STATEMEMT OF CHARLES MATHEWS, ASSOCIATE ADMINISTRATOR, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Mr. MATHEWS. Thank you very much.

The important feature of a space system, of course, is its ability to cover the entire world and do it extremely rapidly. So as compared to other types of information-gathering systems, the satellite system is looked to for timeliness and breadth of coverage.

I think the best way to illustrate that is to talk about something which has reached a high level of maturity-communication satellites.

I think we all understand and appreciate their utility because now telephone communications or television communications can be provided throughout the entire world to nations large and small and can be moved rapidly into place as the need arises.

Communication satellites relate very strongly to agriculture in many ways. We have a very big communications satellite now positioned over Africa, from where it is broadcasting to very small receivers in remote villages in the country of India. One of the chief functions of this cooperative experiment is to provide agricultural-farming type educational information to 5,000 villages.

Some of these villages are very primitive. I have been there myself. They do not at this time have electricity in some cases. The power to run these TV sets is provided by batteries that are charged by bicycle power.

The response to this educational type program has been exceedingly enthusiastic on the pant of these villagers and is producing very marked effects; they continue to ask for educational material as compared to entertainment.

Now, in a very similar way, meteorological satellites have come into being and are serving their useful purposes. We are all aware of their employment for warning of hurricanes and other storms. These satellites now provide very sophisticated information. They can measure temperatures in the atmosphere any place in the world. They provide indications of moisture conditions throughout the world. Furthermore, the information from these satellites, along with ground-based information, is fed into a worldwide network through which information about ongoing weather as well as information to predict the weather is now being provided on a worldwide basis through the auspices of the World Meteorological Association.

The value of weather information to agriculture is obvious: When does the farmer plow ? When does he harvest and so forth?

But in addition to that, agromet—agricultural/meteorological—information, used in certain ways, can be fairly effective in predicting the yield of crops: How much of a given crop is likely to be produced per acre in any particular area of ground.

This is an area that is developing very rapidly and Dr. White, I'm sure, will have more to say about that when he speaks.

Now, the third type of satellite maybe the most important of all as far as agriculture is concerned.

This particular satellite which we call Landsat looks at the Earth and discriminates between various colors, even colors that the human eve cannot sec. T don't want to go into great detail, but it does this an mere at a time and it can do this every place in the world once every 18 days. With this system it is possible to identify crops and measure the acreage in various regions that are associated with particular crops.

Now, the U.S. Department of Agriculture was involved with this idea very early in the game. As a matter of fact they helped us to determine the specifications for the particular satellites that are flying now. Once the first Landsat was up, it was rapidly verified that crops could be identified.

On the basis of this, Dr. Fletcher, the Administrator of NASA, proposed to Secretary Butz in 1973 that a very large scale experiment 'be undertaken to determine the utility of LandSat in estimating the world's wheat production. We are now involved with that experiment. It, is an experiment called LACIE—Large Area Crop Inventory Experiment--and it was initiated in 1974, and includes ***not*** only NASA and the Department of Agriculture, but also the National Oceanic and Atmospheric Administration. It is a 3-year program. We have completed the first year.

I am sure Dr. Hill from the U.S. Department of Agriculture. will have more to say about LACIE.

In general the results of the first -year are quite satisfactory. Those results were obtained in the Great Plains region of the United States which was chosen as a pilot area because w-e have very good information from conventional sources which will serve as a basis for determining the performance of LACIE. In the next 2 years we will be moving into foreign regions to make similar estimates.

As a result of this, the Department of Agriculture is commencing to establish specifications for a system that could operationally provide global production information, assuming the LACIE experiment works out satisfactorily.

In addition, the Department is working in other areas, such as using the satellite data for help in the domestic estimates as an adjunct to their existing system which indeed is a very good system.

That's a very direct and understandable use of satellite data in the area of agriculture. There are many other important agricultural uses. We can inventory irrigated land. How much land in this country or other countries is under irrigation? We can monitor the change between the rural and the urban and. How much agricultural land is being used up and going into cities and suburbs?

We can monitor the characteristics of water sheds in terms of how they absorb and flow the water. We can monitor the area] extent of snow cover which is very important in terms of water availability, say. in the western part of this country.

We can monitor seasonal variations and range conditions so that cattle or sheep grazing can be regulated. We can also use this in terms of supporting exploration geology in the mineral and energy areas. Energy is as important a consideration in agriculture as it is in everything else.

So it is obvious that many agencies are involved. I don't want to say much more about these uses. I think Dr. DeNoyer will say more about, that later.

The capabilities of Landsat I believe, have met every expectation, but just like everything else, it is possible to provide for improvement.

So we in NASA are now moving to the next generation of sensing capabilities where the performance of the instrument will be considerably improved. For example, instead of being able to look at 1 acre at a time, it will be able to look at one-fifth of an acre at a time.

This means we will be able to survey smaller fields where, for instance, crops like rice are grown. Also, we will be able to get more data on plant stress as well as identification of the crops themselves.

Using radar frequently (microwave) sensors in the future, we will be able to detect and measure such things as the moisture in the soil. We will be able to classify soils. We will also be able to look right through the clouds, something you can't do with an instrument that works at visible or infrared wavelengths.

To return again for just a moment to agrimeteorology, our present basis in the LACIE program for determining the yield of the wheat crop, we feel has indeed been quite satisfactory, Satellites perform an important role in providing this meteorological information, along with the very useful ground information that is also available.

I might say the combination of meteorological satellites and Landsats may be a very good way of identifying promising new lands that are potentially arable; in opening up new lands to increase the world's potential for agricultural production.

Before concluding, I would like to mention one other area that is in its very early stages and that is climate research.

It is very obvious that monthly or seasonal predictions of what is happening to climate are very important to the farmer. Will it be wet or dry this season as compared to last year at this time?

It is also important in a longer term sense, not from the standpoint of whether we are approaching an ice age or something like that again. That's important scientifically. But in terms of considerations such as desertification of arable lands, like those in the Sahel region of Africa, for example, and the reasons behind that and what can be done about it. In fact, the understanding of climate on a regional basis may well enable the return of desert to farmland.

Now, the only way I really know to develop an understanding of the climate program is by means of satellite systems that can measure the radiant energy that leaves the Earth and can measure the incoming radiations from the Sun as it enters the environs of the Earth.

We have systems that are capable of these measurements and we intend to initiate activities in the near future to begin to attain an understanding of this and hopefully a use of this new technology.

So I hope, Mr. Chairman. that I have indicated to you that remote sensing from space is indeed a very powerful tool.

Satellites can handle global problems. Agriculture now is indeed a global problem as you well know.

I think these satellites are certainly a major contributor now to the efficiency of our agricultural activities worldwide.

Thank you very much.

Chairman HUMPHREY. Thank you very much, Mr. Mathews.

[The following report was requested from NASA by OTA.]

REPORT TO THE OFFICE OF TECHNOLOGY ASSESSMENT, FOOD ADVISORY COMMITTEE, TECHNOLOGY ASSESSMENT BOARD, BY THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

A contribution to the Board's Assessment of the Application of Advanced Technology to World Agricultural Information Systems

## I. INTRODUCTION

> The lesson of the failure of the food and agriculture information system in 1972-1973 is that we must have more information on food production and market demand in other parts of the world and our analytical capabilities must be increased. *

The management of food supplies is no longer just a problem on a country to country basis. It is a global problem, the dimensions of which have only recently become evident. In order to deal with this problem, better management is needed. Better management is greatly dependent on the acquisition of much better food supply and demand data on a worldwide basis, a system to process and analyze these data to produce useful information on a timely and cost effective basis, and an organization that can use this information to make decisions to alleviate the problem. This is a fairly revolutionary undertaking as it involves detailed and accurate data gathering on an unprecedented scale along with the requirement for systems to process tremendous amounts of data into useful information so meaningful decisions can be made. Traditional systems can contribute to the solution of these problems. But traditional systems were designed to cope with traditional problems, which the international food crisis is not. To be effective, contributions from new systems will be required. In this report, we will describe new systems that can address major requirements for:

1. Worldwide, standardized data collection relating primarily to food supply, but also to food demand;
2. Rapid data processing; and,
3. Accurate data analysis.

These techniques involve the use of remote sensing satellites to provide large area, worldwide, repetitive coverage to monitor changes in agricultural crop acreage as well as weather conditions affecting agricultural field. These satellites utilize advanced sensors which gather data in the most effective regions of the spectrum (the visible, infrared and eventually, microwave wave lengths), not just the visual wavelengths to which cameras are essentially limited. Another advantage of these sensors is that their data can be produced in digital form, permitting rapid processing and analysis by computer. This is essential both for handling the large volumes of data acquired and also to get the most information out of the data. With the marriage of the satellite sensor and computer, and in conjunction with traditional techniques, a worldwide food information system is possible.

In this report, we present an overview of the total spectrum of current programs in which NASA is involved and a look at future developments currently in the planning stage.

At the present time, the satellites primarily being used for such purposes are Landsats-1 and -2; the information they provide include: acreage devoted to agriculture both in the U.S. and within other nations, soil classification, the encroachment of urbanization on agricultural areas, water demand (irrigation), water supply (snow cover), the carrying capacity of range land, and demography. The Large Area Crop Inventory Experiment (LACIE), uses data from these satellites, and from meteorological satellites and existing worldwide meteorological ground data systems, in an experiment aimed at improving global crop production estimates by the USDA Foreign Agricultural Service. LACIE will provide estimates of wheat production in the major wheat producing regions of the world. LACIE has already made estimates of wheat production in

*Quote from the Report of the Food Advisory **Committee,** June 19'75, p. 40.

the United States great plains area which compare favorably with USDA/SRS official estimates. LACIE is described within this report as well as several other current projects applying satellite technology in food-related applications.

Also discussed is our current thinking concerning future satellites and their more sophisticated sensors such as the Thematic Mapper which will provide better information, particularly for crops grown in small fields. Major contributions to yield information are also expected from meteorological satellites.

Also of great importance to our ability to cope with food management problems of the future is an understanding of the effect of climate on food production and the effect of man on climate. Well documented, but imperfectly understood, changes in seasonal weather patterns since the 1960's, have spotlighted an urgent national and international need for a climatic research program and for the development of a climatic forecasting capability. Because of the capability of satellite systems to provide large-scale synoptic views and to acquire the type of data to assist in understanding and predicting climatic changes, NASA is strongly pointing towards an expanded climatic research program. This also is touched upon briefly in this report.

Our initial efforts in food-related activities convince us that space-based technology has much to offer as we tackle the formidable problems of the future.

## II. CURRENT PROGRAMS AND CAPABILITIES

In this section of the report, we will describe some of the food-related activities underway utilizing satellite remote sensing data. Sub-section A is devoted to the Large Area Crop Inventory Experiment (LACIE). Other current activities are discussed in Sub-section B.

### A. LARGE AREA CROP INVENTORY EXPERIMENT (LACIE)

The current world food shortages and fuel and energy scarcity with their negative impact on future food supplies has focused worldwide attention on the U.S. in its role as the major exporter of agricultural commodities and has created a greater need both here and abroad for more accurate and timely knowledge of current and projected world crop production. This information is required in planning and affecting crop production and distribution. Exports to other countries, possibly involving millions of tons of grain, could be more effectively planned with less disruption to domestic markets and with better general economic effectiveness if world crop production could be reliably estimated more in advance and on a continuing basis. Planting, marketing, aid, and transportation decisions in producing countries are all based on crop inventory information which is often available only after harvest and is frequently of uncertain accuracy in many countries. Also, crop disasters can occur anywhere on the globe and such events must be made known in a timely way and as accurately as techniques and resources permit.

A crop inventory system utilizing remote sensing technology and the global meteorological system appears to offer great potential for upgrading existing information-gathering capabilities and for contributing to a long-range solution of the food supply problem. The launch of the first earth resources technology satellite (ERTS-1, now called Landsat-1) in 1972, and the results of subsequent experiments utilizing various remote sensing techniques including the digital analysis of multi-spectral data collected by ERTS-1, indicated that applications supporting the U.S. Department of Agriculture's (USDA) information needs in the area of crop production reporting, were feasible. Based on these results, a close working relationship was established between the National Aeronautic and Space Administration and USDA for the purpose of exploiting Landsat technology.

#### 1. LACIE---WHAT IT IS

As a result of progress made In Landsat-based technology and in the use of agrometeorological modeling by NOAA and others to predict crop yields, three agencies of the United States Government (USDA; NOAA of the Department of Commerce: and NASA) designed a specific project to test these technologies in a large-scale quasi-operational undertaking called the Large Area Crop Inventory Experiment (LACIE). A memorandum of understanding among the three agencies was signed in November 1974. LACIE is intended to demonstrate the capability of relatively new remote sensing techniques and data processing systems in combination with more conventional techniques and historical data to forecast the production of an important world crop. LACIE will utilize data gathered by the Landsat earth resources survey satellites in conjunction with meteorological and climatological data gathered both by satellite and conventional techniques. Wheat was selected as the test crop for the LACIE demonstration. The objective is to provide global wheat production forecasts with an improvement over existing methods in terms of accuracy, timeliness and objectivity.

LACIE will extend over three global crop years; the early phases will concentrate primarily on the wheat growing regions of the United States. Then the experiment will be extended to include other major wheat growing regions of the world.

## 2. LACIE TECHNICAL BACKGROUND

### *(u) Identification of Crops*

***NASA*** Landsat satellites have the capability to view each area of the earth once every 18 days. An electronic sensor carried on the satellite measures the radiant energy reflected from the earth's surface in four different wavelength bands. Two bands measure visible light radiation and two measure infrared radiation.

Energy arriving at the earth from the sun is absorbed or reflected. The wavelength at which energy is absorbed by the plant for growth is dependent upon the plant type, plant maturity and overall condition. This makes it possible to determine the identity of plant communities by the unique way they reflect energy from the sun.

Just as the eye sees reflected sunlight in visible wavelengths (such as blue, green, red) electronic sensors measure the reflection. Electronic sensors, however, are sensitive to more wavelengths than the eye. They can "see" ultraviolet and infrared wavelengths as well as color visible to the human eye. Electronic sensors can also be made much more sensitive and precise than the eye. The data are obtained in a way to make it easier to use in computers which can be used to extract a wealth of information collected by the sensor and particularly to determine the class of crop (wheat, corn, soybean, etc. ) growing in a specific field.

### (b) ***Prediction of Yield***

The Agro-Met models used in the prediction of yield are simply sets of mathematical equations which estimate agricultural (Agro) yields from meteorological (Met) observations and perhaps other factors affecting the crop throughout its development. The accuracy of yield models depends upon knowledge of plant response to the many possible combinations of weather elements, cropping practices, soil fertility, insect and disease damage, and weed control. Generally, these weather factors are the easiest to include in the model. Although some of the others can be obtained quite adequately from knowledge of historical trends.

## 3. LACIE--TECHINICAL APPROACH

The approach in LACIE is to estimate the production of wheat on a region-by-region basis. To estimate wheat production, two components of production must be determined: yield, the amount of wheat (bushels, metric tons, etc. ) for a given area (acres, ***hectares, etc. )*** of harvested crop, and the areal extent of that crop. Simply stated, production is area times yield. Both of these components, area and yield, are estimated for local areas and aggregated to regional and country levels.

Within a region, the total area planted in a given crop such as wheat and the yield from that area, will vary from year to year. In the total variation, both items, area planted and yield, are important. The area planted will vary as a function of economics, weather at planting time, and governmental decisions. Weather throughout the growing season is the prime factor causing changes in yield from year to year in a specific area.

### *(a) Crop Area Information*

Multispectral scanner data of the selected wheat growing areas involved in the LACIE experiment are received from the Landsats and are processed into computer-compatible magnetic tapes at the Goddard Space Flight Center in Greenbelt, Maryland. The tape reels are shipped to the Johnson Space Center in Houston, Texas, where a computer-assisted analysis of the data is made to identify wheat crops and to integrate the selected sample areas into an overall regional acreage estimate, Such information Will be assembled a number of times during the growing season.

The smallest geographical subdivision for which these estimates are made is an area where similar soils, climatic conditions, and cropping practices usually produce similar wheat crops and yields These small areas, for example, counties in the United States, are summed or aggregated to estimate the total crop area within a larger region. The regions are further aggregated to estimate the total crop area within a country.

The sampled segments measured by the Landsats are also combined with historical patterns for a large area such as a country to obtain the total area currently planted with a specific crop. Historical patterns of crop acreage, cropping practices, and planting trends are well established for agricultural regions. The use of sophisticated sampling strategies makes it possible that only 5/10,000 of the total wheat growing area surveyed is actually subjected to detailed analysis including human interpretation. This is described in Figure 1.

(b) ***Crop Yield Information***

Yield is directly associated with weather, soils, and agricultural technology and damage factors. The soil moisture at the time of planting, the rainfall during the growing season, and the temperature are the main weather factors. Agricultural technology includes such things as improved varieties of hybrids, fertilizer usage, insect and disease control, and irrigation.

As already mentioned, agro-met models are used to estimate agricultural yields based upon a knowledge of historical trends and current meteorological observations. Model development work is done at NOAA's Environmental Data Service Center for Climatic and Environmental Assessment (CCEA) at Columbia, Mo. Weather observations are collected daily by NOAA. Rainfall, temperature, etc., are measured from the ground only at certain points, while crops of course grow continuously over large areas. Therefore, ground sampling of weather permits errors to be induced into the equation. To fill these gaps, the NOAA environmental satellites daily provide total coverage of weather between sampling points.

CLASSIFICATION AND MENSURATION CONCEPT

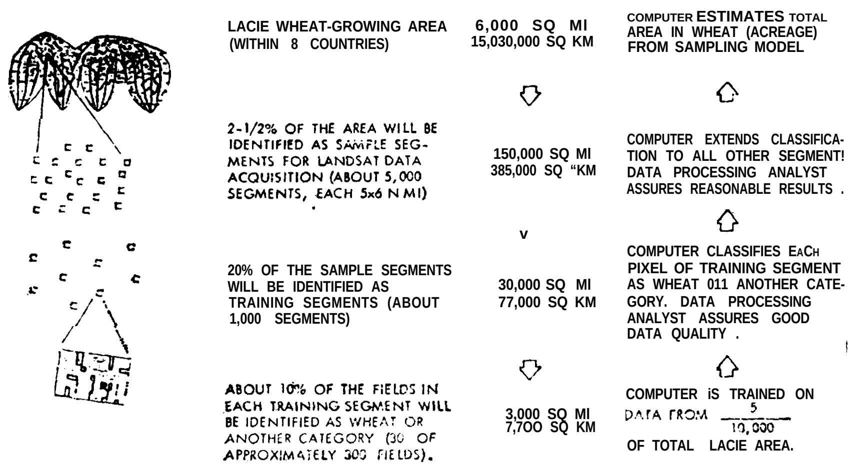


FIGURE 1

(c) ***Output Products***

Products generated as a result of the LACIE analysis are periodic assessments of the area, yield, and production of wheat from specific regions. The wheat assessment reports contain the area of wheat that has been identified as well as the stages of wheat growth and all source data used to derive the assessments. An estimate of the yield will also be included in the assessments. The wheat production estimate will be provided with each assessment, but only the final output assessment will be based upon results after crop maturity occurs across the entire region being reported. Thus, the accuracy of the wheat assessment reports should improve as the growing season progresses.

The Department of Agriculture is the only agency authorized to publish crop reports. USDA studies the utilization of these experimentally derived estimates in its crop reports, which are made public as a routine service to the domestic and international agricultural community. Comparisons are made with conventional forecasts and against actual production on a selected basis.

NASA, NOAA, and USDA publish retrospective research reports for each phase of the experiment that describe in general terms the degree of LACIE success. NASA and USDA publish research results on development of acreage estimation techniques and statistical sampling strategies, and NOAA and USDA similarly publish research reports on the development of their agromet models and on the validity of the derived yield factors.

### 4. LACIE--STATUS AND OUTLOOK

Emphasis during the first year of LACIE, the 1974-1975 crop year, was placed upon making acreage estimates in the United States Great Plains States, the major wheat producing area of the country. Although LACIE is designed to produce information concerning foreign wheat production, it is important to make estimates also in an area where good standard information already is produced, because that information is used as the baseline against which LACIE performance is evaluated. Data collection for this first year was accomplish as planned, and currently we are assessing the results for those nine states. Data is being collected and analysis has started for the 1975-1976 crop year. In addition to acreage estimates, yield and production estimates will be made during this second crop year. The major area of coverage will remain the U.S. Great Plains; however, Canada will be included, and selected foreign regions outside North America will be analyzed. It is anticipated that during the third year, the 1976-1977 crop year, acreage, yield, and production estimates will be made for all the foreign regions tentatively selected for inclusion in the LACIE demonstration; this will include most of the major wheat producing countries of the world.

Preliminary indications, based upon our initial assessment of the first year's performance, are that the LACIE acreage estimation techniques are generally adequate, and that with incorporation of certain technical changes, desired accuracy goals can be achieved. One of our concerns has been the ability to handle in a routine manner the vast quantities of data required for analysis. This is no longer a significant concern for adequate data handling rates have already been attained. Concentration is now being placed upon improving the estimation accuracies and identifying those techniques requiring further improvement, particularly the extrapolation from one small geographic area to another, a process known as signature extension.

Although the first year's focus was upon acreage, as indicated above, considerable effort has been expended, primarily by NOAA, upon the development and testing of the agro-met yield estimation models and crop calendar adjustment models. The provisions for operating these models with meteorological data from the World Meteorological Organization (WMO) network are complete. All the models are operating as intended, and their design and implementation appear to be quite adequate. In addition, initial attempts to aggregate acreage and yield estimates into production estimates for meaningful geographical areas have been successful.

The new techniques being tested and demonstrated in LACIE, in combination with current crop estimating methods and historical production data, will benefit both producers and consumers by helping reduce the annual uncertainties affecting the management and marketing of major crops. Faster, earlier, and more accurate forecasts should assist in rational planning for the most effective use of supplies, as well as in emergency food distribution both in the United States and abroad.

## B. OTHER FOOD RELATED ACTIVITIES

### 1. WATER RESOURCES

Agricultural production is vitally dependent upon the availability of water, as the Sahelian drought in the early 1970's vividly demonstrated. Landsat can inventory surface water bodies such as rivers, lakes, ponds and streams and monitor changes over time. Water quality information can be obtained on these water bodies as well, although it is important to have corollary measurements taken at the surface (ground truth) if specific pollutants are to be identified. This ground truth can be obtained through Landsat by utilizing ground platforms with in-situ sensors and relaying the data to a central data collection facility through the satellites' Data Collection System (DCS). This system serves as a communications transponder between the ground sensing Platform, which may be placed in a river or lake to acquire direct water quality data, and a central analysis laboratory.

Landsat data have been used as well to identify rock formations which serve as ground water aquifers in arid regions. This work has been performed in the southwestern United States but the techniques are applicable in other regions.

Other techniques are well under development to measure snow cover and monitor its depletion in the spring. Vast regions in the Eastern and Western hemispheres depend on snow to provide water for agriculture. This includes the direct contribution of snow as soil moisture and also the runoff that can be expected for river flow forecasting and reservoir management. It is expected that in the future water will become a far more scarce commodity and that steps will have to be taken to manage its use more efficiently for agricultural (irrigation) and other uses. Landsat data can make a real contribution in this area.

The foregoing relates to water supply problems, but estimating water demand is also important. A principal requirement for water in agricultural areas is for irrigation purposes. Landsat's contribution here can be in identifying and measuring acreages of irrigated lands, measuring annual changes in these lands, and helping to determine sources of irrigation water and methods of irrigation. This demand information gathered on a regional basis can then be used to project trends important to water supply planning. Steps can also be taken if necessary to try to reduce the demand based on objective information.

For the future, a great deal of effort is going into developing the capability to routinely and accurately sense soil moisture from space. This development should prove to be immensely valuable not only for determining crop yield, but also for planning agricultural practices such as determining optimum planting and irrigation times

## 2. SOIL CLASSICATION

Proper soil classification is essential for optimizing agricultural production. Yet many nations of the world, including most developing countries, have very poor soils maps. The Food and Agriculture Organization (FAO) of the United Nations has had an extensive international program for years to try to alleviate this deficiency. Yet a tremendous amount of *effort* remains to be done. A number of investigations have indicated the value of Landsat data for this purpose. In one case, a Mexican scientist identified 28 soils groups over most of Mexico using Landsat imagery. Potential land use maps were prepared based on the properties of these soil units and yield production statistics.

Soil classification mapping using Landsat data provided more and higher quality information than previously obtained, even though the previous work had been accomplished with the assistance of the FAO. The techniques are being further developed and used by the International Bank for Reconstruction and Development (IBRD) in an agricultural assistance program with the (government of India. Even in the United States, where soils are relatively well mapped, Landsat has contributed new and valuable information. Remote sensing techniques can be used to provide considerable benefit in mapping soils for agriculture usage in many parts of the world.

## 8. RANGE MANAGEMENT

The production of beef and most other meat products is directly related to range management decisions which are based on current knowledge of range conditions. At the present time, only gross information based on limited observations and climatological reports is available for this purpose. Landsat–1 investigators from the Bureau of Land Management, the University of Nebraska, and the Remote Sensing Center at Texas A&M have shown that an important indicator of range forage conditions, biomass, can be estimated from Landsat data. In order to be useful, this information needs to be in the hands of range managers within about ten days after it is acquired by the satellite. This is not possible with the present, first generation data processing system. However, we are working to increase our data handling capability in order to meet the required timing. As an example of a promising development in the range area, one investigation in the Great Plains Corridor showed that a correlation between measurements made in two of the Landsat spectral bands (visible red and reflective infrared) and above-ground green biomass and vegetation moisture content could be obtained and appears to be highly promising for range management purposes. Based on these results, a relatively large scale "Wildland Vegetation Inventory Project" is under development by the USDI/Bureau of Land *Management* (BLM) and NASA. One of the objectives of this project is to develop vegetation-type maps, acreage compilations, production estimates and trend indications for rangeland under the control of the BLM The participating agencies are optimistic that positive results will be obtained, which can then be used in even broader area surveys.

### 4. DEMOGRAPHY

In addition to providing information on food supplies, improved information is needed as well on the demand for food. This demand is a function of population, which is often not well ***known,*** particularly in developing countries. At least one investigation has shown that Landsat data have been useful in Africa to determine the location and size of villages for demographic enumeration. This information was combined with genealogical census data to provide an accurrate assessment of population density. Further improvement in the techniques used is possible and could be of considerable value in future international demographic estimates.

### GENERAL COMMENTS

The accuracy of the satellite techniques described above are in most cases dependent on good supporting surface measurements (ground truth). That is, the satellite information generally cannot stand alone without good point source data. The advantage of the satellite is not in replacing the in-situ supporting measurements, but in generalizing these measurements to areas so vast (country or regional scale or larger) that no other known technique can provide the integrating information. The amount of surface measurement data required will vary according to such factors as the application in question, the region in question and the degree of accuracy required.

While very useful results have been achieved to date, there is no question that future satellites with high sensing precision and utilizing additional parts of the spectrum (such as the thermal infrared and microwave) will return data of appreciably greater value.

Since we are dealing with a rapidly advancing technology, both in terms of hardware (sensors, satellites and computers) and software (data analysis techniques, etc. ), rapid advances in applications to a food information system can be expected over the foreseeable future.

## III. FUTURE CAPABILITIES

At the present time, Landsats-1 and -2 are functioning in orbit. While both have a design life of one year, Landsat–1 will be three and one half years old in January 1976, and Landsat-2 exactly one year old. The two tape recorders on Landsat-1 have ceased to function which means that data cannot he obttained over the many portions of the earth where there are no data readout stations. (There are three stations in the U.S. at present and one each in Canada, Brazil and Italy). In addition, one of the two tape recorders on Landsat-2 has failed, leaving only one recorder to gather worldwide data until the next satellite in the series, Landsat-C, is launched in late 1977. Landsat-C will carry improved sensors in the form of a Return Beam Vidicon (RBV) system with 40 meters resolution as compared with the present SO meter capability, and a fifth "thermal" (heat measuring) band on the multispectral scanner (MSS). These developments should assist in providing a better agricultural field identification capability as well as data for improved crop classification. Landsat-C will also carry two tape recorders to acquire worldwide data. These recorders will have certain reliability improvements over those carried on Landsats 1 and 2.

About the same time that Landsat-C is launched, a small research oriented satellite called the HCMM (Heat Capacity Mapping Mission) will be placed in orbit. Its importance for agriculture is that it will be used to develop techniques to detect soil moisture utilizing thermal infrared remote sensing data. The techniques which are developed will be utilized in conjunction with satellites to be launched in the 1980's.

### A. THEMATIC MAPPER

A most significant activity for the future of a world food information system is the development of the Thematic Mapper. It is planned that an improved multispectral scanner-the Thematic Mapper—will be the primary instrument for Earth Resourees surveys after Landsat-C. The Thematic Mapper is to be optimized for vegetation discrimination and for computer assisted analysis.

With a spatial resolution of 30 meters the Thematic Mapper will be able to resolve an area of .2 acres. This compares to the 80 meter 1.2 acre resolution capability presently available with the Landsats-,1 and -2 Multispectral Scanner. Several resolution elements are required to locate and measure individual fields. Figure 2 indicates the minimum size fields that can be resolved with both the Thematic Mapper (TM) and the Multispectral Scanner (MSS) as well as an indication of the field size distribution as a function of country. In addition to locating fields, it is of course also necessary to identify what is growing in the

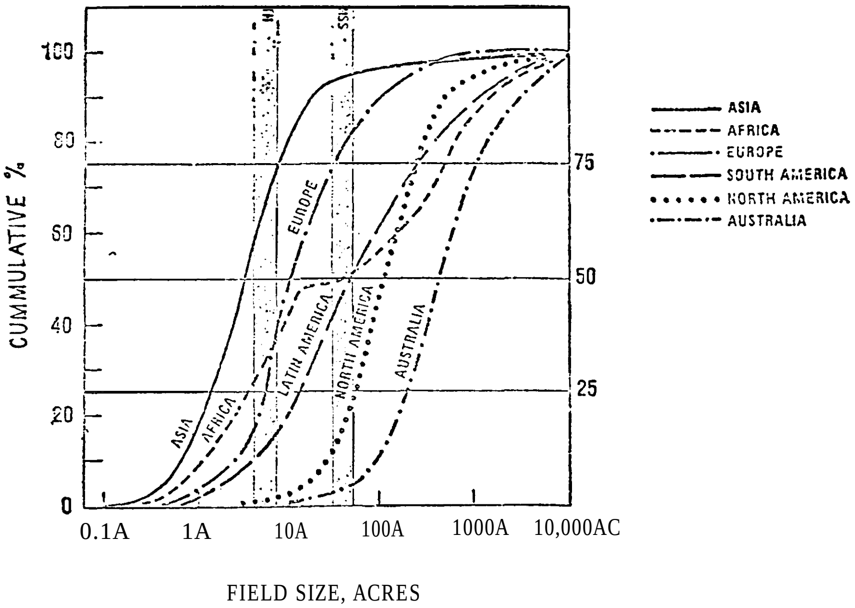


FIGURE 2.—World distribution of cropland fields.

field. The Thematic Mapper will have seven spectral channels (instead of the four bands on Landsats 1 and 2 and the five bands on Landsat-C) that have been selected to meet the vegetation discrimination objective. This, coupled with an improvement in the ability of the instrument to measure small changes in the energy level within each band, will improve the identification of crops by allowing better discrimination among similar crops. This is very important since the Thematic Mapper will help provide the capability to predict the production of major crops, such as rice, that are grown in small fields, and to discriminate among "confusion" crops such as wheat, barley, and rye earlier in the growing season.

A persistent problem in the Landsats-1 and -2 era has been the timely delivery of data to users. To solve this, the Thematic Mapper data flow will be streamlined. Data will be relayed real time via satellite from the Landsat instrument to a ground terminal facility, the TDRS station in White Sands. There, it will be recorded and then retransmitted in near real time via a domestic satellite link to the Landsat data processing facility. The use of such satellite links will allow users to receive data within 45-72 hours of data acquisition rather than having to wait a minimum of seven weeks as presently required.

## B. SPACE TECHNOLOGY IMPACT ON YIELD DETERMINATION

The utility of remote sensing technology for yield estimation/prediction has experienced considerable improvement in recent years. The following paragraphs outline the status of present efforts and take a look at plans and future possibilities to better employ the advantages of space technology for managing monitoring agricultural products with emphasis on the crop yield component of agricultural production.

Crops are affected by a variety of environmental factors which eventually combine to produce the resultant yield. The three principal factors are: a) moisture; b) warmth or temperature; and c) energy available to the plant. The following summarizes future space technology developments in these three areas.

### 1. MOISTURE

***(a) Soil mosture***

Probably the most substantial advances made to date in this area of endeavor have been those in soil moisture monitoring. Thermal infrared measurements taken throughout the day can be related to soil moisture, i.e., the diurnal amplitude in the surface temperature of soil has been shown to be inversely related to the amount of soil moisture in the upper layers of the soil profile (6 cm). Passive microwave measurements have also been shown to be responsive to soil moisture variations. The most effective band is L-band (20 em). This band has been shown to be responsive even when there are moderate amounts of vegetation present over the soil.

Future spacecraft will be attempting to implement the concepts demonstrated in supporting research and technology programs. For instance, HCMM will measure the diurnal range in surface temperature and relate it to soil moisture. Geosynchronous measurements can and will be used to measure surface temperature variations and relate it to soil moisture. Skylab L-Band and X-band data have already been shown to be sensitive ***to*** soil moisture variation. Nimbus 5. Electrically Scanning Microwave Radiometer (ESMR) measurements have been shown to be sensitive to soil moisture variations over sparsely vegetated regions.

Future spacecraft missions using the Shuttle Transportation Concept will fly large antenna instruments that will provide higher spatial resolution, passive microwave measurements of greater utility to agriculture. Spatial resolutions in the 10 km range are expected. To improve the spatial resolution of microwave systems, the Synthetic Aperture Radar approach is now also being actively considered. Present research indicates 25-100 meter resolution is Obtainable with 4-5 GHz and 7-15° depression angles being optimum. Shuttle systems with this capability can be expected in the early 1980's pending favorable results from ground-based and aircraft flights missions presently being analyzed and planned.

(b) ***Precipitation***

***The*** launch of geosynchronous satellites, such as ATS-1 and 111 and SMS-1 and 2, has provided a means to monitor very dynamic cloud features associated with precipitation event% These approaches can monitor cumulonimbus clouds, cloud turrets, and motions that appear useful for monitoring the location of heavy precipitation and augmenting existing rain gauge networks. These data can be used to augment yield prediction systems employing the moisture budgeting/ stress concept and its effect on yield.

Precipitation falling as snow and stored in the mountainous regions of the Western United States serves as valuable stored water for irrigated agriculture. Present satellite systems such as Landsat are measuring snow-cover and this can be used as valuable ancillary data in seasonal snow-runoff prediction procedures. Work is going on to utilize microwave measurements for snowpack moisture equivalent and wetness estimation. At present, the best combination of spectral band measurements is not known. However, multi-frequency microwave measurements on the Shuttle should resolve this problem.

(c) ***Evapotranspiration***

Present satellites (Landsat) can locate vegetated areas, and vegetative density and types within this general category. Making these delineations and monitoring changes with time appears to be a possible tool for separating regions where relative amounts of evapotranspiration are occurring. This concept is under study by the University of California. Additionally, many evapotranspiration techniques require inputs of net radiation. There are indications that key inputs to net radiation estimates may be made from satellites such as reflected solar radiation and emitted long-wave (thermal) radiation. More research is needed, however, in this key area.

**2. TEMPERATURE/ENVIRONMENT**

Besides the utility of surface temperature measurements for use in moisture estimates and plant stress estimates described briefly above it should be emphasized that this information can be used to indicate susceptibility to pest growth and infestation. The launch of HCMM, Landsat-C, and Landsat-D will enhance this area of endeavor.

Surface temperature measurements will also be useful for monitoring surface freezing conditions that are critical to the citrus industry, for example. Geosynchronous satellite measurement and properly timed polar orbiting, satellite-radiometric measurements will be useful in this regard.

Satellite measurements of snowcover are also useful for monitoring the extent of anomalous conditions such as a *lach* of snowcover and the freezing/winter-kill of winter wheat the extent of hail damage, and the extent of flooding.

8. ENERGY

As mentioned earlier, satellites may offer inputs through direct measurements of reflected solar and emitted radiation or cloud-type identification (for transmission purposes) that give an energy input for plant growth.

## G. CLIMATOLOGY

Most of the remarks given above in the discussion of yield determination are associated with assessing the status of the weather or environment at a particular point in time. Probably the most important and challenging area of technology that will improve or contribute to improved agricultural management is improved climatology. The remote sensing program in meteorology is concerned with the causes and effects of long-term changes in climate. It is felt that an assessment of the causes and effects of these changes is necessary in order to assess worldwide shifts of agricultural productivity. The factors which seem to influence the earth's long-term climate are naturally broad in scope and, therefore, amenable to study from earth-orbiting satellites. These factors are:

1. *Variations in the solar constant*. It is believed that variations of as little as 170 in the solar constant can significantly alter the distribution of arable lands. This is because small variations in solar output can have a large effect on energy input to the earth's atmosphere with consequent modifications to weather patterns. Satellite measurements on Nimbus-6 have been monitoring this constant. These measurements will continue, first with the Solar Maximum Mission.

2. ***Variations in the Earth's Radiation Budget.*** Climate is also effected by the amount of energy which is absorbed by the earth's surface. The amount of solar radiation will be determined with a specially-dedicated (Earth Radiation Budget) satellite. Instruments on Nimbus 5 and 6 have been measuring the snow and ice cover which reflects a significant portion of the solar energy. In addition, another instrument on Nimbus 6 is measuring the $CO_2$ content of the atmosphere, variations in which can result in measurable temperature changes at the earth's surface. The ozone composition is currently being mapped using an instrument. on Nimbus-4. This factor, which determines the amount of ultra-violet radiation which reaches the earth's surface, will continue to be monitored by instruments on Atmospheric Explorer-10 and Nimbus-G.

3. *Distribution of thermal energy*. The air-ocean interface, which plays such a large role in our long-term climate will be monitored by satellites which will measure ocean surface temperatures and current circulations (Nimbus-G and Seasat).

In addition, satellites can contribute through long-term, global or regional measurements of changes in vegetation cover and land use. All these areas are amenable to satellite measurement and will be included in NASA's planning.

A recent paper prepared by V. V. Salomonson and T. J. Schmugge of the NASA Goddard Space Flight Center discusses the important relationship among agricultural meteorology, yield estimation and remote sensing. It is included as Appendix 1 to this report.

### D. DEVELOPMENT OF MICROWAVE REMOTE SENSING

The principal advantage of remote sensing in the microwave wavelengths is that microwaves penetrate clouds while observations in the visible and infrared wavelengths do not. Given the fact that a considerable portion of the earth is obscured by clouds at any given time, the development of an aIl weather capability is important. Other advantages are that ***sensing*** can be conducted at night as well as in the daytime; microwaves can penetrate the earth slightly (important for soil moisture determination) ; and, microwaves at certain wavelengths can penetrate vegetation, allowing surface data to be gathered, for example, through a canopy of trees. For these reasons, a high priority is being given to the development of a satellite microwave remote sensing capability for earth resources surveys. Given the fact that microwave sensing is not as developed as sensing in the visible and infrared wavelengths, and that the instrument are relatively large, heavy and complex, it is not expected that dedicated sensors for food information applications will be available before the latter part of the 1980's. When they do become available, they will probably be used in addition to remote sensing at the other wavelengths, and in conjunction with data from traditional systems, to provide an optimum world agricultural information system.

## APPENDIX I

## AGRICULTURAL METEROLOGY, YIELD ESTIMATION AND REMOTE SENSING

(By V. V. Salomonson and T. J. Sehmugge)

Hydrology and Oceanography Branch, Code 913,
Atmospheric and Hydrospheric Applications Division
Applications Directorate,
Goddard Space Flight Center,
Greenbelt, Maryland

### (I) BACKGROUND

Agricultural meteorology is the discipline in which meteorological principles and knowledge are applied to agricultural pursuits. Ultimately all efforts in agrometeorology point toward the possibility of increasing yields. The purpose of this paper is to explore the utility of remotely-sensed data acquired from aircraft and spacecraft in improving predictions and estimates of yield. A special emphasis will be placed on the prediction of yield for wheat inasmuch as there now is considerable involvement of NASA, NOAA, and the U.S. Department of Agriculture in an effort termed the Large Area Crop Inventory Experiment (LACIE). The purpose of LACIE is to test and demonstrate the capability of relatively new remote sensing and data processing systems, in combination with existing and historical data, to forecast the production of an important world crop: namely, wheat. Production is defined as the product of crop area and yield. While it is conceptually rather easy to see how remote sensing might be applied to measure acreage, the utility and application of remote sensing for estimating and predicting yield is less apparent.

Meteorological factors have a considerable impact on wheat yield and, because of this and as part of LACIE, agromet models employing conventional data acquired utilizing the World Meteorological organization (WMO) network will be developed and utilized as the principal mechanism for estimating yield ***in*** the United States and other countries. There is, additionally, considerable interest in exploring the utility of spacecraft data because it offers a uniform and consistent data set that would provide worldwide coverage and easy access. There is a considerable challenge involved in that it is not readily apparent how meteorological parameters related to crop yield may be estimated or inferred from remote sensing or even how the satellite data should be compiled given the relatively small number of yearn of continuous, computer compatible data that now exist and the high data volumes involved. The rest of this paper will attempt to offer a perspective from which to evaluate the possibilities of utilizing remotely sensed data from satellites and to suggest some approaches using remote sensing that appear to have the most potential for providing useful contributions to improved world-wide wheat yield prediction.

## (II) CRITICAL PARAMETERS

' There have been several studies conducted which had the purpose of delineating those variables most affecting crop yield and plant response (for example; Thompson, 1962; Thompson, 1969, Williams, 1969). A review of literature shows that the principal variables are moisture, temperature. and energy. Other factors are also involved that include soil type, technological "factors including fertilizer, pest control, and planting practices, and disease or weather hazards. A listing of 'the parameters that should be considered is given in Exhibit 1.

## (III) YIELD ESTIMATION APPROACHES

Estimating or predicting crop yields is a difficult and complex problem. Typical approaches to this problem often involve the process indicated in Exhibit 2. There are several agromet models that have been utilized to estimate crop yields but overall it seems one can identify two main types of models; namely, statistical/ regression models and more deterministic moisture balance models.

### (A) STATISTICAL MOTELS

The statistical/regression models normally relate temperature, precipitation, solar radiation, potential evapotranspiration, and other variables to yield. Critical to this approach is having a long period of record of high quality, consistent data for a given area. An example of a typical, but very current statistical model is provided in Exhibit 3. This model was developed and implemented by the Center for Climatic and Environmental Assessment (CCEA) In 'Columbia, Missouri (material furnished by N. D. Strommen, Supervisory Meteorologist, CCEA). The model used here requires inputs of monthly mean precipitation values, values of potential evapotranspiration computed using the Thornthwaite Method (Thornthwaite, 1948), and degree days above 90° l?. Besides Kansas. similar formulas have been applied for Oklahoma, North Dakota, South Dakota, parts of Minnesota, Nebraska, and the Texas-Oklahoma Panhadle area, and Colorado. One may note that the forecast of yield improves steadily as the harvest time for wheat approaches.

### (B) MOISTURE BALANCE MODEL

Moisture balance models essentially rely on the fact that plant growth and yield are a function of available moisture. The soil water balance equation can be written:

$$P - O - V - E + \triangle W = O \quad (1)$$

P is precipitation, O is runoff, V is deep drainage, E is evapotranspiration, and $\triangle W$ **is change in the soil water storage of soil moisture (Slatyer, 1968).**

One of the most critical parameters in terms of crop response and eventual yield is the soil moisture. Many efforts have been made to measure soil moisture directly but still soil moisture measurement are not readily available. As a result, efforts have been made to estimate or infer the amount of water available to plants by accounting for other moisture fluxes as indicated in Equation 1. Precipitation values are readily available with usable observational density. Assumptions or approximate relationships can be used to evaluate the amount of runoff (0) and deep drainage (V) in agricultural situations. The principal challenge in using this approach to estimate the moisture available to crops is in obtaining evapotranspiration estimate (E).

With reference to the use of a moisture balance approach and yield estimates one of the most successful efforts has been that described by Baier and Robertson (1966). The details of applying this approach are provided in Baier et al, (1972). The principal equation used in this method is as follows:

$$E_i = \sum_{j=1} \left[ k_i \frac{S_j'(i-1)}{C_j} Z_i PE_i e^{-w(PE_i - \overline{PE})} \right] \quad (2)$$

$E_i$= actual evapotranspiration for day *i*
$j$= refers to zones in the soil profile
$S_j'(i-1)$ =available soil moisture in the j-th zone at the end of day $i-1$
$S_i$=capacity for available water in the *j-th* zone
$Z_i$=adjustment factor for different types of soil dryness curves
$PE_i$=potential evapotranspiration for day *i*
"adjustment function for effects of varying ***PE*** rates on the *AE/PE* ratio
$k_i$=coefficient accounting for soil and plant characteristics
PE=long term average daily PE for a month or season

By monitoring precipitation input and making adjustments for drainage and runoff, Equation 2 can permit daily estimates of E and an accounting of soil moisture that can eventually be related to yield (Baier and Robertson, 1968).

As already indicated, the principal difficulty in using a soil moisture/water budget approach comes in estimating evapotranspiration or with specific reference to Equation 2, potential evapotranspiration (PE). The most analytical formula for estimating PE is that provided by Penman (1948). This formula takes the form:

$$PE=(R_n \cdot \Delta+\gamma \cdot E_{ao})/(\Delta+\gamma), \tag{3}$$

where

$$E_{ao}=0.35\ (0.5+V/100)(e_o-e_a)$$

In this equation $R_n$ is the net radiation at the surface, A is the slope of the saturation vapor pressure curve at air temperature, V is the wind speed, and $e_o$ and $e_a$ are the vapor pressures at the surface and at weather shelter height. This formula requires some data that are not normally available. As a result daily estimates of PE are commonly obtained by regression techniques using standard meteorological data. Use of the regression techniques makes it more difficult to extend the estimates over long distances or times.

In both the statistical methods and the moisture balance methods it is still necessary at some point to regress some variable(s) against yield. At their best, the two methods are roughly comparable in the level of yield estimates that are obtained. The statistical methods are certainly less difficult to implement, but are, in general, less physically related to the growth of the plant. The moisture balance method, even though more complex and subject to error, has been successful because soil moisture is so critical and related to crop response.

## (C) PHENOLOGICAL/CROP CONDITION MODELS

One method by which *one* can predict yield is to observe the crop at some time, $t_i$, and use this as an estimator of its condition at some later time, t+ At. This technique, of course, can be improved by observing the crop at a series of times so as to monitor its rate of growth and maturation and, thereby, estimate its condition at harvest time and the commensurate yield. An example of work where the morphology of the plant is related to its development is provided by Haun (1973) .

A very valuable concept for monitoring crop growth and for relating climatological variables to crop yield concerns the use of the crop calendar concept or the biometeorological time (BMT) concept. When the average data at various stages of crop growth is known and documented the result is commonly called a "crop calendar". This approach is often amplified wherein meteorological variables are used to predict when significant points in crop growth will be reached. Robertson (1968) has used this general approach to establish the BMT concept wherein biometeorological time establishes the rate of development toward maturity as computed from maximum and minimum air temperatures and day length (photo thermal units). For wheat there are six critical BMT stages namely: planting, emergence jointing, heading, softdough, and ripe. There has been appreciable success achieved in averaging meteorological and moisture budget variables over the BMT time periods and regressing the results against yield. The disadvantage of this approach as opposed to using monthly averages, for example, is that more data processing is usually involved. The reason more data processing is involved is that monthly averages can be obtained directly from the National Climatic Data Center in Asheville, North Carolina whereas averages for BMT periods must be constructed from daily data.

## (D) CLIMATOLOGICAL MODELS

Many of the techniques just discussed must assume that normal conditions *or* present conditions at the time of the forecast will prevail until the harvest is accomplished. An accurate forecast of the climate to be expected during this intervening period would undoubtedly allow the predicted yield to be much more accurate. In places where data may be difficult to obtain, an accurate climatic model applicable to or encompassing that location or region would permit yield forecasts to be made using the meteorological variables provided by the model. Certainly the value of accurate climatic models cannot be underestimated for improvements in yield prediction and better management of world food resources. However, there is much to be done before reliable, accurate models applicable to crop producing regions is realized. An excellent review of the present state of climate modelling is provided by Schneider and Dickinson (1974).

### (E) METEOROLOGICAL EPISODES

Present yield prediction models do not adequately treat anomalous events that severely limit yield or destroy a crop. Such events or episodes would include severe drought, freezing, hail, abnormally heavy rains and wind storms, or diseases. These events are probably best accounted for by having a monitoring system that adequately detects anomalous events, surveys the extent of damage to the crops, and permits an estimate of the effect on yield. A satellite-based remote sensing system allowing repetitive global coverage and thereby permitting crop condition to be monitored should be very appropriate here. This possibility along with other remote-sensing applications in yield forecasting will be described briefly in the next section.

## (IV) THE APPLICABILITY OF REMOTE SENSING

As indicated earlier the primary variables that affect yield are moisture, temperature, and energy. The applicability of remote sensing for monitoring these parameters as well as others given in Exhibit 1 is conceptually quite clear in terms of providing high observational density observations on a repetitive basis over large regions. However, it has not been conclusively demonstrated that these parameters can be observed with sufficient accuracy from spacecraft or high altitude aircraft to make this approach a viable tool for yield forecasting, in particular, and agricultural climatology, in general.

### (A) REMOTE SENSING---STATISTICAL MODELS

For input into statistical models exact correspondence with conventional information must be established for remote sensing information so that it can be directly incorporated into existing models, or a data set sufficiently large for establishment of statistically viable relationships and yield predictions based on satellite observations must be available. Exhibit 4 provides a summary that primarily describes the availability of digital data on computer-compatible magnetic tapes. Overall, the most consistent, nearly continuous digital data is "atmospheric window" 10-12 urn data obtained by radiometers on the Nimbus series, primarily, but more recently available from the NOAA satellites and from the Defense Meteorological Satellite Program (DMSP). Since these data would reflect variations in cloudiness, surface moisture, and crop cover, there may be a possibility that some useful statistical relationships could be obtained between some function involving satellite brightness temperature (perhaps just a simple average) observed at different points in time during the growing season and crop yield.

Another observation from meteorological satellites that is consistently available since approximately 1966 is cloud cover as depicted in satellite imagery. Because cloud cover is related to incoming energy, precipitation occurrence, and the general climate prevailing in a given area, data extraction and processing techniques involving cloud cover estimates from imagery may offer a viable alternative for improved yield prediction, particularly in regions where data is sparse or difficult to obtain.

Averages of precipitation amounts, net radiation, or incoming solar energy can be substantially in error over large regions because of the wide spacing, low observational density of conventional observations, Huff (1970) describes sampling errors in the measurement of mean precipitation. Existing satellite data, such as that from the Synchronous Meteorological Satellite (SMS) series, should be useful in providing, in conjunction with conventional rain gauges, more accurate mean precipitation input over areas of various size extending from county-sized areas to the state or regional scale. It may also be possible to provide useful measures of precipitation ***over*** data sparse regions using satellite data alone. This possibility has been studied by Follansbee (1973). A general review of rainfall estimation methods from satellites is proved by Martin and Scherer (1973) .

### @) REMOTE SENSING---MOISTURE BUDGET METHODS

As indicated previously, the fact that satellite remote sensing observations offer a high observational density capability with which to augment conventional observations suggests that its utility and the accuracy advantages' should be explored. There are many yield prediction models which work at a given location but fail when applied to other areas or over wide regions. These models fail many times because the conventional data input does not adequately reflect the spatial variability of parameters such as precipitation, net radiation, soil moisture, and evapotranspiration. This problem exists not only with the moisture budget models but also the statistical models. The possibilities of providing improved model inputs of precipitation and evapotranspiration estimates using the Penman Equation (3) need to be explored in detail. Some recent work by the Earth Satellite Corporation • indicates that there is potential for remote sensing in this area of endeavor with eventual application in the soil moisture accounting appreach (Equation 2).

The fact that soil moisture is such a critical parameter for crop growth coupled with the indications that remote sensing can be applied for this purpose suggests that substantial research needs to be accomplished to ascertain the exact applicability of remote sensing measurements of soil moisture. Published results describing the possibilities with albedo data (Idso et al., 1975), thermal infrared (Idso et al., 1975) and microwave data (Schmugge et al., 1974) are available. The fact that microwave data provides a soil profile penetrating and vegetation penetrating capability makes it appear to be a particularly attractive approach to be explored as rapidly as circumstances may permit.

### (C) CROP CONDITION MONITORING

There are several studies that indicate the condition of a crop can be observed and perhaps used to estimate its condition at a future time such as harvest. Among the investigators who have described relevant results are Morain (1974), Rouse (1973), and Wiegand (1974). These reports show that by using ratios of Landsat bands such relevant features as leaf area index, biomass, and crops under stress can be observed. The data developed by Dr. K. Ranamasu (Morain, 1974) show that a peak in the value of the (0.5--0.6)/(0.6-0.7) micrometer reflectance ratio is reached approximately 40 days before harvest. The level of this peak appears to be related to wheat yield. The presence of disease, insect festation, moisture stress, and fertilizer deficiency may also be observable from space and used to adjust yield estimates.

### (D) METEOROLOGICAL EPISODES

Since meteorological conditions such as freezing, hail damage, or the effects of unusually heavy rains can severely reduce yield and should alter the spectral appearance of crops, the possibility of monitoring the occurrence and extent of these phenomena with remote sensing would be explored. The persistence of snowcover, or below normal, or above normal soil temperature conditions, flooding and other abnormal conditions may possibly be successfully monitored from satellites alone or in combination with conventional observations. There is a ***recognized*** need to do this kind of monitoring and the opportunity for successful monitoring from space platforms seems quite real.

### (V) SOURCES OF COMPARISON AND GROUND TRUTH

The most sophisticated crop production forecasting system available today is that applied by the U.S. Dept. of Agriculture Statistical Reporting Service. The average error in yield forecasts is about 2% with the standard deviation in the error being about 8 percent 9 months before harvest (Castruccio and Loats, 1974). These figures apply to national production forecasts. The error increases as one goes to smaller and smaller reporting units. The average error at the state level at harvest is estimated to be 4-6% and the crop reporting district level it is estimated to be approximately 10%. The yield component contributes about 50% of the total variance in production.

The accuracies mentioned above are the standards of comparison for new methods using remote sensing applied in the United States. If comparability between yield forecasting methods employing remote sensing and conventional methods can be established in the United States, these same remote sensing methods should provide valuable information concerning crop yield in countries outside the United States. It should be explicitly pointed out that the first priority goal is to provide national crop production estimates.

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● Private communication with Mr. Earl Merritt, Earth Satellite Corporation, Washington, D.C.

For national and state or regional estimates of yield the USDA/SRS estimates serve as a standard of comparison. Because the SRS technique is essentially a small sample technique it cannot serve as a very effective standard of comparison at the crop reporting district and county level. At present there is not clear requirement for accurate yield estimates at the county level, but it may be hypothesized that as food supplies become more critical, and if a Capability for providing such a result can be demonstrated, such information may be quite useful at the local/county level@ improve national and state yield estimates at the same time A remote sensing system may offer this potential but in order to validate such a system accurate ground truth systems are needed. These ground truth systems would provide accurate, local yield measurements, and measurements of soil moisture, precipitation, evapotranspiration, and crop condition that would validate remote sensing measurements and yield estimates employing remote sensing. The LACIE system of ground truth/test sites is a step in the appropriate direction

## (Vi) CONCLUSIONS

There is a clear need to improve the ability of this nation and the world to predict crop production and manage food resources. Remote sensing from spacecraft and aircraft appears to offer some opportunities for improvement in yield prediction, but considerable research and data analysis is needed before this apparent potential is substantiated. Conventional methods use readily available data that is relatively easy to process and provide predictions in the U.S. that are comparable to nationwide estimates provided by the U.S. Department of Agriculture. Remote sensing may provide a uniform, consistent data source that can be obtained over all regions without depending on an international network of ground-based stations. It, furthermore, may provide a means of improving model input on all scales by capturing more accurately spatial variability in parameters such as precipitation and net radiation. Additionally, any improvements that are produced must be evaluated in terms of the greater data processing complexity associated with models using remote sensing data as compared to methods using conventional meteorological data.

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EXHIBIT 1

# FACTORS IN WHEAT YIELD FORCASTING

| PRIMARY | | SECONDARY |
|---|---|---|
| ENERGY | (Net Radiation / Incoming Solar Energy) | Light (no. of cloudy days} |
| | | Wind (damage) |
| | | $CO_2$ (Yield $\alpha$ $CO_2$) |
| | | Soil Type |
| WARMTH | (Temperature) | Date of Planting |
| | | Rate of Planting |
| MOISTURE | (Soil Moisture / Precipitation) | Depth of Planting |
| | | Diseases, weeds |
| | | Nutrients |
| | | Leaf area and leaf area index |
| | | Variety |

EXHIBIT 2

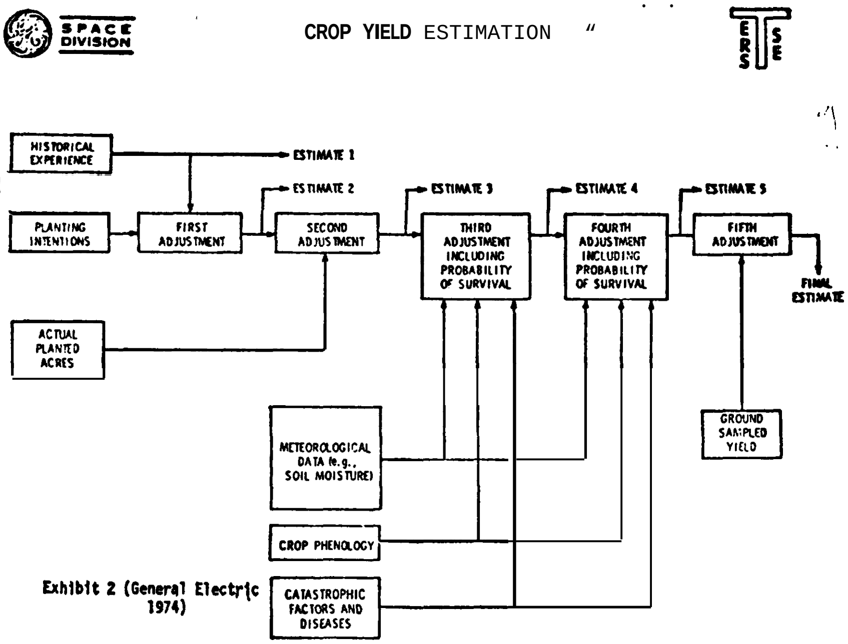


Exhibit 2 (General Electric 1974)

### Exhibit 3

**TRUNCATED MODELS FOR KANSAS WINTER WHEAT (1931-74)**

| VARIABLE | | TIME OF TRUNCATION: TREND | FEBRUARY | MARCH | MAY | JUNE |
|---|---|---|---|---|---|---|
| Constant | | 10.383 | 10.471 | 11.407 | 13.263 | 13.347 |
| Linear Trend | 1931-55 | 0.250 | 0.268 | 0.213 | 0.208 | 0.225 |
| | 1955-74 | 0.819 | 0.741 | 0.811 | 0.775 | 0.759 |
| Aug-Feb Prec. (in.) | DFN | ------- | 0.521 | 0.343 | 0.283 | 0.284 |
| March Prec.-P.E.T. | DFN | ------- | ------- | 1.875 | 1.487 | 1.591 |
| (in.) | SDFN | ------- | ------- | -0.170 | -0.120 | -0.139 |
| May Prec. (in.) | SDFN | ------- | ------- | ------- | -0.369 | -0.292 |
| May Degree Days Above 90°F | | ------- | ------- | ------- | -2.424 | -2.453 |
| June Prec. (in.) | DFN | ------- | ------- | ------- | ------- | -0.133 |
| | SDFN | ------- | ------- | ------- | ------- | -0.119 |
| Standard Error (bu/acre) | | 3.68 | 3.48 | 2.90 | 2.53 | 2.48 |
| $R^2$ | | 0.77 | 0.80 | 0.86 | 0.90 | 0.91 |

Standard Deviation of Yields = 7.42 bu/acre

DFN = Departure from normal
SDFN = Squared departure from normal