Global Crop Forecasting

R. B. MacDonald and F. G. Hall

International trade decisions based on inadequate information regarding the global food supply can have severe economic and social effects. In 1972 and again in 1977, advance knowledge of the shortfall in the Soviet grain crop could have had a positive effect on the U.S. economy, rather than the negative effect that resulted from the lack of good information.

Proper management of U.S. agricultural production is crucial to both the American and foreign economies. In recent years, U.S. grain has comprised more than half of world grain exports. Each year, the sale of American agricultural products to foreign nations represents several billions of dollars; it is the single most important export factor in the U.S. balance of trade.

Summary. Many foreign countries are as dependent on imports of food as the United States is on imports of oil. As the world's largest exporter of food, the United States needs reliable information on fluctuating foreign crop production. But available information is often inadequate and at best untimely. It is gathered by the foreign governments' often outmoded systems and its release may be delayed out of economic self-interest. Recently three U.S. government agencies put together a crop inventory system using satellite remote sensing and worldwide weather reporting and tested it in the Large Area Crop Inventory Experiment (LACIE). A 1977 real-time forecast of U.S.S.R. wheat production indicates that the approach works and may be expandable to other areas and other crops.

A major problem faced by the United States in foreign trade decisions is the lack of timely, accurate information on the potential resupply from new harvests overseas. These crop outlooks are extremely variable. Wheat, the most important internationally traded food grain, is grown mostly in semiarid regions, where small variations in weather can bring agricultural disaster or bumper crops.

While the United States publicizes accurate forecasts of its wheat crop, many other nations either do not make reliable estimates of their crop or do not release their figures until annual purchases are completed. Such organizations as the U.N. Food and Agriculture Organization (FAO) and the U.S. Department of Agriculture (USDA) are chartered to provide information on global food production, but their reports have been heavily reliant on information generated by the countries themselves.

Space remote sensing technology is emerging from more than a decade of research to provide a way to make much better global forecasts. In 1974, the Large Area Crop Inventory Experiment (LACIE), a joint effort of NASA, the USDA, and the National Oceanic and Atmospheric Administration (NOAA), began to apply this technology on an experimental basis to forecasting harvests in important wheat production areas. Completed in 1978, LACIE demonstrated that remote sensing from earth-orbiting satellites can provide information on foreign commodity production with an accuracy and timeliness significantly better than those of previous systems.

Three years of intensive evaluation of LACIE estimates for the U.S. crop and 2 years of experience in estimating the Soviet crop indicated that accuracy commensurate with USDA performance goals for foreign wheat production forecasting was achievable in regions where fields are sufficiently large to be resolved by Landsat. In a 1977 quasi-operational test, the LACIE in-season forecast of a 30 percent shortfall in the 1977 Soviet spring wheat crop came within 10 percent of official Soviet figures released several months after harvest. LACIE midseason winter wheat forecasts also predicted, within 7 percent, a 23 percent above normal Soviet winter wheat crop several months before harvest. Although an operational error caused winter wheat estimates later in the season to be inflated some 10 to 15 percent, LACIE total wheat estimates were within 6 percent of the final Soviet figures 6 months before their release. The coefficient of variation of the LACIE total wheat estimate for the U.S.S.R. was 3.8 percent, well within that required by USDA accuracy goals.

These experimental wheat forecasting results have spurred the USDA, NASA, and NOAA to expand their efforts over the next several years to develop and evaluate space remote sensing technology for other major commodities and global crop regions.

This article discusses the need for improved crop forecasts, describes the remote sensing approach to global crop forecasting, and provides a summary of key LACIE results (*1*–*4*).

Current Forecast Systems

The USDA and the FAO compile commodity supply estimates produced by individual nations and report world supply estimates. The quality of these estimates is a direct function of the quality of the reporting systems in the various countries (*5*, *6*).

Agricultural information should have the qualities of objectivity, reliability, timeliness, adequacy of coverage, efficiency, and effectiveness. Production statistics in many important agricultural countries do not meet any of these standards. Fewer than ten have a system that provides adequate crop production estimates. A larger number have a system providing only annual production data for major crops. Close to half the countries of the world have either very simple or no agricultural production estimates except those provided by a census of agriculture conducted every 10 years. Several countries lack any formal system for acquiring agricultural statistics. The United States, which recently started issuing measures of precision for its domestic crop production forecasts, is the only country that publishes information on survey methodology and reliability of estimates. The chief reasons for the absence of quality agricultural production

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statistics are (i) lack of funds for collecting and tabulating data, (ii) inadequate technical capability to formulate sound sampling and data collection procedures, (iii) absence of a suitable sampling frame, and (iv) difficulty in quantifying the benefits of improved information. Table 1 shows the current accuracy of USDA forecasts of foreign commodity production and the accuracy goals for 1985. For example, the accuracy of at-harvest estimates for the U.S.S.R. is 65/90. This means that only 65 percent of the time will the USDA at-harvest estimate be within 10 percent of the final U.S.S.R. estimate. Note that the most accurate system is that for the United States.

The frequency and magnitude of the differences between the early-season, at-harvest, and final estimates can be explained in part by the fact that the in-season estimates generally incorporate the assumption that historical trends in weather and planting patterns will prevail. Usually, these estimates are based on the foreign government's own reports of planted hectarage and the historical average for yield. Because weather patterns differ widely from year to year, the probability is low that in any one year actual hectarage, actual yield, or actual production will be within 10 percent of its average value.

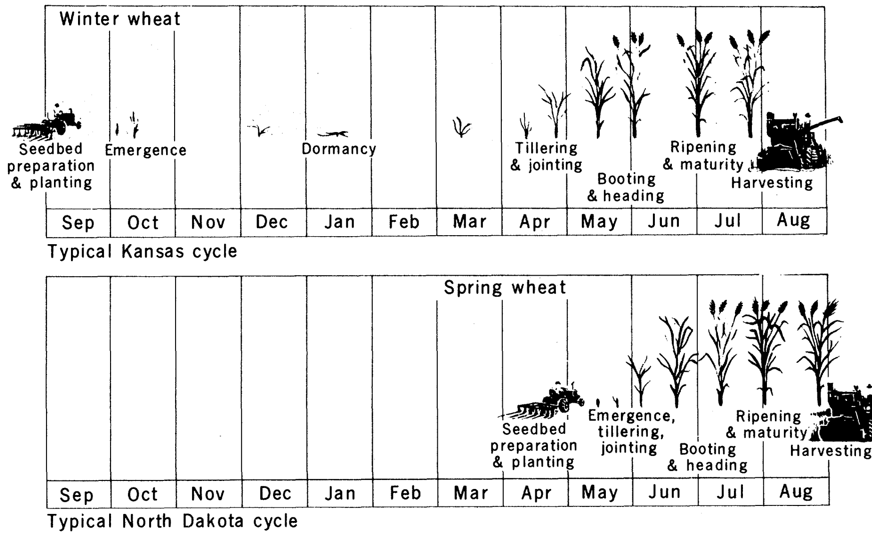


Fig. 1. Growth stages of winter and spring wheat.

Elements of Crop Production Forecasts

Before discussing LACIE technology, it is necessary to review the basics of crop production forecasting. Accurate crop production forecasts require accurate forecasts of the hectarage for harvest, its geographic distribution, and the associated crop yield (*7*) as determined by local growing conditions. Both crop hectarage and yield are sufficiently variable from year to year and within a year to require periodic monitoring. These variations are created by slowly changing factors, such as irrigation, fertilization, and climate, and by rapidly changing factors, such as weather, market price, and government policy.

To quantify the complex effects of these factors on crop production, both hectarage and yield must be assessed at subregional levels (strata) where the limited ranges and simple interactions of the factors permit successful modeling and estimation. For example, a yield forecast stratum should be sufficiently homogeneous in soil type, crop variety, land use, and climate to preclude the necessity for hopelessly complex yield forecast models. Hectarage and yield of significantly different crop subclasses should be individually considered. For example, there are two major growth habits of wheat (Fig. 1). Winter wheat, planted in the fall, can have twice the yield of spring wheat, but it is subject to freeze damage during its dormancy period. Thus, despite its lower yield, spring wheat is often planted in severely cold regions. A single yield model cannot adequately describe the response of both types of wheat to such a wide range of weather conditions.

It should be emphasized that existing operational crop forecast systems do not really predict the future. Weather forecasts and the vagaries of policy and human factors being what they are, crop forecasters must be content to assess as accurately as possible the impacts of preceding and current conditions on future harvest production. In this context, the ideal forecast system is one that can accurately assess current crop status and can detect and rapidly respond to changes in relevant conditions.

During the first half of the crop year, hectarage information has traditionally played a dominant role in market price (*6*) because early in the season crop hectarage is more predictable than is crop yield. The forecast accuracy of even the perfect yield model is limited by uncertainty about future events. As harvest time approaches, yield information increases in value because plant processes are closer to completion and the chances of a major perturbation by an unforeseen event are reduced. Thus, the crop forecast system should aim to produce reliable crop hectarage information early in the season and then concentrate on increasingly accurate yield and production forecasts as the crop nears harvest.

Table 1. USDA current forecast accuracies and 1985 goals for wheat production estimates in six countries.

Country	Forecast			
	Early season*	Mid-season†	Pre-harvest‡	At harvest
		Current accuracy		
Argentina	46/90		61/90	64/90
Brazil	8/90		31/90	31/90
Canada	26/90		45/90	94/90
India	57/90	64/90	88/90	
U.S.S.R.	23/90	31/90	34/90	65/90
United States	90/90§	100/90	100/90	100/90
		1985 goal		
Argentina	60/90		75/90	80/90
Brazil	30/90		50/90	60/90
Canada	50/90		60/90	95/90
India	70/90	75/90	90/90	90/90
U.S.S.R.	50/90	60/90	65/90	85/90
United States	90/92	95/95	99/95	99/95

*From 90 to 120 days before harvest. †From 45 to 60 days before harvest. ‡From 15 to 30 days before harvest. §Winter wheat only, 1 June.

The Large Area Crop Inventory Experiment

Although the need for improved crop forecasts had been recognized for some time, the means did not exist to make such forecasts in inaccessible regions of the globe. It was the concerted efforts of remote sensing scientists and other researchers over the past two decades that made available for the first time a promising solution. Major technological developments included (i) multispectral scanners capable of scanning the earth's surface and producing a quantitative radiometric map at visible, near-infrared, and thermal infrared wavelengths; (ii) pattern recognition techniques that permitted crops to be identified on the basis of differences in spectral reflectance during the year; (iii) high-speed digital computers; (iv) the 1972 launch by NASA of the first of the Landsat series of polar-orbiting satellites—synoptic platforms for the multispectral scanners—making it possible to monitor each point on the globe every 18 days; (v) the development of a global weather-reporting network by the World Meteorological Organization (WMO); and (vi) the development of models capable of relating weather to crop yields.

A proof-of-concept experiment, LACIE was designed (i) to assimilate this remote sensing technology, (ii) to apply the resultant experimental system to monitoring wheat production worldwide, (iii) to isolate and rank key technical problems, (iv) to modify the approach as necessary and conceivable, and (v) to demonstrate the technical and cost feasibility of a global agricultural monitoring system.

In the LACIE design, heavy emphasis was placed on an objective, quantitative evaluation of the technology under as many representative global agricultural conditions as possible. Timeliness and accuracy goals were established. The LACIE experimental inventory system was designed to achieve monthly at-harvest production estimates that would converge to within 10 percent of the true estimate at the national level with a confidence of 90 percent. To evaluate the LACIE system, an extensive accuracy assessment effort (*8*) was incorporated into the design. In addition, peer groups consisting of recognized experts in industry, the academic community, and government were periodically invited to review in depth the technical approach and results. During the course of LACIE there were six reviews of 3 to 4 days each involving more than 75 peer group members.

LACIE was conducted in three phases, each covering a global crop year. In phase I, beginning in November 1974, existing remote sensing technology was tested over the nine-state U.S. Central Plains region. Test results were sufficiently encouraging to expand testing in phase II to include wheat regions in the U.S.S.R. and Canada. In this same period, technology problems uncovered in phase I were addressed by the supporting research effort. In phase III, a second-generation technology, developed in phases I and II, was used to forecast the 1977 Soviet wheat crop at the country level. Evaluations were continued in the U.S. nine-state region, where detailed ground observations and USDA crop estimates were available for comparison. A limited amount of ground-observed data was collected in Canada as well. The project also conducted exploratory studies in India, China, Australia, Argentina, and Brazil.

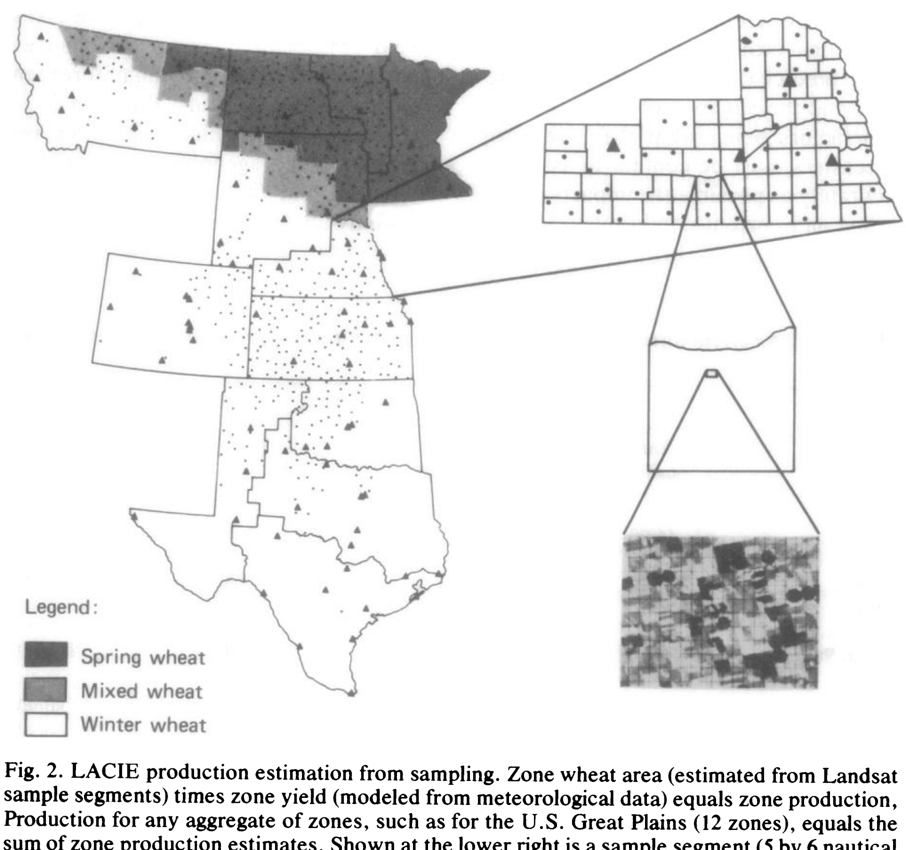


Fig. 2. LACIE production estimation from sampling. Zone wheat area (estimated from Landsat sample segments) times zone yield (modeled from meteorological data) equals zone production, Production for any aggregate of zones, such as for the U.S. Great Plains (12 zones), equals the sum of zone production estimates. Shown at the lower right is a sample segment (5 by 6 nautical miles) used for classification analysis of Landsat data; there are 601 segments in the Great Plains. Triangles denote zone primary weather stations.

Crop Forecast Technology

The remote sensing crop forecast system developed and evaluated by LACIE used Landsat multispectral scanner data to identify crops and estimate their hectarage for harvest and used global weather data from the WMO ground network to forecast yield for harvested hectares. Instead of complete coverage by Landsat, a stratified random sample was employed. This 2 percent statistical sample of the data incurs a sampling error of less than 2 percent.

Locations of the sample unit sites and temporal windows for Landsat data acquisitions were specified by LACIE personnel at the Johnson Space Center (JSC) in Houston and transmitted to Goddard Space Flight Center in Greenbelt, Maryland. Goddard personnel then commanded the satellite to acquire the requested data. These acquisitions were edited out of the data stream, spatially registered to previous acquisitions, and transmitted to Houston for entry into a large electronic data base. During LACIE, nearly 40,000 acquisitions were transmitted, 18,000 during phase III. Processing of these data for episodic event detection and crop area estimation was conducted at JSC.

The global meteorological data were acquired from the Global Telecommunications System of the WMO, the U.S. Air Force Environmental Technical Applications Center, and the NOAA Environmental Satellite Service. These data were stored on computer data bases at the National Meteorological Center in

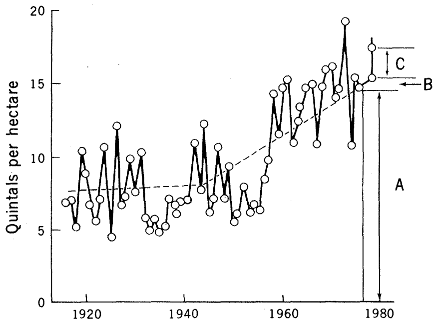


Fig. 3. LACIE yield determination by mathematical models. Yield = A (preceding year yield for average weather) + B (yearly adjustment for technology trend) + C (effects of current weather).

Production was computed as the product of the zone wheat hectarage and the zone yield. The variances of these estimates were also computed. Estimates of area, yield, and production, as well as the variance estimates, could then be summed to obtain estimates and their precisions for any aggregate of zones. Figure 2 summarizes the LACIE production estimation scheme. Such aggregations were made monthly throughout the growing season. Reports for the U.S. Great Plains, the U.S.S.R., and Canada were mailed to the USDA before the USDA released independent estimates for the same regions. The variance estimates, as well as comparisons with the USDA estimates, were used to assess the accuracy of LACIE estimates in terms of the 90/90 criterion.

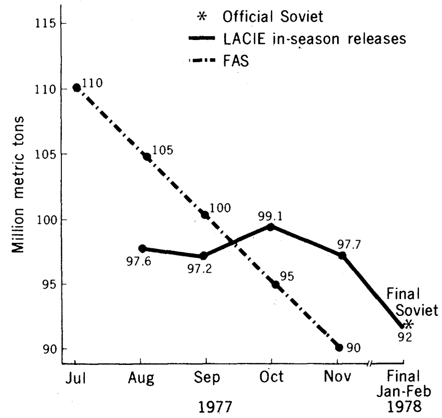


Fig. 4. LACIE phase III total U.S.S.R. wheat production results for 1977 compared to FAS and official Soviet estimates.

Suitland, Maryland. Processing of these data for yield forecasting and crop maturity stage estimation was controlled by NOAA's Center for Climatic and Environmental Assessment at Columbia, Missouri. Yield forecasts were transmitted to JSC for input to the production forecasts. Regional meteorological and qualitative crop condition summaries, used in crop identification, were provided by NOAA personnel at JSC.

Although ground-acquired data on crop identification and crop condition were not used directly to estimate crop area in the LACIE system, such data were used to develop techniques and to assess the accuracy of the LACIE crop forecasts. To support the development of techniques, spectrometer and other field measurements were acquired at several intensive study sites.

Sampling and aggregation. A stratified random sample of Landsat data was used to estimate area. In the United States the strata were counties, in the U.S.S.R. they were oblasts, and in Canada census districts. The sample unit was a segment measuring 5 by 6 nautical miles. Although this relatively large unit was not the most efficient for sampling, it was needed to give analysts sufficient spatial context to identify crops. The United States was allocated 601 such samples, the U.S.S.R. 1947, and Canada 283. The Landsat data acquired from a sample segment were used to estimate the areal proportion of wheat growing in that segment. An average of all segments in each stratum was used to compute the stratum wheat hectarage. Stratum hectarages were then aggregated to "zones" selected to be relatively homogeneous with respect to wheat distribution, climate, and soils. Meteorological data from the primary weather stations were used as input to zone-specific yield models to compute zone yields. In the U.S. Great Plains there were 12 such zones.

Landsat data analysis procedures. Before LACIE, techniques for analyzing multispectral data to identify crops were highly manual and required analysts experienced in machine processing theory. To identify the crops in a data segment took an analyst 2 weeks or more during the Corn Blight Watch Experiment (*9*), a large-area test of remote sensing that preceded LACIE. For LACIE, with anticipated data loads in excess of 50 segments a day, manual analysis requirements had to be significantly reduced. An analysis procedure had to be designed so that one person could analyze a segment in no more than 1 day, and that person should not have to be highly trained in machine processing theory. Much effort was expended before and during LACIE to achieve these ends. These efforts culminated in a machine processing procedure named Procedure 1. Procedure 1 was a four-step process.

First, the Landsat computer-generated film imagery and ancillary data were prepared and assembled into packets to be used by analysts to identify crops. Landsat data included available full-frame (100 by 100 nautical miles) color-infrared (CIR) film and segment-level CIR film products generated at JSC from digital data, as well as graphic and numerical representations of multispectral scanner data. Ancillary data included such historical agronomic information as crop maturity calendars, cropping practices, and field size, as well as modeled adjustments to the normal wheat crop calendar in response to the current year's weather (*10*) and summaries of the meteorological and crop conditions for the current crop year.

Next, the analyst used image interpretation procedures to label as "small grain" or "other" about 100 Landsat pixels (picture elements, each representing about 1 acre) preselected at random from a grid covering the segment. With spectral data from a proper sequence of Landsat acquisitions and estimates of the stages of development of small grains and confusion crops at those dates, the analyst could, in most instances, identify small grains and distinguish them from other crops. The analyst depended primarily on temporal differences in the visible and infrared reflectances of small grains and other crops. These temporal differences result from differences in the densities and colors of the various crops growing and maturing at different rates. The analyst used the ancillary agricultural data to determine what other crops had to be separated from small grains. The meteorological summaries were needed so that the analyst could note unusual conditions such as droughts or floods that could affect crop appearance.

Third, about 40 of the 100 analyst-labeled pixels were used to train clustering and maximum likelihood classification algorithms to classify as small grain or other each of the segment's 23,000 pixels. Analyst and computer identifications for the remaining 50 analyst-labeled pixels were then compared to estimate the frequency of agreement between analyst and computer. This frequency of agreement was used to "correct" the percentage of pixels computer-classified as small grain to estimate the proportion of the segment area where small grains were growing. A projection of the hectarage ratio of wheat to small grain, based on econometric models (*11*), was used to convert the estimate to wheat.

Finally, the analyst evaluated the acceptability of the result before submitting the data to production aggregation. Thus, the Landsat data analysis can be characterized as a manually assisted machine processing approach. The analyst typically spent 2 to 3 hours on a segment

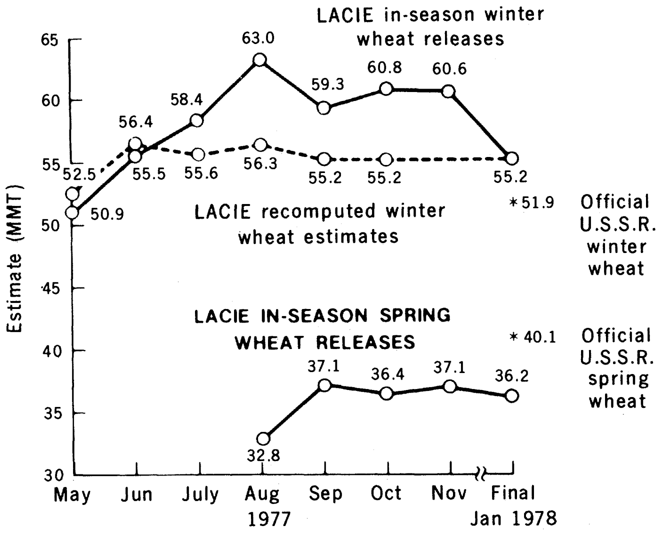


Fig. 5 Contributions of LACIE estimates of U.S.S.R. winter and spring wheat production for 1977 to total production results (Fig. 4).

to label 100 pixels, while the machine labeled all 23,000 pixels in the segment in 2 to 3 minutes.

Yield forecast procedures. The yield for harvested hectares was forecast in LACIE through the use of regression models that incorporated weather variables obtained from the stations of the WMO network. These models (*12*), referred to as agrometeorological models, were based on multiple linear regressions of historical yields and monthly averages of temperature and precipitation effects (Fig. 3). In the U.S. Great Plains yardstick region, nine winter wheat and five spring wheat models covered 12 zones. These zones were Montana, South Dakota, North Dakota, the Red River Valley, Minnesota, Nebraska, Colorado, Kansas, Oklahoma, the Texas Panhandle, the Texas Lower Plains, and the Edwards Plateau. The data series used to develop the U.S. models was approximately 45 years long. In the U.S.S.R., 15 winter wheat and 16 spring wheat models covered 33 zones. The data series available to develop these models was only 10 years long. In both the United States and the U.S.S.R., the historical yield data for each zone consisted of a hectarage-weighted sum of the data for the smallest reporting areas within the zone. For example, the average monthly temperature for a U.S. zone was the sum of the average monthly temperatures for the counties weighted by each county's proportion of the hectarage.

Accuracy Assessment and Evaluation

An extensive accuracy assessment program was conducted to evaluate the performance of the LACIE technology; error contributions from the various technology components were estimated, as were the effects on performance of key agricultural and climatological factors. The accuracies of area, yield, and production estimates were established by statistical comparisons to ground observations and independent government figures. Statistical approaches were used to test the hypothesis that relative differences between LACIE at-harvest production estimates and actual production would be no greater than 10 percent in 9 out of 10 years. To test such a hypothesis, without actually operating for many years, required that several assumptions be made. First, as described in (*13*), this test was based on the assumption that, over a period of many years, the production estimates would be normally distributed. Second, the variance of this normal distribution was assumed to be related to estimates of the area and yield variances for a single year by the relation

$$V(\hat{P}) = \sum_{1}^{n} [V(\hat{Y}_i)A_i^2 + Y_i^2V(\hat{A}_i) + V(\hat{A}_i)V(\hat{Y}_i)] \quad (1)$$

where $V(\hat{Y}_i)$ is the square of the yield prediction error for the ith zone; A_i is the historical average wheat area for the zone; Y_i is the historical average yield for the zone; and $V(\hat{A}_i)$, the variance of the LACIE wheat area estimates, $\hat{A}_i$, is estimated directly from the component segment estimates and depends strongly on

$$V(\hat{A}_i) = \frac{1}{n-1} \sum_{j}^{n} [\hat{A}_j - E(\hat{A})]^2 \quad (2)$$

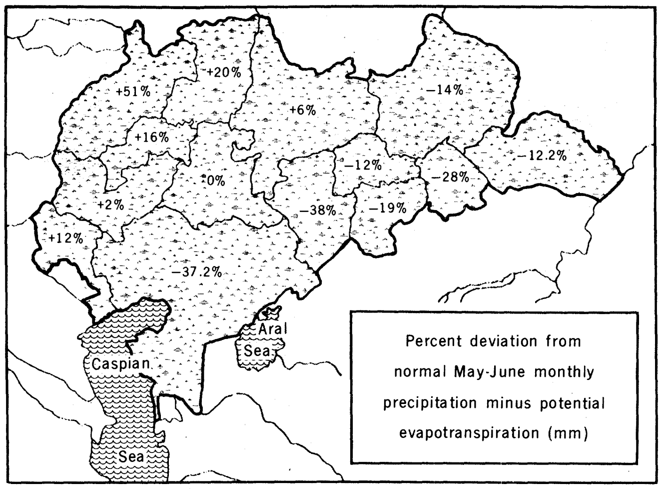
Equation 1 requires independence of the segment area estimates, independence of the zone yield estimates, and independence of the area and yield estimates from each other. While statistical independence is not strictly satisfied, empirical observations indicate that the effects of dependence on Eq. 1 are reasonably small.

An additional assumption results from the fact that in Eq. 1, $V(\hat{A}_i)$ and $V(\hat{Y}_i)$ are estimates of the variance pertaining to a specific year; thus, estimates of $V(\hat{P})$ pertain to the conditions in that year. An evaluation of the 90/90 criterion using this estimate of $V(\hat{P})$ requires that a single-year estimate be representative of several years of operation. The $V(\hat{A}_i)$ and $V(\hat{Y}_i)$ estimated during LACIE (3 years for area, 10 years for yield) were observed to change very little between years. Thus, $V(\hat{P})$ as estimated by Eq. 1 is believed to be reasonably representative of the between-year variance over several years.

Perhaps the most important issue concerning performance is estimation of the bias, $E(\hat{P} - P)$, where P is the reference estimate of the actual production. As discussed in (*13*), for a given value of the coefficient of variation (CV) of $\hat{P}$, which is defined by $[V(\hat{P})]^{1/2}/E(\hat{P})$, the 90/90 criterion will be satisfied only when the bias is within a given tolerance; however, this tolerance is about equal to CV ($\hat{P}$). For the country-level estimates, the LACIE sample was designed to achieve a CV($\hat{P}$) of about 5 percent. To satisfy 90/90, the concomitant relative bias must be less than 4 percent.

Given a single-year observation of $\hat{P} - P$ and statistical noise in $\hat{P}$ of 5 percent, the hypothesis that the relative bias is less than 4 percent cannot be accepted with a large degree of confidence. LACIE estimates of the Soviet wheat crop during 1977 had a CV of 3.8 percent. For a CV of 3.8 percent, a relative bias of about 5.5 percent is tolerable. An at-harvest difference of only 1 percent was observed between the LACIE estimate and the Soviet *estimates* of their actual production (*14*). Thus, while this single observation of the relative difference is well within tolerance, it does not guarantee a relative bias of 5.5 percent when averaged over a longer period of operation.

While the 90/90 evaluations must be viewed in the light of the required assumptions, strong additional verification was obtained from the intensive evaluation of the technology components in the United States, where USDA estimates are believed to be quite reliable and where extensive ground observations in 175 sample segments were available. At these sites, USDA agents acquired data in each field and recorded them on high-altitude aerial photographs. The photography was then digitized and spatially registered to the Landsat data to permit automatic comparisons between ground



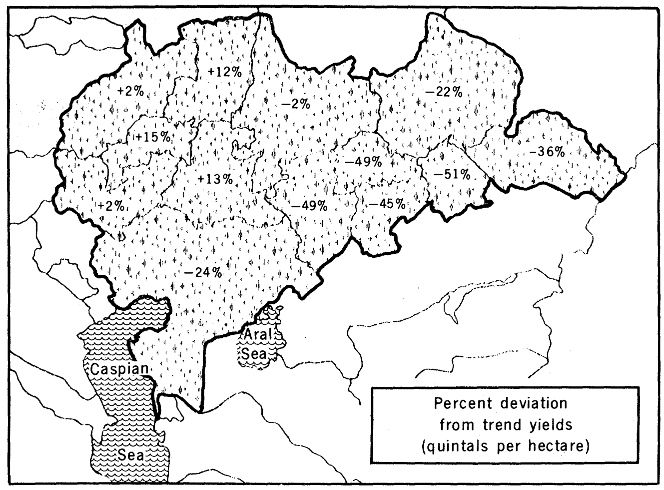


Fig. 6 (left). Percent deviation from normal May-June monthly precipitation minus potential evapotranspiration (computed by the Thornthwaite method) for U.S.S.R. spring wheat regions during 1977. Fig. 7 (right). Percent deviation from trend yields in 1977, as forecast by the LACIE yield models for U.S.S.R. spring wheat.

observations and analysis results. These comparisons permitted the total area estimation error to be assessed in terms of bias and variance due to classification error. The probability of correct identification of wheat could also be assessed at the segment, field, or pixel level and related to observed agricultural and meteorological events.

Since yield was modeled at the zone level, it could not be evaluated at the segment level as could area. A statistical test utilizing historical data at the zone level was developed to test these models. Each model was tested for its ability to predict zone yields with sufficient accuracy to support the 90/90 criterion for ten independent test years within a historical series of yield data. These tests are reported in detail in (*8*), as are all the accuracy assessment methods.

System Performance

The efficiency and capacity of the LACIE system improved markedly during the 3 years of operation. While the scope increased fourfold in the number of active segments (700 in phase I to 3000 in phase III), ninefold in the number of Landsat acquisitions (2000 in phase I to 18,000 in phase III), and fivefold in the number of segments that were machine processed (1100 in phase I to 5000 in phase III), the number of analysts declined slightly. This was possible because more efficient analysis procedures reduced the analyst contact time to 2 hours per segment, one-fourth the phase I level. Yield estimates, weather summaries, and crop calendar estimates increased by a factor of 4 and were generally provided on schedule. The number of commodity and accuracy assessment reports also increased by a factor of 4.

It was generally concluded from these results that current data processing technology coupled with sound statistical sampling practices can cope with the volume of data required to monitor major crop regions of the world.

Results and Discussion

Phase III Soviet results. In 1977 LACIE monitored U.S.S.R. wheat production from early season through harvest. Monthly commodity production forecasts were sent to the USDA in Washington the day before the corresponding public release by its Foreign Agricultural Service (FAS). LACIE made its first forecast of Soviet winter wheat production on 1 April 1977 and its first forecast of spring and total wheat on 8 August 1977. Figure 4 shows the LACIE in-season forecasts for U.S.S.R. total wheat, the FAS forecasts, and the official Soviet estimate.

The initial LACIE in-season forecast of total U.S.S.R. wheat production was 97.6 million metric tons (MMT), about 11 percent below the FAS projection and 6 percent above the final U.S.S.R. figure of 92.0 MMT (*15*). The final LACIE estimate of 91.4 MMT differed from the final Soviet figure by about 1 percent. The estimated coefficient of variation in the final LACIE estimate was 3.8 percent. This difference and CV are consistent with those required for the 90/90 accuracy criterion.

The early-season LACIE forecasts for U.S.S.R. winter wheat ranged from 51 to 55 MMT, indicating a near-record winter wheat crop (Fig. 5). The LACIE April and May winter wheat area estimate of about 21 million hectares indicated that U.S.S.R. planting was 15 percent above average and 22 percent above the 1976 figure. Moreover, LACIE yield forecasts stood at 25.5 quintals per hectare, 11 percent above the Soviet average. By July, spring wheat fields had grown to the point of detectability by Landsat. The August area estimate of 39 million hectares indicated that the U.S.S.R. spring wheat planting was almost 9 percent below average. This, combined with the LACIE yield model forecast of a 20.5 percent decline in yield from average, indicated that the Soviet spring wheat production would suffer a major reduction, falling 30 percent below average (*16*). These trends held and LACIE correctly forecast that the U.S.S.R. would achieve only an average total wheat crop.

The FAS estimated Soviet wheat at about 97 MMT in February 1977 (*17*) and steadily increased its forecast to a high of 110 MMT in July (*18*), primarily in response to its expectation of a much better than average Soviet winter wheat crop and its forecast of an average or better spring wheat crop. As can be seen in Fig. 4, FAS began to decrease its U.S.S.R. forecast in August. The final FAS release, on 20 October 1977 (*19*), carried a wheat estimate of 90 MMT.

In late January 1978, the U.S.S.R. announced its 1977 wheat production as 92 MMT—51.9 MMT of winter wheat (9.8 MMT above average) and 40.1 MMT of spring wheat (8.1 MMT below average). The LACIE final winter and spring wheat area, yield, and production estimates did not differ significantly from the Soviet figures. These accuracies are also consistent with the 90/90 criterion.

As Fig. 5 shows, the LACIE winter

wheat forecast increased from the May to the August report. Previous experience indicated that the increase from May to June was the result of steadily increasing visibility to Landsat of the emerging winter wheat canopy in March and April. However, since winter wheat had completely emerged by June, the continued increase in the winter wheat hectarage estimate through July and August had no known physical basis. The spring wheat estimate stabilized as expected. An analysis of the winter wheat problem indicated that, for about 20 percent of the winter wheat segments, Landsat data were mistakenly not acquired during March and April. This period is critical for distinguishing between the two major grain types because winter grains are greening after their dormancy and spring grains have not yet emerged. Estimates were being made for segments with May Landsat passes only, and analysts could not separate spring and winter grains. To determine the effect of this error on the estimates of hectarage, estimates in the affected segments were treated as total grain hectarages. They were reduced to winter wheat hectarages by multiplying them by historical ratios of winter wheat to total grain hectarage for the local region.

Table 2. Comparison of FAS and LACIE phase II estimates for U.S.S.R. winter and spring wheat indicator regions, 1976.

Estimate	Area (10^6 ha)	Yield (quintal/ha)	Production (MMT)
	Winter wheat		
FAS	11.3	27.6	31.2
LACIE	14.2	24.6	34.9
Relative difference, percent*	20.4	−12.2	10.6
Coefficient of variation, percent	6	5	7
	Spring wheat		
FAS	17.1	11.3	19.3
LACIE	19.1	10.5	20.1
Relative difference, percent*	10.5	−7.6	4
Coefficient of variation, percent	4	8	9

*Calculated as [(LACIE − FAS) ÷ LACIE] × 100.

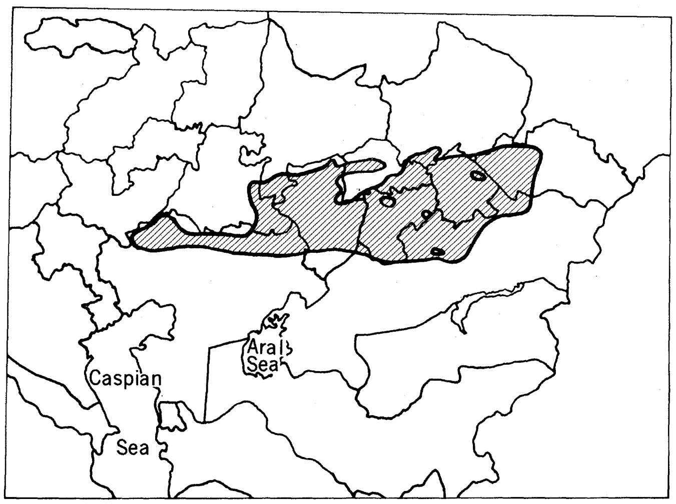


Fig. 8. Stressed vegetation areas (shaded) mapped from Landsat radiometric measurements of U.S.S.R. spring wheat areas in July 1977.

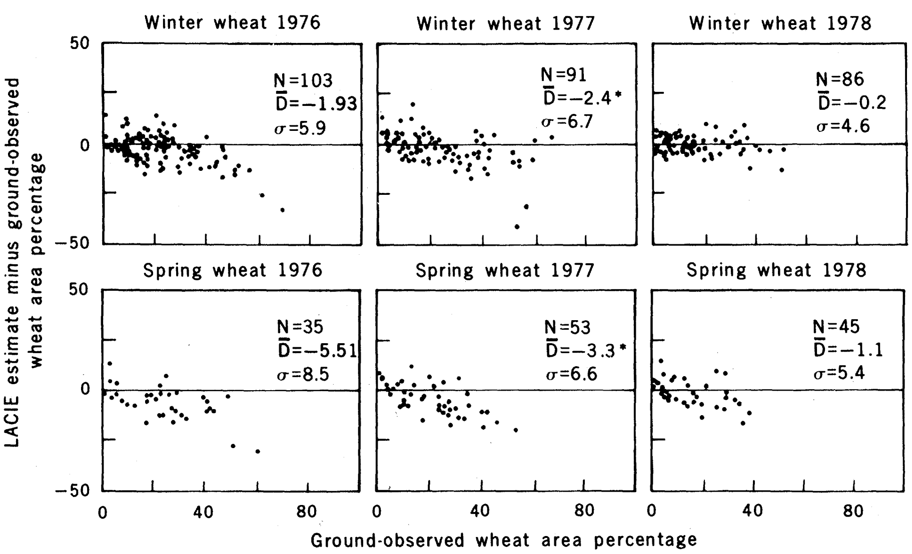


Fig. 9. LACIE estimates compared with ground observations for test sites in the U.S. Great Plains (1978 data are from LACIE follow-on). N is number of blind sites for which Landsat acquisitions were adequate to make estimates; $\bar{D}$ is the average of the sequential differences between LACIE estimates; ●, ground observations; σ, standard deviation of the difference; *, significant bias at a 10 percent level of confidence.

The dashed line of Fig. 5 shows the recomputed winter wheat production estimates obtained in this way. The recomputed estimates represent the seasonal forecasts that would be expected operationally. As winter wheat completed its emergence, the production estimates stabilized. Fluctuations thereafter were dominated by changing estimates of yield. A similar behavior can be noted in the real-time estimates of Soviet spring wheat, which were unaffected by the Landsat data order error.

From the meteorological inputs (monthly average temperature and precipitation) to the LACIE yield models, a clear pattern of drought emerged, the apparent result of a shortage in available soil moisture. Available soil moisture, a predominant term in the yield models, was estimated for a Soviet crop region as the difference between the monthly precipitation and the potential evapotranspiration (*20*) for the region. Figure 6, a display by crop region of the percent deviation from normal in estimated available soil moisture, indicates a clear pattern of potential drought in the heart of the Soviet spring wheat region. Consequently, LACIE yield estimates for these regions decreased, as shown in Fig. 7.

This pattern of drought and consequent yield reduction was corroborated by the Landsat data. In each LACIE sample segment, the level of drought stress was estimated from Landsat digital data by the method of Thompson and Wehmanen (*21*). Figure 8 indicates the geographic area for which the Landsat data were indicating severe drought stress. This area overlaps every region where the LACIE technology was forecasting a below-normal yield.

For the northern crop regions, however, LACIE was forecasting above-average yields. The total effect on production of these counterbalancing tendencies could be assessed only if the wheat area in each of these crop regions was known. Thus, the LACIE hectarage estimates for each crop region were multiplied by the yield forecasts to obtain production estimates. When these individual production figures were summed, the overall estimate of spring wheat production was 36.3 MMT, about 21 percent below normal, which, as discussed earlier, compares quite favorably with the Soviet estimate.

Phase II Soviet results. In the initial test of the LACIE technology for the Soviet Union, a portion of their wheat crop was monitored over "indicator regions" during the second year of LACIE. The analysis procedures, however, were not those used in phase III but those used in phase I. The comparison of LACIE estimates with Soviet estimates was also complicated by the lack of complete Soviet figures at the indicator region level; however, as can be seen from Table 2, the LACIE final estimates of area, yield, and production were in reasonable agreement with FAS estimates for these regions. Although differences between these estimates cannot be considered statistically significant, a tendency to overestimate Soviet winter wheat area was observed. In general, however, because of the much larger fields on the Soviet state farms, analysts judged the Soviet Union an easier analysis task than the United States and Canada, with their much smaller farms and fields. The phase II results were sufficiently encouraging that the LACIE Soviet test was expanded to the full-country level in order to obtain a more reliable set of comparison statistics and encounter the full range of variability in the Soviet wheat crop.

Table 3. Relative differences between LACIE and USDA final figures for the U.S. Great Plains with coefficients of variation.

Period	Area	Yield	Production
	Winter wheat reference region		
Phase I (1975)	− 0.1 ± 7.0	4.2 ± 2.6	5.0 ± 7.0
Phase II (1976)	− 7.3 ± 5.0	0 ± 5.0	− 7.2 ± 7.0
Phase III (1977)	4.6 ± 3.2	− 8.2 ± 5.1	− 3.4 ± 5.8
	Spring wheat reference region		
Phase I (1975)	−30 ± 9.8	4.7 ± 4.1	−25 ± 11
Phase II (1976)	−26 ± 6.0	3.4 ± 7.0	−22 ± 10
Phase III (1977)	− 8.5 ± 3.5	−16 ± 8.4	−26 ± 9.0
	Total wheat—spring and winter		
Phase I (1975)	−11 ± 5.7	4.3 ± 4.0	− 5.6 ± 5.9
Phase II (1976)	−14 ± 4.0	1.1 ± 4.0	−12 ± 5.0
Phase III (1977)	0.4 ± 2.4	−10 ± 4.3	−10 ± 4.8

U.S. and Canadian experiments. The U.S. test area was comprised of winter wheat and spring wheat regions in the U.S. Great Plains. The spring wheat region included an area where no winter grains were grown and an area where spring and winter grains were mixed. LACIE technology was also evaluated throughout Canada, a country that grows only spring wheat with practices similar to those used in the U.S. northern Great Plains. In these two countries, independent and very reliable data were available for comparison at the regional, state, sample segment, and field levels. The LACIE estimates of winter and spring wheat hectarage for test sites in the reference region were compared to ground observations. The results for the 1976, 1977, and 1978 crop years are shown in Fig. 9. Substantial improvement was realized with increased experience and better procedures (*22*). At the Great Plains level, the LACIE estimates of winter wheat production, yield, and hectarage ranged from satisfactory to excellent in replications of the experiment in the reference region over three crop years (Table 3).

Although significant improvements were also realized in U.S. spring wheat estimates over the three crop years, the accuracies achieved were much lower than those for the U.S. winter wheat region. The poorer area estimation accuracies were due to the predominance of narrow fields and to confusion crops. LACIE significantly underestimated the hectarage of spring wheat in both the United States and Canada in 1975 and again in 1976. The ground-observed sample sites clearly showed that a primary source of the error was the limited resolution of the Landsat multispectral sensor. The sensor was not able to resolve the narrow strip-fallow wheat fields (Fig. 10). As a result, these fields were misclassified and the area of wheat underestimated (*23*).

While this strip-fallow practice is

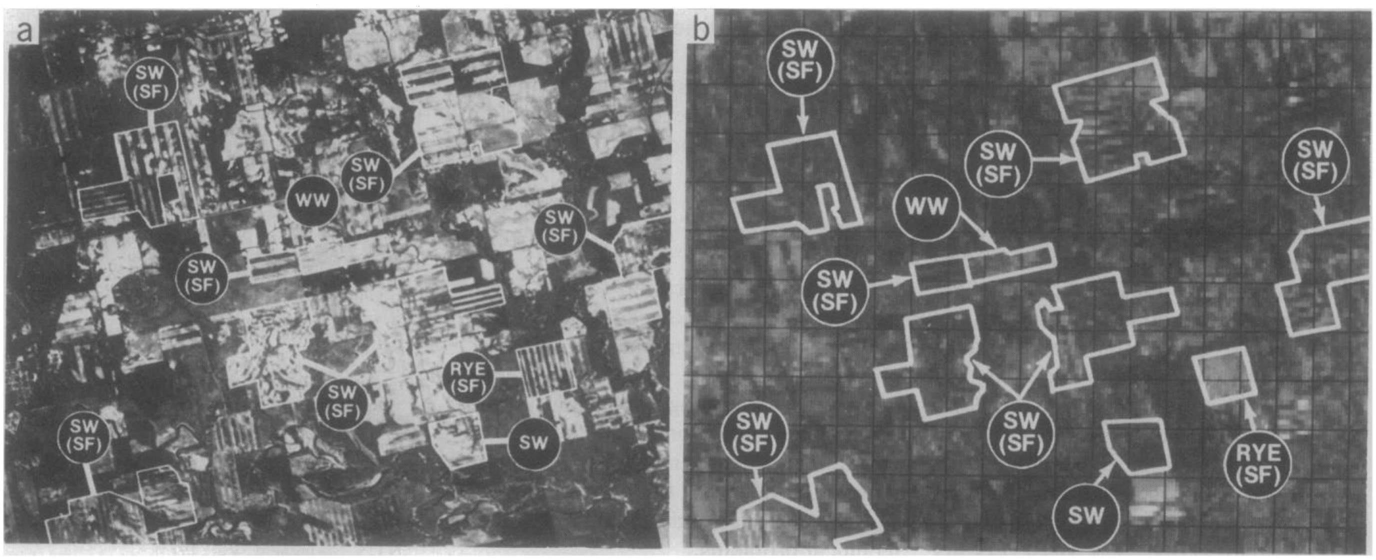


Fig. 10. Comparison of (a) low-altitude aerial photograph of strip fields with (b) Landsat image of the same area. Abbreviations: *SW*, spring wheat; *WW*, winter wheat; *SF*, strip fields.

widely followed in the northern United States and Canada, it is not prevalent in the U.S.S.R. Therefore, the Landsat resolution was found adequate for the U.S. hard red winter wheat region with its relatively large fields and for the still larger fields in both the winter and spring wheat regions of the U.S.S.R. Thus, while the U.S. and Canadian investigations substantiated the performance of the LACIE approach used in the U.S.S.R., they also revealed that, where field width is on the order of the current Landsat sensor resolution (80 meters), better sensor resolution, such as that to be provided on Landsat D, is required.

Another factor contributing to wheat area estimation errors in some regions was the presence of certain confusion crops such as spring barley, which looks very much like spring wheat. In the spring wheat region, a two-step process was used to estimate wheat hectarage. The area of spring grains was first estimated from Landsat data and then econometric models were used to infer wheat hectarage. These models used a time series of crop hectarages to predict the hectarage ratio of wheat to small grains for the current year.

The performance of the U.S. ratio models was reasonably good. However, such econometric models are inapplicable to many foreign situations. Therefore, there continued to be a need to estimate wheat directly from the Landsat data. Work done after the completion of LACIE has shown that barley can be discriminated from wheat given Landsat coverage after barley begins to ripen and before wheat begins to ripen, about 2 weeks later. During this period, the preharvest gold of ripening barley can be readily distinguished from other, still green vegetation such as wheat.

Evaluations of the U.S. yield models using 10 years of historical data indicated a performance consistent with the 90/90 criterion except for years with extreme agricultural or meteorological conditions. Table 4 shows the results. The models were developed with data for the 45 years preceding each of the test years. A nonparametric statistical test employed to analyze these 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 would have been rejected. In addition, the root mean squared error (RMSE) of 1.9 bushels per acre is larger than desirable for a 90/90 estimator. It should be noted that 1974 was a very dry year in the U.S. Great Plains and wheat yields were very poor. The LACIE yield models failed to respond to this deviation and overestimated the yield by 4.6 bushels per acre. Without 1974, the RSME would drop from 1.9 to 1.3 bushels per acre, which is not significantly different from that required for a 90/90 estimator. It thus appears that the yield models may satisfy the 90/90 criterion in years without extreme departures from normal yield. As reported earlier, the LACIE yield models were responsive to the departure of the 1977 Soviet spring wheat crop, a departure which, while not extreme, was of great economic importance to the United States and other countries.

Table 4. Results of an evaluation of the LACIE phase III U.S. yield models by comparison with 10 years of independent test data.

Year	Estimate (bushel/acre)		Error*	Within tolerance?
	USDA	LACIE		
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†	27.5	24.9	−2.6	

*Mean error, −0.1 bushel/acre; RMSE, 1.90 bushel/acre. †For comparison only, LACIE 1977 estimates.

Other foreign regions. Exploratory investigations in other wheat regions of the world indicate that the current area estimation technology is generally applicable to regions in the Southern Hemisphere such as Australia and Argentina. The improved sensor resolution of Landsat D will be required for regions such as China and India, where fields are small. Yield model tests in these countries indicate that models less dependent on historical data will be needed for Australia, China, Argentina, and Brazil.

Outlook

LACIE is a major step toward a remote sensing technology capable of global food and fiber monitoring. It has proved the concept of this new technology by providing significantly improved information on one major crop—wheat. The experiment has demonstrated the utility of this technology for several countries and has identified key technical problems.

The next logical steps are (i) continuing refinement of the technology and subsequent transfer to operational test systems and (ii) adaptation of the technology to forecast production of other food and fiber crops such as corn, rice, soybeans, and forest products.

The LACIE participants—NASA, the USDA, and NOAA—and the U.S. Department of the Interior and the Agency for International Development are planning a technology development program to support the possible implementation of an operational global monitoring system.

The Secretary of Agriculture recently announced a new initiative to develop improved uses of aerospace technology for agricultural purposes. The initiative sets the following priorities:

1) Early warning of changes affecting production and quality of renewable resources.

2) Commodity production forecasts.

3) Land-use classification and measurement.

4) Renewable resources inventory and assessment.

5) Land productivity estimates.

6) Conservation practices assessment.

7) Pollution detection and impact evaluation.

While all seven requirements are of major importance to the USDA, the first two requirements essentially capture the department's most urgent need for better, more timely information on world crop conditions and expected production. The agencies that participated in LACIE are planning a follow-on activity for the early 1980's that will build on the LACIE experience and address the broader needs of the USDA.

References and Notes

1. The detailed results of LACIE as well as peer review papers were presented in a 4-day symposium in October 1978. Proceedings of the symposium are available as three reports (*2*–*4*) from the National Technical Information Service (NTIS).
2. *Independent Peer Evaluation of the Large Area Crop Inventory Experiment* (NASA JSC-14550, NTIS, Springfield, Va., 1978).
3. *Proceedings of Plenary Session* (NASA JSC-14551, NTIS, Springfield, Va., 1978).
4. *Proceedings of Technical Sessions* (NASA JSC-16015, NTIS, Springfield, Va., 1978).
5. The discussion of the need for a new crop forecasting system is based on a paper presented by H. W. Hjort to the U.S. Congress, Office of Technology Assessment, 1974, and Scherr *et al.* (*6*).
6. B. A. Scherr, W. E. Kibler, F. G. Hall, in (*3*), pp. 1-16.
7. The term yield is not interchangeable with the term production. Crop yield refers to the average production per unit of crop area; for example, bushels per acre. Crop production refers to the total quantity of produce for a crop; for example, bushels.
8. A. G. Houston, A. H. Feiveson, R. S. Chhikara, E. M. Hsu, in (*4*), pp. 115-130.
9. *Corn Blight Watch Experiment, Summary Report*, vol. 3, *Experiment Results* (NASA SP-353, NTIS, Springfield, Va., 1974).
10. G. W. Robertson, *Int. J. Biometeorol.* **12**, 191 (1968).
11. D. E. Umberger, M. H. Proctor, J. E. Clark, L.

M. Eisgruber, C. B. Braschler, in (4), pp. 19–46.

12. *LACIE: Wheat Yield Models for the United States* (NASA JSC LACIE-00431, rev. A, NTIS, Springfield, Va., 1977); C. M. Sakamoto and S. K. LeDuc, *NASA Tech. Memo. TM-74834* (1977); S. K. LeDuc, *NASA Tech. Memo. TM-74833* (1976). Each LACIE yield model was a zone-specific polynomial based on multiple linear regression of the form $y = x\beta + \epsilon$. The prediction error for this model was computed in the standard statistical manner:

$$(\text{Prediction error})^2 = S^2[1 + x_k'(x_k'x_k)^{-1}x_k]$$

13. The accuracy goal referred to as the 90/90 criterion is equivalent to the probability statement Pr $[|\hat{P} - P| \leq 0.1P] \geq 0.9$, where $\hat{P}$ is the LACIE estimate for a region and P is the true production of the region. Under the assumption that $\hat{P}$ is normally distributed, this probability statement can be written in terms of the coefficient of variation of $\hat{P}$, $\mathrm{CV}(\hat{P})$, and the bias, $B = E(\hat{P}) - P$. In terms of B and $\mathrm{CV}(\hat{P})$, the probability statement becomes

$$\Phi\left[\frac{0.1 - 1.1\,B/E(\hat{P})}{\mathrm{CV}(\hat{P})}\right] - \Phi\left[\frac{-0.1 - 0.9\,B/E(\hat{P})}{\mathrm{CV}(\hat{P})}\right] \geq 0.9$$

where Φ represents the cumulative standard normal distribution. To estimate B, estimates of $E(\hat{P})$ and P are necessary. Direct estimation of $E(\hat{P})$ requires replications of the LACIE analysis at the country level, which limited resources prevented. The true production, P, is also unknown. We assumed the final government estimates to represent P. Fortunately, accurate estimation of $\mathrm{CV}(\hat{P})$ requires no independent government estimates. In all countries where the LACIE system was tested, $\mathrm{CV}(\hat{P})$ was sufficiently small to satisfy the 90/90 criterion (with no bias, $\mathrm{CV} \leq 0.061$). Since $\mathrm{CV}(\hat{P})$ could be accurately estimated, it was treated as a parameter, and the probability equation was solved to determine tolerances $[B_0,B_1]$ on B that would satisfy the 90/90 criterion. We then tested the null hypothesis, H_0, that the LACIE production estimate, $\hat{P}$, resulted from a 90/90 estimator. To test H_0, we first fixed a value of B, say B^*, where $B^* \in [B_0,B_1]$, and tested the subhypothesis $B = B^*$ against the alternative $B \neq B^*$, using the statistic $\hat{B} = \hat{P} - P$ (the single-year estimate of bias at the country level) and assuming $\hat{B} \sim N(B, \hat{\sigma}_{\hat{P}}^2)$. A "probability value" for this test is given by $\Pi(B^*) = \Pr[|B - B^*| > |b - B^*|]$, given $B \sim N(B^*, \hat{\sigma}_{\hat{P}}^2)$, where b is the observed difference between the LACIE and the official government production estimate. The overall hypothesis, H_0, is rejected if $\max_{B^* \in [B_0,B_1]} \Pi(B^*) < \alpha$, where α is a predetermined significance level.

14. A critical issue for technology evaluation in foreign countries is the reliability of the government's assessment of its own crop. In the U.S.S.R., reliability estimates are not available. Soviet production estimates are believed to be more reliable (6) than area or yield. The Soviets have no national survey for yield and only an incomplete survey for harvested area.

15. The U.S.S.R. releases a planning figure for total grain production early in the year and a post-harvest estimate of total grain production in early November; wheat statistics are not released until the following January or February.

16. For the years 1971 to 1976, averages are given in *U.S. Dep. Agric. Econ. Res. Serv. Foreign Agric. Econ. Rep. 132* (April 1977).

17. "Wheat situation," *U.S. Dep. Agric. Econ. Res. Serv. Rep. WS-239* (February 1977).

18. "Second forecast of 1977 Soviet grain crop," *U.S. Dep. Agric. Foreign Agric. Serv. Rep. FG 10-77* (8 July 1977).

19. "World grain situation 1977/78, crop and trade development," *U.S. Dep. Agric. Foreign Agric. Serv. Rep. FG 21-77* (20 October 1977).

20. Computed by the method of C. W. Thornthwaite, *Geogr. Rev.* **38**, 55 (1948).

21. D. R. Thompson and O. A. Wehmanen, *Photogramm. Eng. Remote Sensing* **45**, 201 (1979).

22. No test sites were available in 1975 for the total U.S. Great Plains. Most recent results of 1978 LACIE follow-on testing are included in Fig. 8 for comparison with 1976 and 1977.

23. A strip-fallow field is a series of narrow, alternating strips of small grain and fallow soil, which are rotated on a yearly basis to collect a soil moisture reserve before planting.

A Federalist Strategy for Nuclear Waste Management

Kai N. Lee

Summary. The federal government plans to rely on a policy of "consultation and concurrence" with state governments in developing nuclear waste repositories. The weaknesses of the concurrence approach are analyzed, and an alternative institutional framework for locating a waste repository is proposed: a siting jury that provides representation for state and local interests, while maintaining a high level of technical review. The proposal could be tested in the siting of away-from-reactor storage facilities for spent nuclear fuel.

Once or perhaps twice in the remainder of this century the U.S. government will establish a permanent repository for high-level radioactive wastes. Entangled in the wider controversy over nuclear energy, the siting of a waste repository has become an unwieldy and controversial task. Since March 1977 more than 15 states have enacted laws that regulate storage or forbid disposal of radioactive wastes within their borders (1).

President Carter announced on 12 February a new policy on nuclear wastes (2). His statement embraces many of the recommendations of the Interagency Review Group on Nuclear Waste Management (IRG) chartered by the President in 1977 (3). The new policy provides that state governments are to have a "continuing role in decision-making with regard to the federal government's actions" (4) in nuclear waste disposal. This is the principle of "consultation and concurrence."

"Consultation and concurrence" is, perhaps unwittingly, a reaffirmation of traditional American values. Beer wrote of the Constitution (5),

> The essence of the invention of 1787 was the use of the same electorate to choose two sets of governments, each with constitutional protection. . . . Governing himself through two governments, the voter views the political world from two perspectives, one shaped by the social pluralism of the general government, the other shaped by the territorial pluralism of the state government.

The idea of giving state governments a role commensurate with federal executive agencies is so old that it has had to be rediscovered.

There is consensus on consultation. Sharing of information between federal and state authorities is widely thought to be an essential steppingstone toward orderly siting (6).

If consultation enjoys support, "concurrence" elicits delicate evasion and postponement. "States and localities will accept their share of responsibility," an interpretation by the Department of Energy (DOE) assumes (6), without suggesting why this acceptance should be expected. Indeed, no state will generate enough waste from commercial nuclear power to approach the capacity of a single geologic repository; what does a fair "share of responsibility" comprise? Which decisions should be taken to be final, once ratified by federal executive agencies and state governments? Land tenure, financing and capitalization, and transfer payments to mitigate localized impacts could presumably be settled in this fashion. But what about the roles of local government, citizen groups, or the Nuclear Regulatory Commission (NRC)? More generally, how are long-run interests and short-term pressures to be reconciled? Environmental pollution

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