. Some researchers have studied the responses of individual plants to the weather, while others have investigated the subject on a larger scale to determine the relationship between average yield and normal climatic conditions in specific regions. Several of these studies, undertaken at Iowa State University around 1970, investigated key relationships among yield, agricultural technology, and climate in the major grain-producing area of the United States. On the basis of that work NOAA initiated a study in 1973 to evaluate the likelihood of drought in the Midwest and the possible effects of such a drought on grain production.

LACIE was a logical next step. By then, a technological apparatus consisting of earth observation satellites, environmental satellites, communications links, computer processing equipment and mathematical models had been created. In LACIE these elements were assembled into a system capable of large-scale monitoring of global wheat production.

8.1.2 Roles of the Federal Agencies

Each of the three federal agencies participating in LACIE brought specific expertise and experience to the planning and implementation of the experiment. Most of the LACIE tasks required the integrated efforts of at least two of the three agencies; however, various lead responsibilities were assigned. Figure 8.1 illustrates the participation of the three agencies.

8.1.3 Role of Universities and Industry

Researchers from universities and industry played a key role in the experiment through the development of improved techniques that were evaluated in later phases of LACIE and through participation in technical review sessions held

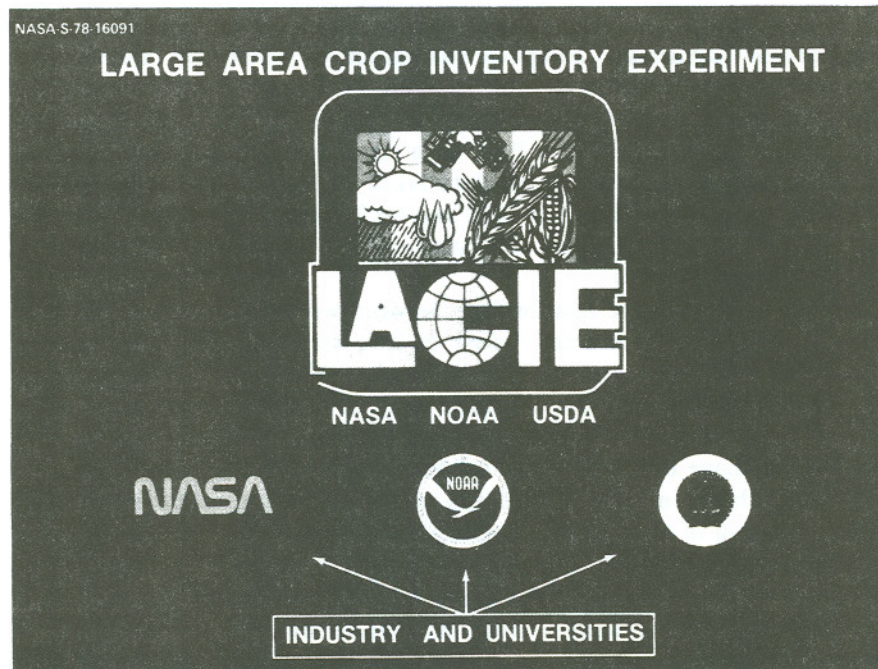


Figure 8.1 The three federal agencies participating in LACIE

periodically throughout the experiment. In addition key industries were, through contracts from the agencies, vital to the implementation and operation of the experiment.

8.2 THE LACIE EXPERIMENT

8.2.1 Objectives of the Experiment

The objectives of LACIE included the following:

- (1) To demonstrate an economically important application of repetitive, multispectral, remote sensing from space;
- (2) To test the capability of the LANDSAT, together with climatological, meteorological and conventional data sources, to estimate the production of an important world food crop;
- (3) To validate techniques that can provide timely estimates of crop production;
- (4) To provide estimates of the area planted in wheat, to provide estimates of wheat yield and to combine these area and yield estimates to estimate total production;
- (5) To develop data processing and delivery techniques so that a selected sample could be made available for analysis no later than 14 days after acquisition of the data;
- (6) To develop a LACIE system design that with a minimum of redesign and conversion, could be used to develop an operational system within USDA;
- (7) To monitor and assess crop progress from a surface data base and evaluate the model potential for yield and surface data.

Ancillary goal-oriented activities included:

- (1) Periodic crop assessment from planting through harvest;
- (2) Support for a research and development (R and D) programme to improve methodology and performance;
- (3) An objective test and evaluation programme to quantify the results of R and D.

To maintain the experimental nature of LACIE, it was decided that crop assessment reports would be prepared on a monthly basis during the crop season and mailed to USDA the day before the official USDA monthly report was released. The goal was to make periodic estimates of production that would be, on the average, within ± 10 per cent of actual production 90 per cent of the time (referred to as the 90/90 criterion). An additional goal was to establish the accuracy of these estimates early in the season (the first quarter of the crop cycle) and continue their accuracy through the harvest period. The three agencies agreed that achievement of the 90/90 criterion would be an improvement over information available from conventional data sources.

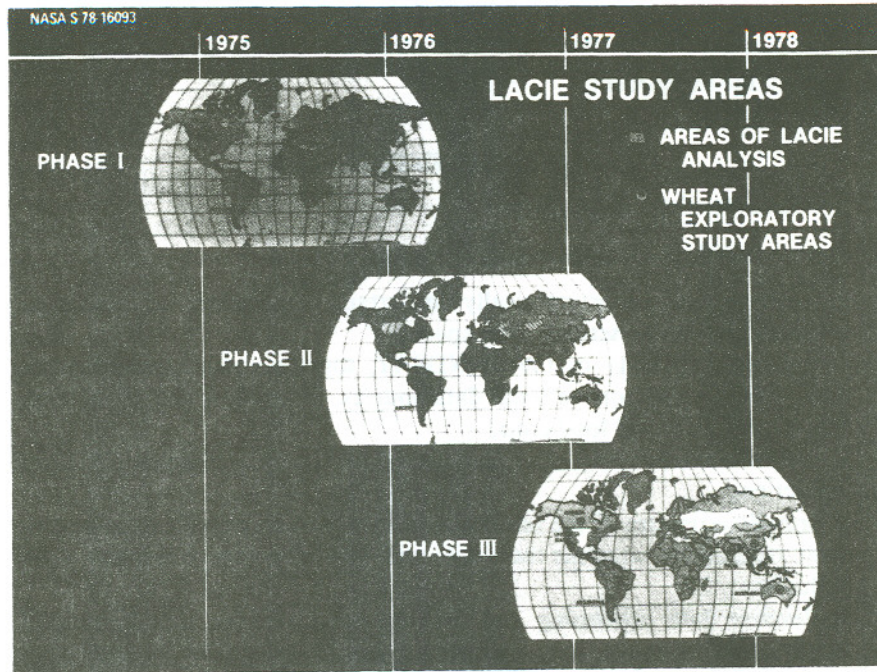


Figure 8.2 LACIE study areas

8.2.2 Scope of the Experiment

The LACIE experiment was designed to monitor production in selected wheat-producing regions of the world. The experiment extended over three global crop seasons and was designed to include up to eight regions (Figure 8.2). The early phases of the experiment concentrated primarily on the nine-state wheat region in the US Great Plains, where current information about wheat production and the components of production was available to permit quantitative evaluation of LACIE operations. As the experiment progressed, it expanded to include the monitoring of wheat production in two other major wheat-producing countries, Canada and the USSR. This expansion also included exploratory studies for monitoring wheat production in India, China, Australia, Argentina and Brazil (Figure 8.2). In addition, management decisions by USDA resulted in the incorporation of a USDA User System within the USDA-LACIE effort.

Phase I of LACIE (global crop year 1974-75) focused on the integration of components into a system to estimate the proportion of the major producing regions planted in wheat, and on the development and feasibility testing of yield and production estimation systems. At the end of the season, a report on

LACIE estimates of wheat and small grains production in various areas of the US Great Plains was prepared.

In Phase II (global crop year 1975–76) the technique, as modified during Phase I, was evaluated for its accuracy in monitoring wheat production on the US Great Plains, in Canada, and in 'indicator regions' in the USSR. Monthly reports of area, yield and production estimates of wheat for these regions were prepared.

8.2.3 Technical Approach

The technical approach to LACIE (Figure 8.3) was to estimate wheat production on a region-by-region basis. Both the area planted in wheat and the yield were estimated for local areas and aggregated to regional and country levels to determine production. Maximum use was made of computer-aided analysis in order to provide the most timely estimates possible. The estimates were made throughout the crop season, and evaluations were conducted to verify the accuracy of the LACIE technique and to identify technical problems.

Estimates of the area in wheat were from LANDSAT 2 multispectral scanner (MSS) data acquired for land segments of 5×6 nautical miles. The use of LANDSAT full-frame imagery allowed the taking of samples from agricultural areas only and meant that an analysis of only two per cent of the sample was sufficient. Sampling error was less than two per cent. The techniques of statistical pattern recognition employed in LACIE were designed to take advantage of the changing spectral response of crop types over time. Thus, LANDSAT data were acquired throughout the crop season, screened to determine cloud cover, and registered to previous acquisitions. The sample segments were then extracted in a digital format. Trained analysts then labelled a small part (less than one per cent) of each sample segment as either wheat or not wheat. In general, the analysts were not able to distinguish wheat from other small grains in a reliable manner. Therefore, the labelling was generally of small grains, and historically derived ratios were applied to the small grains estimates to estimate wheat. (A procedure for direct identification of spring wheat, based on subtle differences in crop stages and appearances was tested late in Phase III.) The labelling was based on the appearance of wheat as observed over time on digital film imagery of each segment and on graphical plots indicating the response in each of the spectral channels. Because the spectral appearance of the crop is a strong indication of its stage of growth, models were developed for estimating the growth stage, based on local weather data. The analysts were also provided with summaries of seasonal weather and of local cropping practices for each region.

Wheat yield was estimated using statistical regression models based on recorded wheat yields and weather in each region. These regression models

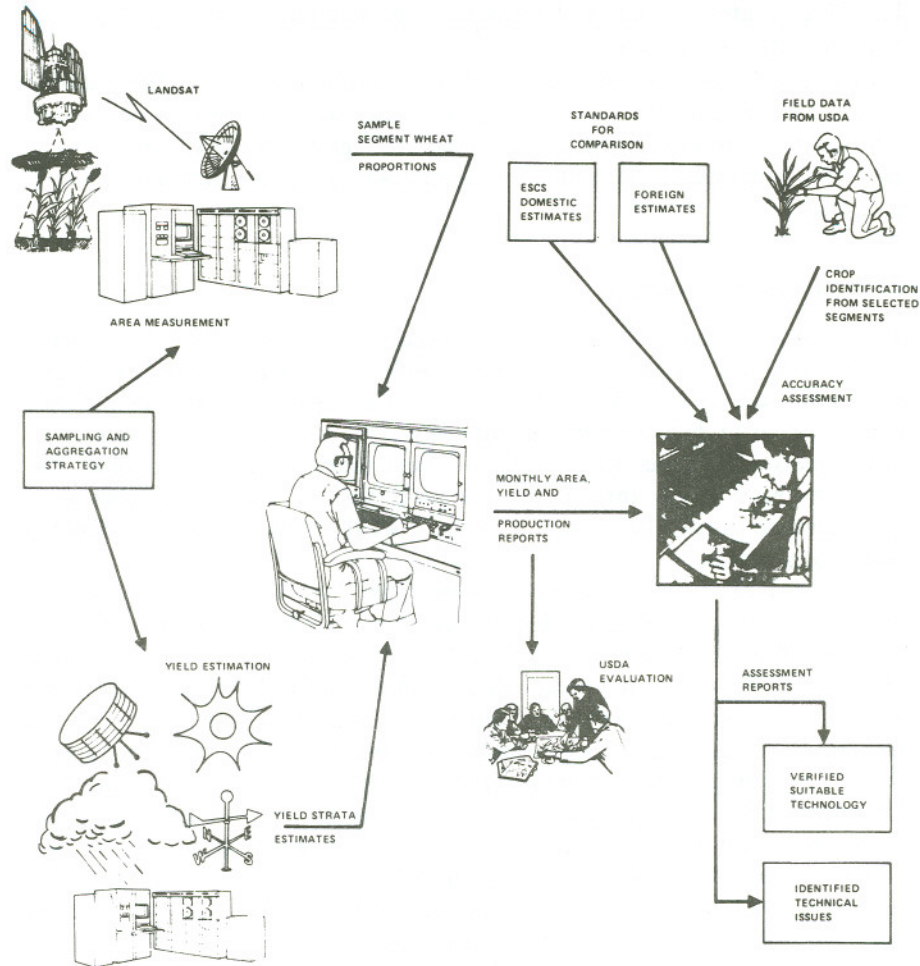


Figure 8.3 LACIE technical approach

forecast yield for fairly broad geographic regions, using calendar month values of average air temperature and cumulative precipitation. Meteorological data for these models (as well as the growth stage models) and weather summaries for the Great Plains were obtained primarily from surface stations of the National Weather Service, the Federal Aviation Agency and the Department of Defense. In foreign areas the data were collected by each country's weather service and were made available to LACIE by means of network of the World Meteorological Organization. Imagery for both foreign and domestic areas that was obtained by satellites was used to refine the precipitation analyses, which were based on cloud patterns. Models were developed to make yield

estimates early in the season, throughout the growing season and at harvest. Estimates of winter wheat yields in the northern hemisphere began in December and were updated until harvest in June or July. Estimates of spring wheat yields began as early as March and were revised monthly through August or September. Thus, assessments of potential yields were made almost from the time the plants emerged from the ground.

8.3 RESULTS OF THE EXPERIMENT

Perhaps the most important results of the LACIE experiment were of a technique to provide dramatically improved information on wheat production in important global regions and the demonstration that the technique could respond in a timely manner to large weather-induced changes in production. The most graphic example of this capability involved the LACIE prediction of the 1977 Soviet wheat crop.

8.3.1 The Phase III Results from the USSR

As shown in Figure 8.4, in January 1977 the Soviet Union set a goal of 120×10^6 metric tons (MT) for its wheat crop that year. In August 1977 the LACIE experiments made an initial forecast that total Soviet wheat

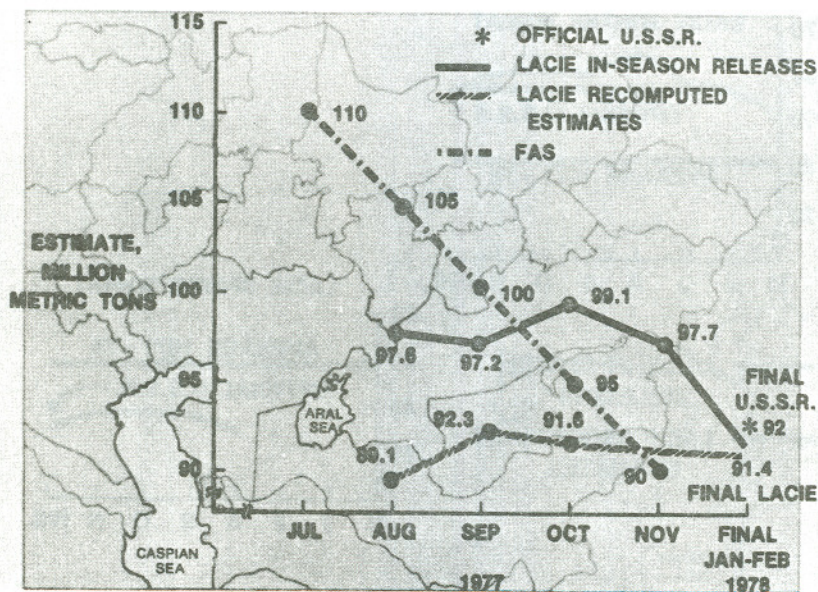


Figure 8.4 LACIE 1977 USSR forecasts: Total wheat

production would amount to 97.6×10^6 MT, or 20 per cent below the January goal of the Russians. This was only six per cent above the final Soviet figure of 92.0×10^6 MT. The final LACIE estimate of 91.4×10^6 MT differed from the final Soviet figure by about one per cent.

In comparison with the accuracy and timeliness of wheat crop information emanating from the USSR, these results showed an important advance in forecasting ability. Prior to the LACIE experiment, it was necessary to rely heavily on statistics and reports released by foreign countries themselves. Apart from questions about the reliability of such information, the major problem is its timeliness. The Russians, for example, release only a planning figure for grain production early in the year and a post-harvest estimate of total grain production in early November. Actual statistics are not released until the January or February following the harvest. The wheat production forecasts of the Foreign Agricultural Service (FAS) of USDA (shown in Figure 8.4) were based to a large extent on Soviet reports and to a lesser extent on reports from foreign agricultural attachés. The LACIE-recomputed estimates in Figure 8.4 resulted from a smoothly functioning operational system that could produce estimates of wheat production 30 days following the acquisition of data by the LANDSAT.

Figure 8.5 shows the separate winter and spring wheat estimates that constitute the totals in Figure 8.4. The May and June forecasts of winter wheat

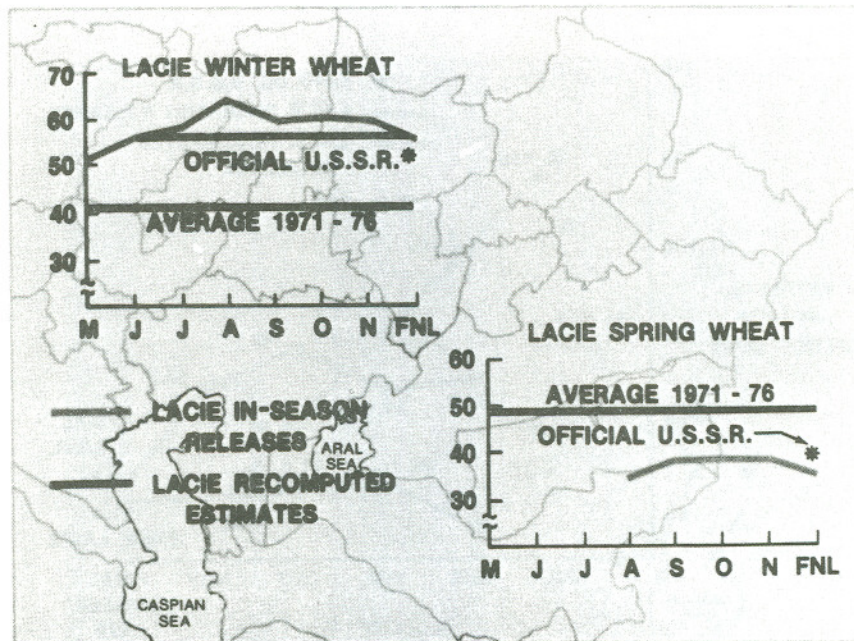


Figure 8.5 LACIE 1977 USSR forecasts. Winter and spring wheat

were for a normal to above-normal crop. The increase from May to June was known (because of LACIE forecasting experience in the US) to be the result of the steadily increasing visibility of the wheat crop to the LANDSAT. However, the continued increases in the July and August forecasts of winter wheat could not be justified, either on the basis of improving detectability or improving weather. Thus, alerted to technical problems, LACIE analysts initiated efforts to isolate the source of these reports of further increases. (Spring wheat estimates were unaffected by the problem and stabilized, as expected, following the August forecast.)

By November the problem in the forecast of winter wheat was discovered to be the result of a faulty LANDSAT data acquisition order, which led to the loss of key early season data on about 20 per cent of the sample segments of winter wheat. For these segments, only spring data were available, and LANDSAT analysts could not differentiate between winter wheat and small spring grains, such as barley, which had already become detectable. Even though the LACIE forecasts were accurate despite the implementation problems, 'recomputed estimates' were generated in December of 1977 to simulate the performance of a system without the data order problem. To generate the recomputed estimates, wheat output for the winter wheat areas affected by the faulty data orders was computed by utilizing the original estimate for those areas as an estimate of total small grain production, which was then reduced to a winter wheat figure using historic ratios of winter wheat to total small grains. In addition, a problem arising from using data 45 to 60 days old in current reports was eliminated by utilizing data acquired up to 30 days prior to the reporting date.

The clues to the production shortfall in the spring wheat region of the USSR came early in the season, when weather conditions started on an unfavourable note. The average air temperature for May and June was as much as 55 per cent above normal throughout the region. As a result, the wheat needed a greater amount of moisture than usual. (It is evident from Figure 8.6 that the abnormally high temperatures were widespread.)

But rainfall during the same period was below normal in many of the crop regions, as shown in Figure 8.7. The above-normal need for moisture, combined with the below-normal supply, clearly indicated that a serious problem was developing. (Figure 8.8 shows where the deviations from the normal supply-demand relationship were most pronounced.)

Since differences between precipitation and potential evapotranspiration were used in LACIE models to represent the relative soil moisture available to the crop, it was natural to expect a significant detrimental effect in the eastern and southern crop regions. The drought conditions were clearly observable in the LANDSAT data, and LACIE yield models responded accurately by reducing yield estimates in the affected regions. (As Figure 8.9 shows, the reduction in many cases was 50 per cent below normal.) In response

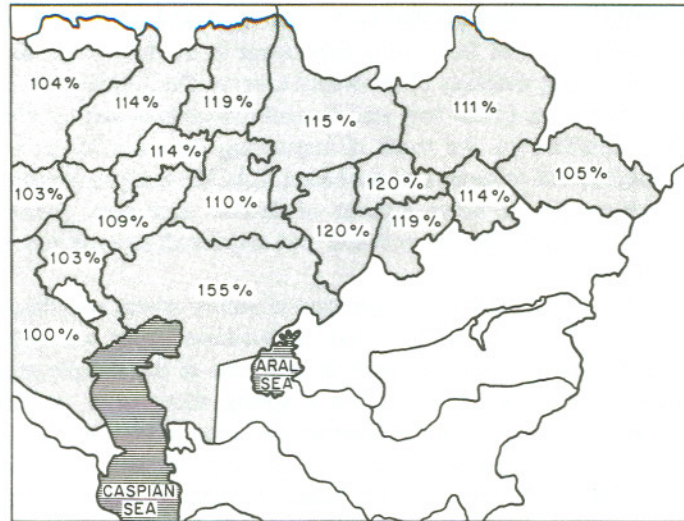


Figure 8.6 USSR spring wheat region: Per cent of normal for May-June air temperature (monthly average, °C)

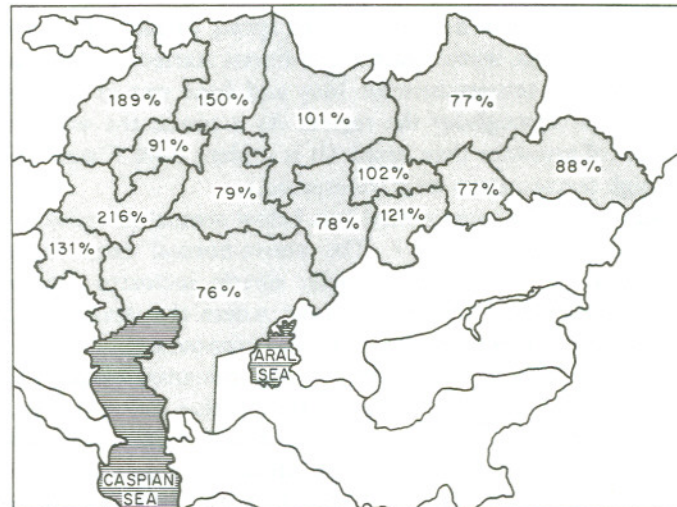


Figure 8.7 USSR spring wheat region: Per cent of normal for May-June monthly precipitation (mm)

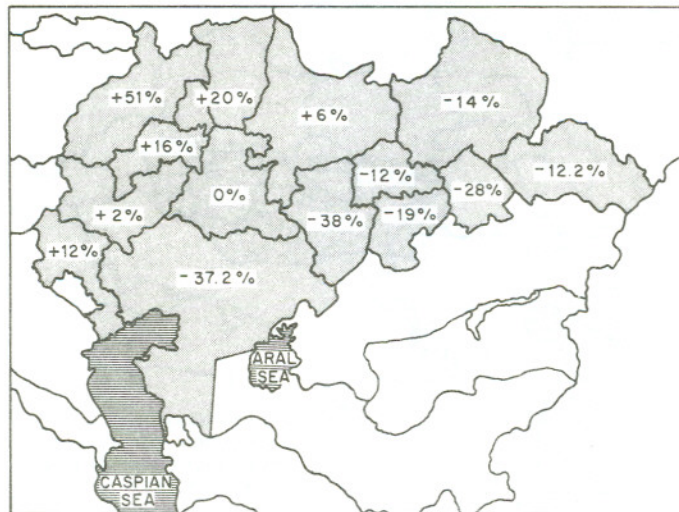


Figure 8.8 USSR spring wheat region: Per cent deviations from normal May-June monthly precipitation minus potential evapotranspiration (PET) (mm)

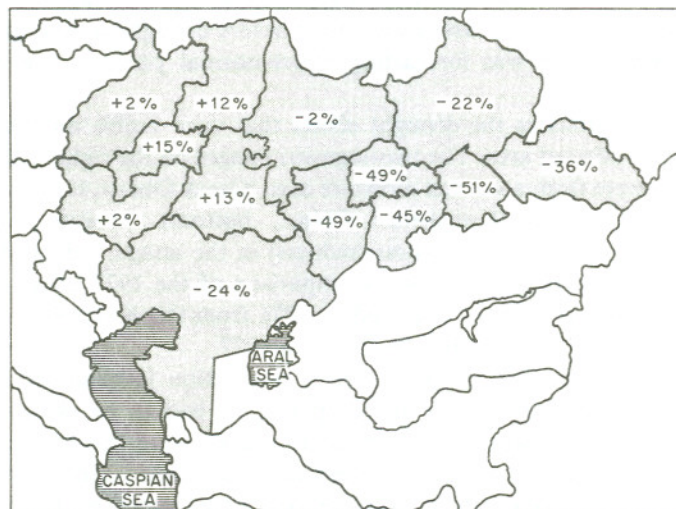


Figure 8.9 USSR spring wheat region: Per cent deviations from trend yields (quintals per hectare) (10^5 g/ha)

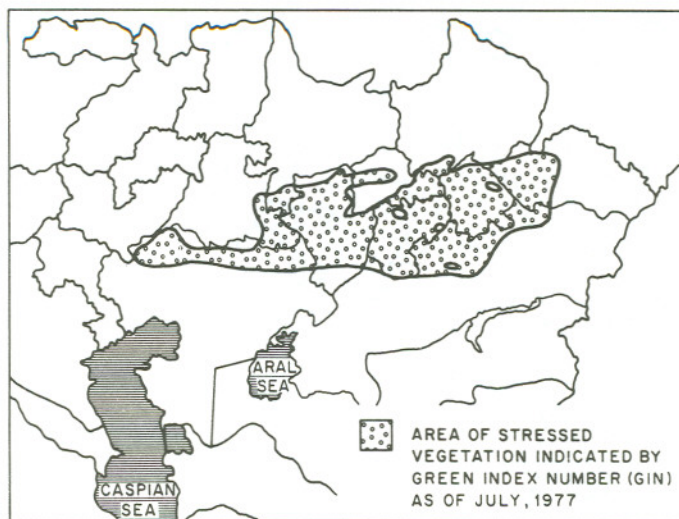


Figure 8.10 USSR stressed vegetation

to the high temperatures in April, before the spring season commenced LACIE yield models showed a probable loss of nearly 2×10^5 g/ha. The continued drought reduced below the normal figure of 11.5×10^5 g/ha. It can be seen in Figure 8.10 that these drought conditions were also quite evident from the LANDSAT data. In this figure, radiometric measurements from LANDSAT known to be related to the condition of the crop canopy substantiated the fact that the crop in the shaded areas was under severe drought conditions. (Note, however, that LACIE was forecasting above-normal yields in the northern regions.)

Figure 8.11 illustrates the drought effects that were visible on LANDSAT imagery of the affected area. The two-segment images on the right, collected on July 4, 1977, were from a normal moisture area (Omsk Oblast, top) and from a moisture-stressed area (Kokchetav Oblast, bottom). Moisture stress is detectable from the lack of darkness (redness) in the image, redness being an indicator of crop canopy condition. Comparison of the 1977 image with the image on the left, which was obtained in 1976 from the Kokchetav segment, shows the dramatic decrease in crop vigour in 1977.

To assess the reduction in spring wheat production in quantitative terms, the total wheat area in each of the crop regions had to be estimated. The LACIE estimates of wheat area in each region were multiplied by the forecasted yield per hectare to obtain estimates for each region. When these production figures were added up, the overall estimate of spring wheat production was 36.3×10^6 MT, a deviation of about 21 per cent below normal.

The LACIE yield and acreage estimates have been empirically tested by a

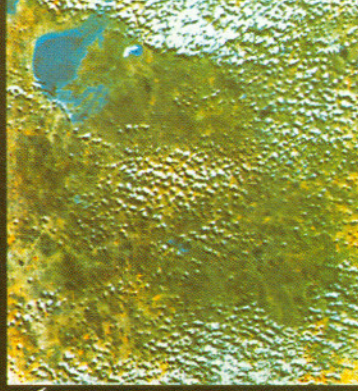
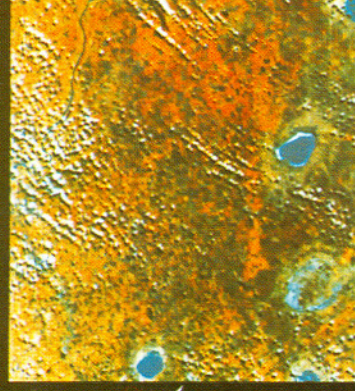
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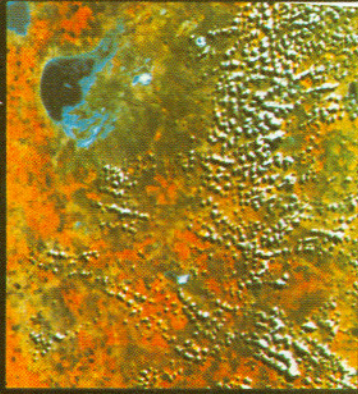
 **NORMAL**
DROUGHT STRESS



COMPARISON OF
LANDSAT
FULL FRAMES
ILLUSTRATING
DROUGHT STRESSED
VERSUS NORMAL
VEGETATION
THE DEGREE OF
REDNESS INDICATES
CROP VIGOR



JULY 4, 1977



JULY 27, 1976

Figure 8.11 USSR drought effects visible on LANDSAT 1977

fairly large number of 'performance experiments'. The LANDSAT-derived estimates of acreage have been evaluated through comparisons with independent ground observations and USDA estimates for the United States, and foreign and USDA estimates for Canada and the USSR.

The LACIE yield models, whose performance is much more sensitive to weather than are the acreage estimates, have been evaluated for the same countries with the aid of more than 10 years of historic data. While these years and regions are quite different from each other and represent a reasonable sample of the potential conditions to be encountered in a global survey, these empirical estimates can be viewed with increasing confidence as their number increases over the years.

Later in this paper it is stated that in some cases the LACIE technique achieved the 90/90 criterion and that in other cases it did not. These statements, based on certain statistical assumptions generally believed to be quite valid, represent inferences drawn from the performance tests described above.

How much confidence can be placed in these statements? LACIE used a standard, well-accepted approach to data that has not contradicted the 90/90 hypothesis except in those cases noted. The experimental data do not contradict the 90/90 for United States winter and USSR total wheat. While a lack of contradiction of this hypothesis implies that the LACIE technology may be satisfying 90/90 in a region, increased confidence can only be gained through additional replications over a number of years.

8.3.2 Phase III Results in the United States

Phase III in the United States further substantiated the conclusion that the technical modifications incorporated into the experiment during Phase II worked well. Overall, the Phase III results (Figure 8.12) showed significant improvement over those of Phase II, as winter wheat estimates were indicative of 90/90 accuracy. In addition, there was significant improvement during Phase III in the ability to estimate the spring wheat area. This reduced the difference between the LACIE estimate and the estimate of the Economics, Statistics and Cooperative Services (ESCS) on wheat area to less than one per cent, compared to a Phase II difference of 13 per cent. Unlike the Phase I and II results, the Phase III estimates of yield were significantly below those of the ESCS and were not supportive of the 90/90 criterion. However, the yield estimates in combination with the improved area estimates resulted in production estimates which differed from those of ESCS by less than 10 per cent. Statistical tests indicated that the Phase III estimates of United States wheat production were probably accurate enough to achieve the 90/90 criterion. The Phase III estimates of area, yield and production for the United States Great Plains region are shown in Figure 8.12. The yield estimates

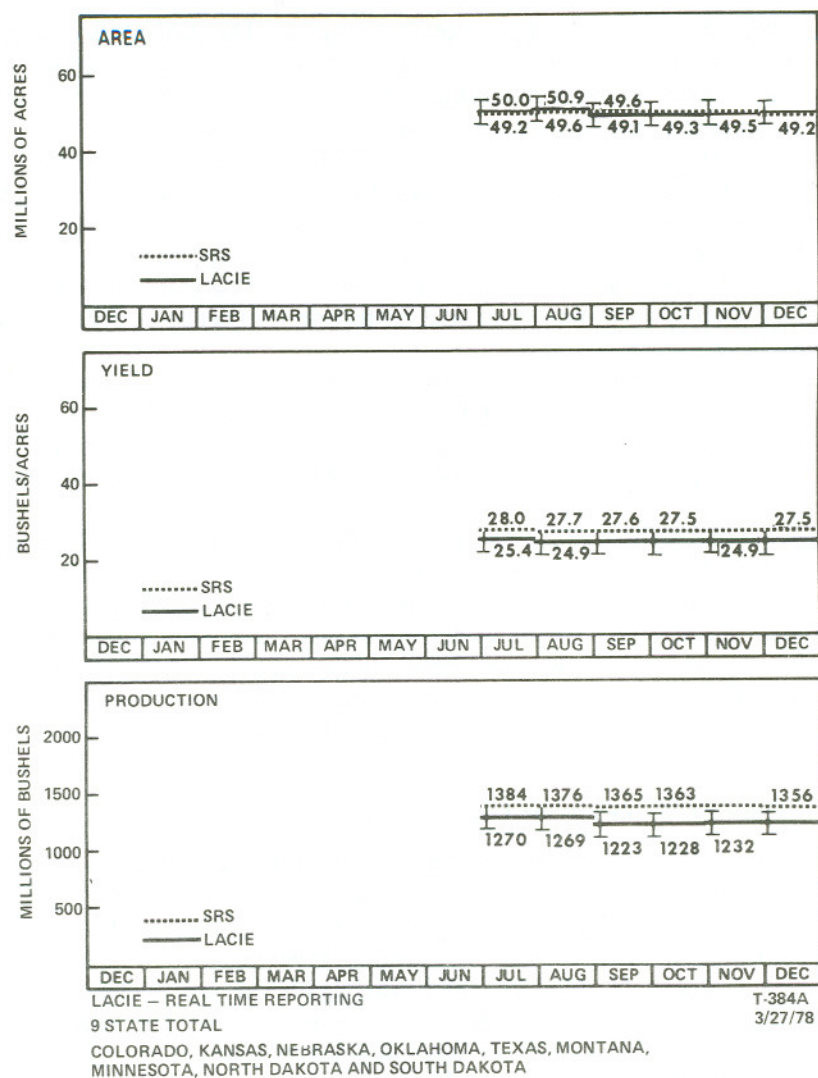


Figure 8.12 Monthly comparison of LACIE and SRS estimates. US Great Plains (9 state total), Phase III

shown are not the results derived from individual yield models, they were derived by dividing total production by total acreage. Even though the final estimate of yield was made in September, the derived value changed slightly as later LANDSAT data were used to refine estimates of area.

More extensive evaluations of the yield models over a 10-year period indicated performance consistent with the 90/90 criterion except in years with

Table 8.1 Results of an evaluation of the LACIE Phase III US yield models on 10 years of independent test data

Year	SRS, bu/acre	LACIE bu/acre	Error	Within tolerance
1967	21.6	22.5	+0.9	Yes
1968	26.0	24.6	-1.4	Yes
1969	28.4	29.4	+1.0	Yes
1970	28.2	26.6	-1.6	Yes
1971	30.8	27.9	-2.9	No
1972	29.3	29.1	-0.2	Yes
1973	30.8	30.6	-0.2	Yes
1974	23.8	28.4	+4.6	No
1975	26.8	27.3	+0.5	Yes
1976	26.4	27.1	+0.7	Yes
1977 ^a	27.5	24.9	-2.6	

Mean error = 0.1 bu/a

RMSE = 1.90 bu/a

^a Phase III results.

extreme agricultural or meteorological conditions. Table 8.1 lists the results of a test of Phase III yield models using data for the years 1967 to 1976. The models were developed from data for the 45 years prior to each of the test years. A non-parametric statistical test employed to analyse this data did not reject the 90/90 hypothesis. However, had the models exceeded the tolerance bounds in at least one more year (as they appear to have done in 1977), the 90/90 hypothesis might have been rejected. In addition, the root mean square error (RMSE) of 1.9 bushels per acre (bu/a) was larger than desirable for determining whether the 90/90 criterion had been achieved. It should be noted, however, that 1974 was a dry year in the Great Plains, and wheat yields were very poor. The LACIE yield models failed to respond to this deviation and overestimated yield by 4.6 bu/a. Omitting 1974, the RMSE would drop to 1.3 bu/a, which is not significantly different from the figure required for a 90/90 estimator. Thus, it appears that the yield models may satisfy the 90/90 criterion in years where there are no extreme fluctuations in yield.

Also, evaluated in Phase III were the LACIE models of the stages of wheat growth. These models, which were of key importance to the analysis of LANDSAT data, predicted the growth stage of wheat given maximum and minimum daily air temperatures. Generally, the Phase III evaluation of these models indicated that improvements were required, particularly the development of a model to predict the planting date. Given accurate data on the planting date, however, the models seemed to perform adequately. Improved growth stage prediction models are also the key to improved yield models.

Phase III testing of alternate sampling strategies in the United States and the USSR indicated that substantial cost savings could be realized through their use. Three improved strategies will permit accurate estimates to be made with significantly reduced amounts of data.

The results achieved during Phase III in predicting production on strip fallow (small field) areas in the spring wheat regions of the United States showed significant improvement but still exhibited a tendency to underestimate the area of small grains. Figure 8.13 shows the experimental estimates in comparison with ESCS estimates. Figure 8.14 compares LACIE estimates of wheat area percentages, at the segment level, with observations of actual percentages made by human observers on the ground ('ground truth'). These 'ground truth' data were prepared independently of, and after, the Phase III estimates from LANDSAT data were produced. This comparison shows the improvement in Phase III results.

The actual time required to analyse a LANDSAT segment, manually select training fields, compute training statistics, and process the nearly 23 000 elements of the segment was reduced from 10 to 12 hours during Phase I to 6 to 8 hours during Phase II and 2 to 4 hours in Phase III. It was also concluded that the experiment showed that the timeliness goal of 14 days could be realized in the future.

The geographically dispersed nature of the LACIE data processing system led to long 'in-work' times (from 30 to 50 days) for segments of LANDSAT data because of the many manual steps required and the fact that the experiment was conducted, for the most part, on a one-shift, five-days-a-week basis. The actual time during which a segment was undergoing processing, however, was within the revised goal of 14 days from acquisition to availability for aggregation, since actual 'contact time' was two to four hours per segment and computer processing time was around five to eight minutes per segment.

8.3.3 Phase II Results in the United States, USSR and Canada

While the Phase III results were very encouraging, they were by no means the whole story. The experimental results obtained in the United States during the three years of LACIE, and in the Soviet Union during Phase II, also substantiate the Phase III results in the USSR. The estimates of US and Canadian spring wheat defined the geographical regions for which improvements in remote sensing technology were needed.

An evaluation of Phase II results indicated that the technique worked well for winter wheat in the United States and for both winter and spring wheat in the USSR. Difficulty was encountered, however, in reliably differentiating spring wheat from other spring small grains, primarily spring barley, in the spring wheat regions of the United States and Canada. The strip fallow fields in these regions were another complicating factor, since their widths were very

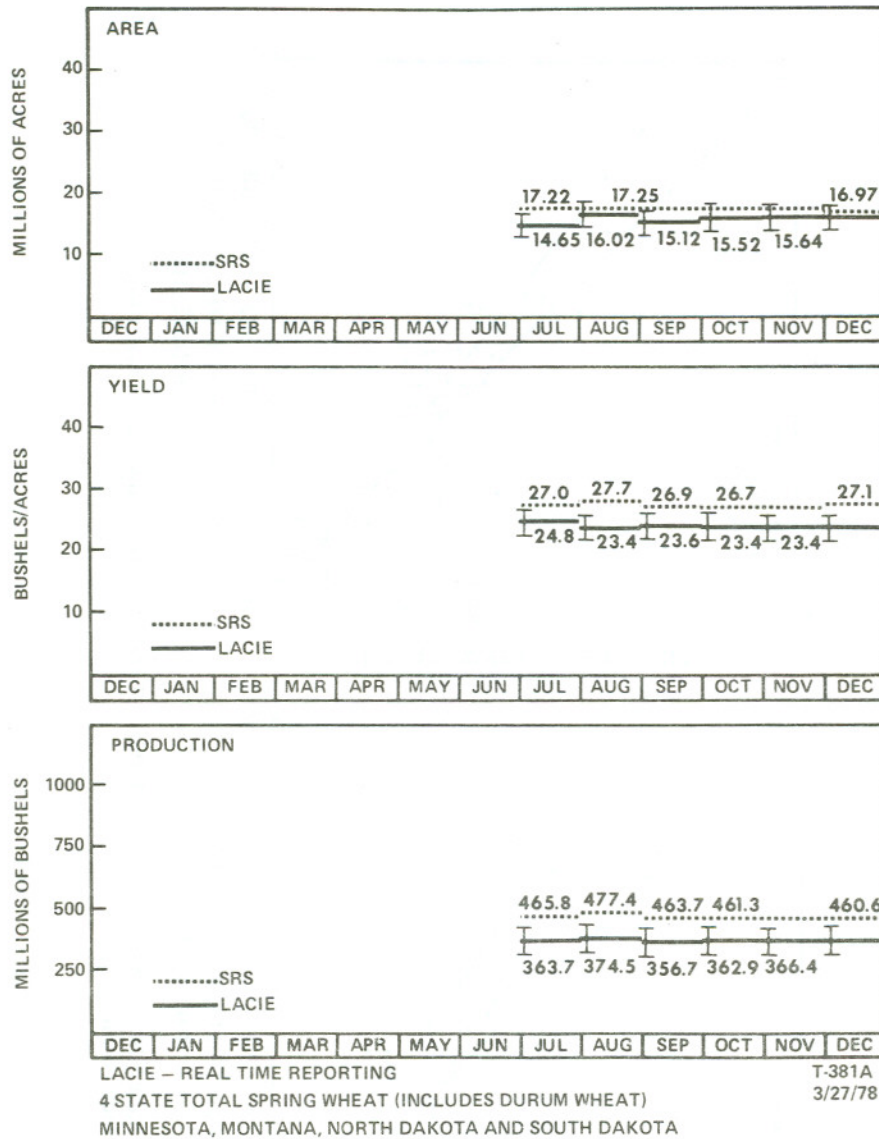


Figure 8.13 Monthly comparison of LACIE and SRS estimates. US Great Plains (4 state total), Phase III

close to LANDSAT resolution limits. Figure 8.15 shows how field size and shape were problems in some areas. On the left part of Figure 8.15 is an aerial photograph and segment of the strip/fallow region of the United States. Note the prevalence of very long and narrow fields, a result of moisture-conserving

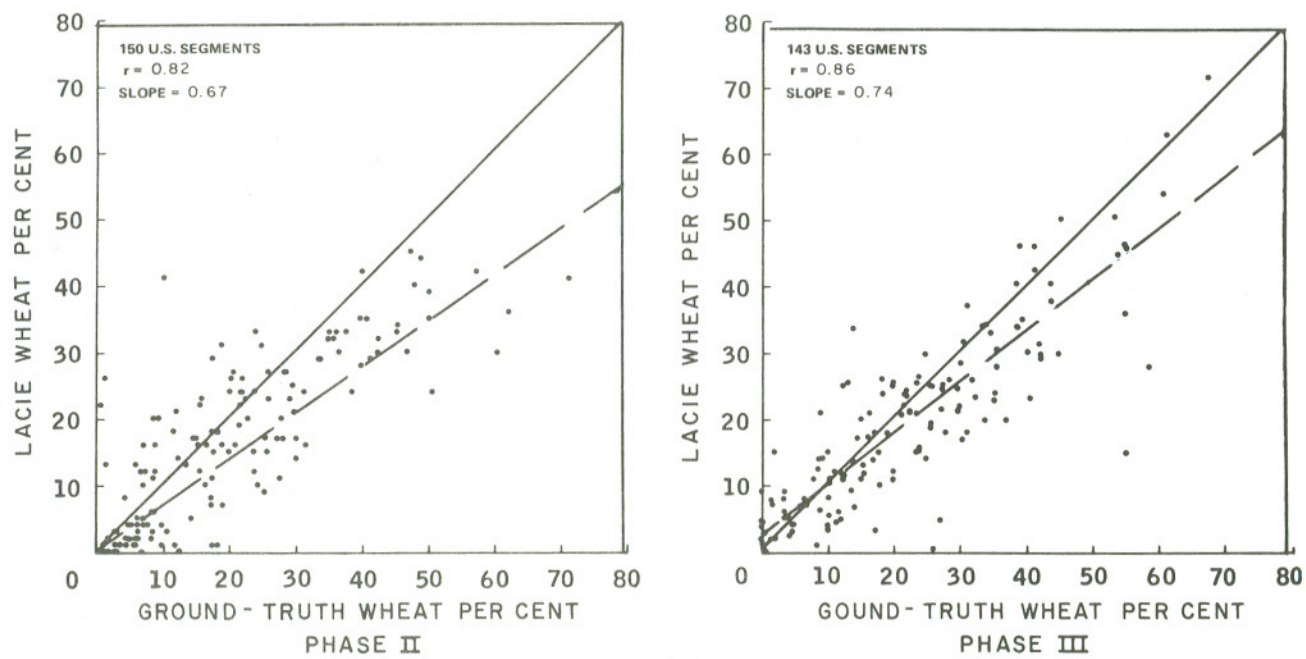


Figure 8.14 Comparison of LACIE Phase II and Phase III total wheat estimates with ground truth

strip/fallow practices. Similar practices are common in Canadian spring wheat areas.

These factors led to significant Phase II underestimates of 29 and 26 per cent for the spring wheat areas of the United States and Canada, respectively. In the spring wheat regions of the USSR, where field sizes are considerably larger and the ratios of wheat to small grains are more stable than in the US and Canadian regions, the Phase II estimates were in reasonable agreement with crude estimates based on official Soviet statistics. In 1977 there were other indications, such as estimates of the coefficient of variation of the LACIE estimates, that the LACIE estimates were of 90/90 quality. Replications are required to verify the achievement of the 90/90 criterion, however. The final LACIE estimate was within one per cent of the Soviet figure. Most encouraging was the accuracy of the estimates made early in the growing season.

The decision to expand the region to be inventoried in the USSR was prompted by the lack of actual production information for the USSR indicator regions and thus the absence of a reliable estimate of the bias of the LACIE estimates. It was also decided to reduce coverage in Canada to 30 segments, where Canadian investigators could use ground observations in an intensified evaluation of the problems of distinguishing spring wheat from other small grains in small fields.

8.3.4 Exploratory Foreign Investigations

Exploratory investigations in Argentina, Australia, Brazil, China and India provided insight into the technical problems of estimating production in other countries. These investigations included the development of yield models, analysis of sample segments and collection of LANDSAT, meteorological and agronomic data. Aggregated estimates of area, yield and production were not attempted.

8.3.4.1 Australia

LANDSAT data collected over Australia indicated field sizes and multi-temporal signatures similar to those of the US Great Plains and the USSR. Yield models have been developed for five states in Australia. A test of these models, using 10 years of independent test data, indicated they would support the 90/90 criterion. A model to predict the stages of crop growth has also been developed, but difficulties have been encountered in using it because wheat varieties in Australia differ from those grown in the United States, where the model was developed. The model was designed for winter wheat with a dormancy period; Australian wheat does not go into dormancy.

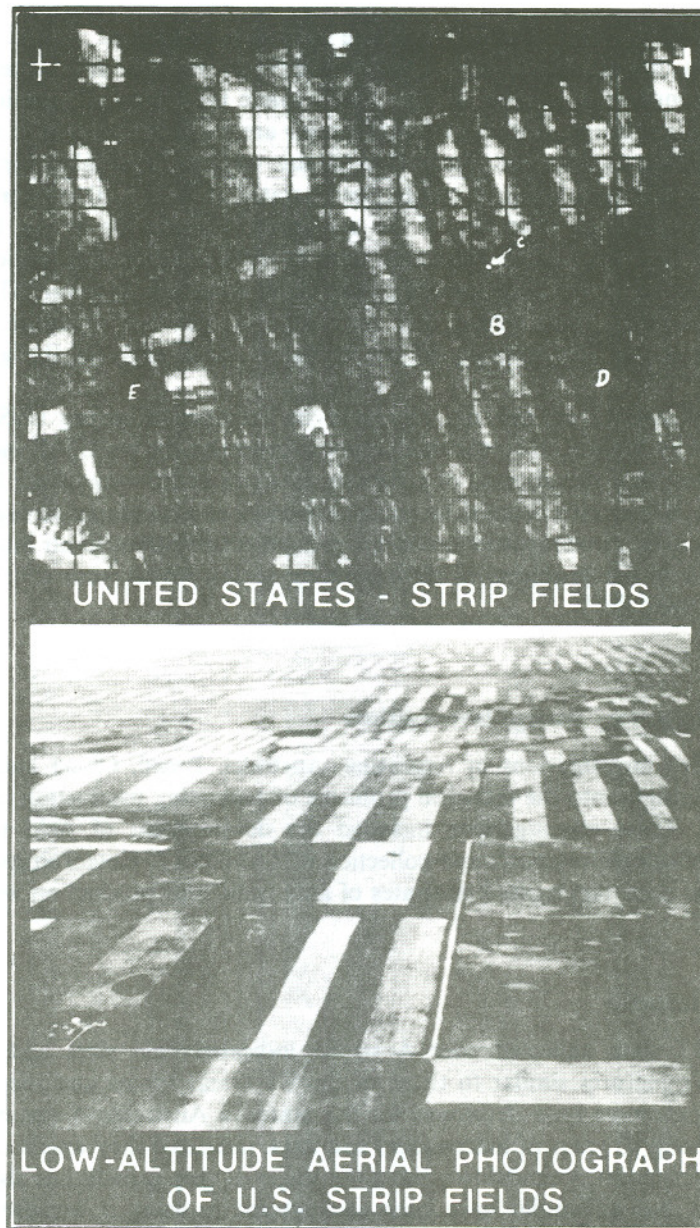


Figure 8.15 Resolution of LANDSAT images

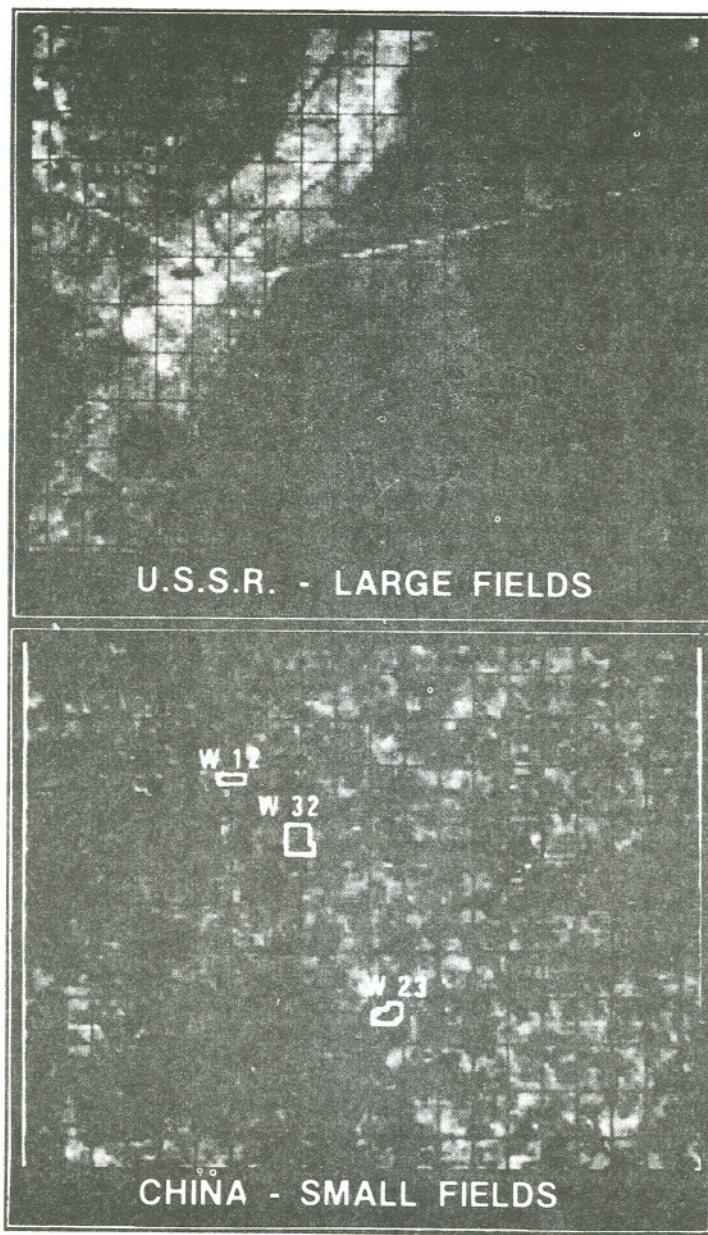


Figure 8.15 (continued)

8.3.4.2 India

The average field in India is smaller than the LANDSAT MSS resolution element. However, the fields tend to be adjacent to each other and may be less of a problem than small strip fields in the United States and Canada. Yield models have been developed for 15 states in India, and exploratory segments have been analysed. Although not tested operationally, these models were tested using historic data, and the test indicated they would support the 90/90 criterion. Models to predict the stages of growth were evaluated and showed very poor results. Many of these can be attributed to differences between United States and Indian wheat strains. Indian wheat does not go into dormancy and has a shorter growth cycle.

8.3.4.3 Argentina and Brazil

Analysis of LANDSAT data indicated that wheat fields in the older and more populated areas of Argentina are similar in size to those in Kansas, while in the less populated frontier areas they are similar in size to wheat fields in the USSR. Ancillary data for Argentina and Brazil were extremely limited, thus hampering both interpretative analysis and the creation of yield models. Yield regression models were developed for five provinces in Argentina and for one state in Brazil, but the quality of the data for building these models was lower than the quality of the data available for equivalent United States areas. Tests of the yield models, using more than 10 years of independent test data, indicated that the models would not support the 90/90 criterion. In general, the crop signatures were typical of those encountered in the United States. LANDSAT data on Brazilian wheat regions showed that cloud cover was more frequent there than in the United States wheat region.

8.3.4.4 China

China, like India, has extremely small wheat fields in its densely populated areas, but field sizes are comparable to those in the United States in the newly developed spring wheat region. Historical data upon which to develop necessary ancillary data could not be found. This lack of information about the stages of crop growth and about crops hard to distinguish from wheat by means of satellite observations meant that less confidence could be placed on the analysis of Chinese wheat production.

8.3.5 Technological Problems Requiring Further Attention

LACIE crystallized problems in the technique and shortcomings in our understanding of certain phenomena. Problems in need of special attention include the following:

- (1) The need to develop yield models that are based on daily or weekly, rather than monthly, averages of temperature and precipitation, and that more closely simulate the critical biological functions of the wheat plant and its interaction with the external environment.
- (2) The need to develop techniques to deal more effectively with the spatial information in LANDSAT data and to improve the accuracy of area estimates in regions where a high percentage of the fields have effective sizes close to the resolution limit of LANDSAT. In addition, further investigation of the improvements resulting from the increased resolution power of LANDSAT-D, as well as the spatial resolution requirements for future LANDSAT satellites, is necessary.
- (3) The need for better understanding of the distinctly different characteristics of wheat grown in tropical regions.
- (4) The need for better quantification of the effects of cloud cover on the acquisition of LANDSAT data at critical periods in the crop season, particularly in more humid environments, such as the United States corn-belt.
- (5) The trade-offs between the need to shorten the time from data acquisition to reporting and the cost of obtaining a quicker response. Although it is possible to reduce this time span, doing so may require substantial additional costs.

8.4 CONCLUSIONS

On the basis of the results obtained by LACIE during three crop years, we conclude that:

- (1) It is now possible to estimate wheat production successfully in geographical regions whose characteristics are similar to those of the Soviet Union's wheat areas and the winter wheat area of the United States.
- (2) Significant improvements in our ability to estimate wheat production in these and other regions can be expected in the near future through additional applied research.
- (3) The remote sensing and weather effects modelling techniques developed in LACIE may be applicable to other major crops and regions of the world.

In addition, several lessons were learned about the planning, management and implementation of programmes to develop improved crop monitoring and estimation techniques:

- (1) Research, development and evaluation require several years of testing with large amounts of data to verify technological issues, due to the wide range of variability in the factors that contribute to the outcome.
- (2) A comprehensive effort to assess accuracy is vital. Substantial amounts of

ground data from domestic 'yardstick' or test regions are essential to understanding experimental results as well as to the identification and correction of deficiencies in the programme. LACIE included this type of assessment.

- (3) A research and development programme involving diverse scientific disciplines, focused on technical issues that arise from a project like LACIE, stimulates applied research and provides an improved understanding of the programme in the academic and industrial communities.
- (4) The periodic use of a peer review, in which critical methodological issues are subjected to the scrutiny of reviewers from university, government and industry provides essential feedback.
- (5) Much was learned about the capabilities of the LANDSAT, together with other data sources, to estimate wheat production. Most importantly, the needs for higher spatial resolution, additional spectral bands, and increased coverage to observe smaller fields and to distinguish wheat from other crops, were identified. LANDSAT-D will provide a data source to support solution of technical problems related to these needs.

8.5 OUTLOOK

As a result of (1) USDA's continued interest in exploiting this technique to provide improved information about crop production throughout the world, (2) the success achieved thus far with wheat and (3) the identification by LACIE of technical issues requiring further investigation, the US Secretary of Agriculture called for the creation of a multiagency programme to develop improved uses of aerospace technology for agricultural purposes. The AgRISTARS programme focuses on the following:

- (a) early warning of environmental or technological changes that may affect the production or the quality of renewable resources;
- (b) improved commodity production forecasts;
- (c) land-use classification and measurements;
- (d) renewable resources inventory and assessment;
- (e) land productivity estimates;
- (f) assessment of conservation practices; and
- (g) pollution detection and evaluation.

While all seven of these are of major importance to USDA, the first two express the Department's urgent need for better and more timely objective information on world crop conditions and expected production. The agencies that participated in LACIE planned activities for the early 1980s that would build on the LACIE experiment and address the broader needs of USDA.

The results of the LACIE experiment also provide a partial basis for judging

the feasibility of measuring global vegetation and its changes. LACIE provided numerous research results that are also relevant to forest and rangeland measurements, to the use of imaging radar, and to measuring insolation and solar temperatures by means of meteorological satellites. Generally speaking, these research areas show promise but have not been evaluated on a global scale to demonstrate that reliable technology has been achieved.

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