PREDICTING SOIL MOISTURE AND WHEAT VEGETATIVE GROWTH FROM ERTS-1 IMAGERY

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by

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INTRODUCTION

An expanding population has brought about an awareness that there are only limited resources on the Earth. This realization comes at a time when resource use is greater than ever before. Adequate informational techniques are necessary for improved resource development. These techniques can aid in wise resource management.

The magnitude of the data required for improved resource management has led to the development of automatic recognition techniques for agriculture. These systems utilize remote sensing from aircraft and spacecraft. Earth Resources Technology Satellite program is a major step in combining space and remote sensing technologies into a system for developing and demonstrating the techniques for efficient management of the Earth's resources (NASA Earth Resources Technology Satellite Data Users Handbook, 1972).

Over 400 million acres of land are irrigated in the world (Israelsen and Hansen, 1967). Some of the water applied is needlessly lost by excess applications. Irrigation scheduling can help to better conserve this valuable resource. One method of scheduling irrigation requires the determination of crop water use (evapotranspiration). Actual evapotranspiration is dependent upon potential evapotranspiration and a crop coefficient. One possible approach to predicting the crop coefficient is the use of a plant's actual growth which may be determined by its reflection of solar radiation from the plant canopy (Myers et al., 1966). If this method is to be used, the relationship between reflectance, soil moisture and vegetative growth must be established.

The purpose of this research is to evaluate reflectance for prediction of soil moisture and vegetative growth, and to determine the feasibility of using vegetative growth to evaluate the winter wheat crop coefficient.

REVIEW OF LITERATURE

Remote Sensing

Remote sensing refers to the acquiring of data at a distance by detecting the radiant energy which the object either reflects or emits. Detection devices can be field spectrometers and cameras or instruments designed for installation in aircraft and space vehicles.

Albedo is the ratio of the entire solar radiation spectrum reflected from a body to the total incident radiation (Ashburn and Weldon, 1956), while reflectance is the ratio of reflected radiation to the total incident radiation at a specific wavelength. At any specified wavelength, Reflectance + Absorptance + Transmittance = 1. Transmittance of any opaque material is zero; thus a decrease in reflectance will cause an equal increase in absorption.

Physical Properties that Affect Reflectance

Soil Factors

The albedo of various soil surfaces was compiled by Kondrat'yev (1965). The soils had extremely variable albedos. The variability was attributed to the different soil color, soil moisture content, organic matter and particle size. The soil moisture content was considered the most important factor. He pointed out that a decrease in albedo with an increase in moisture was due to water's low albedo. Bowers (1971) indicated that the relationship between soil moisture and reflectance is precise enough to utilize reflectance techniques to measure surface moisture (Fig. 1). However, due to the soil color, a calibration is necessary for each soil type.

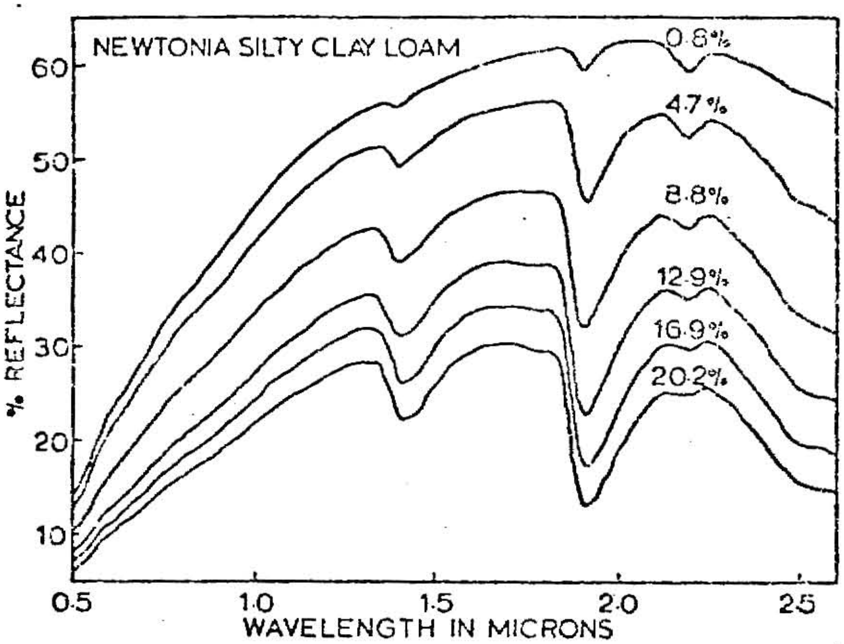

Fig. 1. Reflectance from Newtonia Silty Clay Loam at Different Soil Moisture Percentages (Figure reproduced from Bowers, 1971).

Allen and Sewell (1973) concluded that the use of infrared films and electronic scanner detectors could detect fallow soil moisture over a range of 1 to 24 percent dry weight. Their prediction equations for both the surface soil moisture and soil moisture at the 4 inch depth had regression coefficients (R^2) of at least 0.94.

Organic matter also influences reflectance. A study by Bowers (1971) shows that an oxidized soil sample compared to the check or control sample has a greater reflectance. He also states that some of the change could have been due to oxidation of the carbonates, although in one soil no carbonate was detected.

Bowers (1971) and Myers and Allen (1968) also reported that particle size has an effect on reflectance. In most cases an increase in particle size decreased the reflectance. This was due to the fine particles filling the volume more completely, thus a more even surface. Coarse aggregates, having an irregular shape, formed a large number of pores and cracks in the surface. When the soil surface was wet and pulverized there was very little difference in reflectance from soils, instead the real contrast was at a low moisture content.

Vegetative Factors

The main factor that causes variation in reflectance from crop canopies is leaf density or leaf area index. Leaf area index is defined as the ratio of the leaf area to soil area. Stanhill et al. (1968) reported that leaf area index is linearly correlated to albedo or shortwave reflection. The plant albedo increases with increasing plant development to a maximum at full plant canopy. The suggested model indicates internal trapping of radiation, which decreases albedo. Internal trapping is almost complete after the second reflection with hardly any effect by height after a minimum value. In the near infrared region, reflectance increased 17 percent with two leaf layers and only slightly more for each additional leaf layer. When the crop cover is incomplete all of the soil factors mentioned previously, including soil color, soil moisture, particle size and organic matter, caused variation in reflectance. In addition, leaf reflectance also is affected by stand geometry and leaf morphology, most significantly in the near infrared region (Gates, 1965), as well as the variety and relative maturity of the crop (Remote Multispectral Sensing in Agriculture, 1970).

A comparison of different varieties of a crop by Interpretation of Remote Multispectral Imagery of Agricultural Crops (1967) and Remote Multispectral Sensing in Agriculture (1967) indicated that the spectral responses were statistically different. These differences could also have been attributed to variations in crop canopy or leaf area index and crop maturity. In mid-season it could have been due to weed infestations, diseases or farming practices.

Variations of reflectance were found with spectral bands. In the visible region, the striking feature of the leaf spectrum was the high absorptance from 0.4 to 0.5 μ, the reduced absorptance from 0.5 to 0.6 μ, the high absorptance from 0.6 to 0.7 μ and the low transmittance in the entire region (Fig. 2). This was mainly due to the chlorophyll and carotene absorption that predominates in this region (Remote Sensing, 1970). Sinclair, et al. (1973) reported that cell walls scatter the light diffusively, but the chlorophyll or other pigments are present to absorb the light. The absorbing process is a dominate factor in influencing the spectral response in the visible region. If water deficits occur, the metabolic

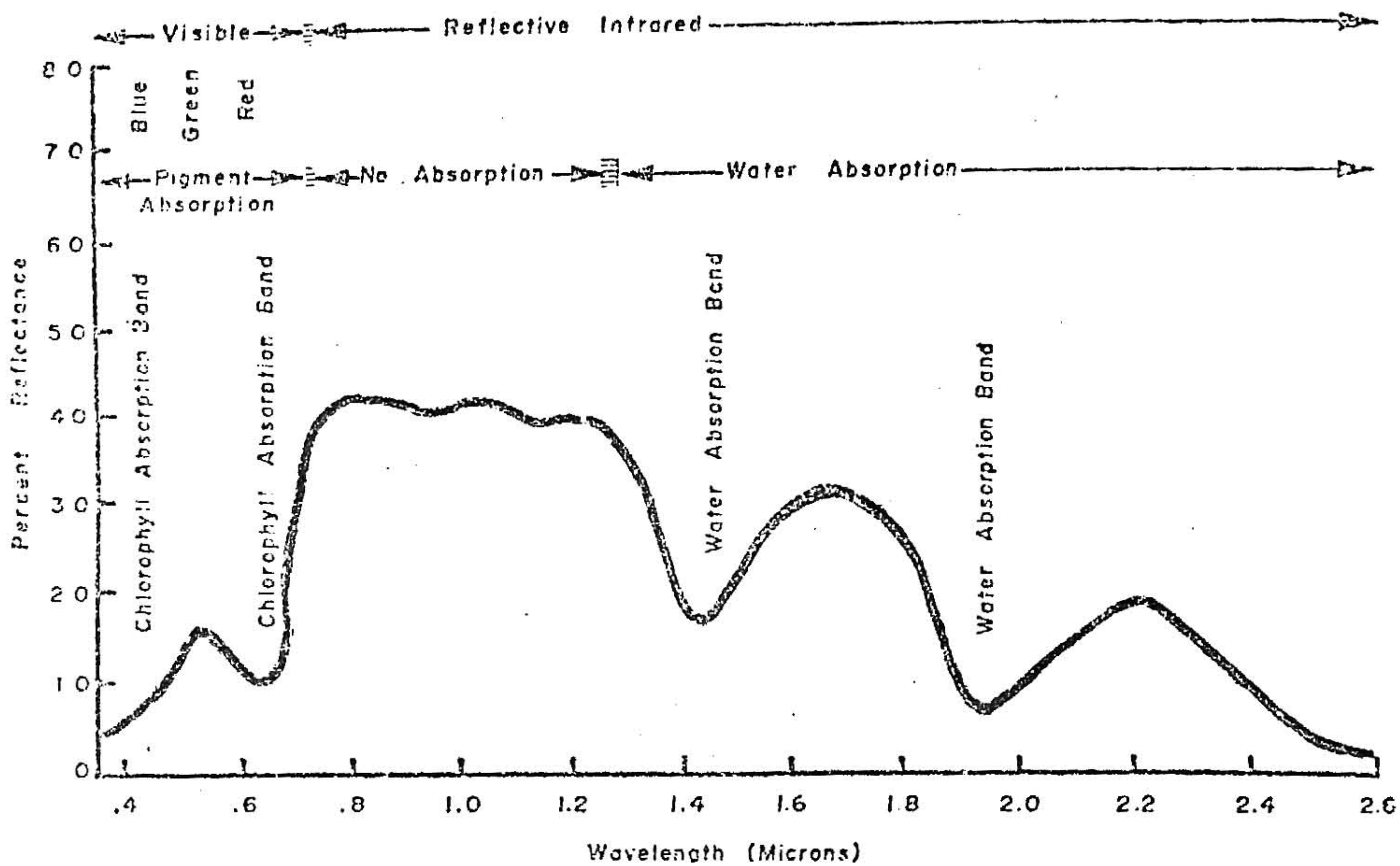

Fig. 2. Characteristic Spectral Reflectance Curve of a Green Leaf (Figure reproduced from Remote Multispectral Sensing in Agriculture, 1970).

processes slow down resulting in the breakdown of carbohydrates and protein within the plant cell. As the stress becomes more severe, accelerated migration of soluble leaf phosphorous and nitrogen compounds to the stem occurs. The loss of chlorophyll accompanying the breakdown and migration results in higher reflectance (David, 1969). Therefore, reflectance is related to the amount of plant pigments. Other factors may result in the loss of chlorophyll such as leaf maturity, salinity, disease or mineral deficiencies. Severe nitrogen deficiences increase reflection (Remote Sensing, 1970), but differences in available nitrogen produce differences in vegetative growth (Bhangoo, 1956, Bolaria, 1956, and Monteith, 1959).

In the near infrared region (0.7 to 1.3 μ) reflectance is caused by the lack of pigment absorption and by the lack of absorption by liquid water (Remote Sensing, 1970). Sinclair, et al. (1973) suggested that reflectance had to occur at interfaces within the leaf where total or critical reflectance was possible. The requirements for total or critical reflectance are that the radiation pass from a material with a high index of refraction to a material with a low index of refraction and that the angle of incidence must be sufficiently large. The increase in reflectance as the leaves become more nitrogen deficient suggests that the leaves are thicker since reflectance increases exponentially as leaf thickness increases. Moisture stress causes physiological changes in the leaf that cause the infrared reflectance to decrease with an increase in moisture stress. The low absorption or high reflectance in this region is a distinctive feature of vegetative. Remote Sensing (1970) reports that of the total incident radiation which strikes a leaf, about 50 percent is reflected, 45 percent is transmitted and the remaining is absorbed. Sinclair et al. (1973) provide a more detailed explanation of the reflectance of an individual leaf in both the visible and near infrared regions.

Sun angle and attenuation are two factors that affect reflection from an object. At low sun angles the reflectance of an object increases compared to a large sun angle. Attenuation is defined by Remote Sensing (1970) as including losses from a beam of radiation by either atmospheric absorption or scattering. In the visible region absorption plays only a minor role compared to scattering. Scattering is caused by interaction between radiation and small particles (dust or water droplets usually in the form of a cloud or haze).

Estimating Soil Moisture

A large amount of time and effort has been expended in the research of transpiration and evaporation with only recent applications in the modeling of evapotranspiration for management of irrigated land. This comes at a time when studies indicate that the timing of irrigations and the amount of water applied have changed very little (Jensen et al., 1971). If a model is to be used on a practical basis for irrigation scheduling, necessary information must be relatively simple to obtain.

Jensen et al. (1971) have developed a computerized model to estimate soil moisture depletion. One of the model's primary objectives is the orientation for the user instead of the researcher. To calculate the potential evaporative flux, the Penman combination equation is used (Penman, 1963). The meteorological data necessary to evaluate the equation include minimum and maximum daily air temperatures, daily solar radiation, dew point temperature at 8 AM and daily wind run.

The crop coefficient used in the computer model represents the effects of the resistance of water movement from the soil to the evaporating surfaces, the resistance to the diffusion of water vapor from the surfaces to the atmosphere and the amount of available energy compared to the reference crop (Jensen, 1968). Thus the crop coefficient is limited by the available soil moisture as well as the daily meteorological conditions and stage of plant growth. For each separate crop a coefficient must be developed for the model. A more detailed explanation can be obtained from Jensen et al. (1971).

Ritchie and Burnett (1971) and Ritchie (1972) determined a nonlinear relationship between the leaf area index of a crop and the ratio of the plant's evapotranspiration to the potential evapotranspiration. They reported that while an adequate supply of water is available in the soil, plant factors influence evapotranspiration rates.

INVESTIGATION

Objectives

This work was concerned with problems dealing with utilizing remote sensing data. The objectives of the study were: (1) to evaluate reflectance for prediction of soil moisture and vegetative growth, (2) to determine the feasibility of using vegetative growth to evaluate the winter wheat crop coefficient, and (3) to evaluate the winter wheat crop coefficient in the mathematical model by Jensen et al. (1971) for irrigation scheduling.

Equipment

ERTS-1 satellite revolves in a circular orbit around the Earth every 103 minutes at 914 km above sea level. The satellite travels over the research area in midmorning in a north to south direction. It passes over any location on the Earth's surface once every 18 days at the same time of day.

The Multispectral Scanner (MSS) is a line-scanning device that operates in two bands of the visible spectrum and two in the near infrared. Band 4 included the spectrum between 0.5 and 0.6 μ, band 5 between 0.6 and 0.7 μ, band 6 between 0.7 and 0.8 μ and band 7 between 0.8 and 1.1 μ. Fig. 3 shows the 4 bands with the energy emitted in the solar and thermal spectrum. An oscillating mirror in the MSS causes light energy from a 185 km swath to be swept across the focus of a small telescope. At the focus is a four-by-six array of 24 optical fibers (6 for each band). The fibers carry the energy from the light through spectral filters to detectors that convert it to an electrical signal. An area of 79 meters square is contained in each

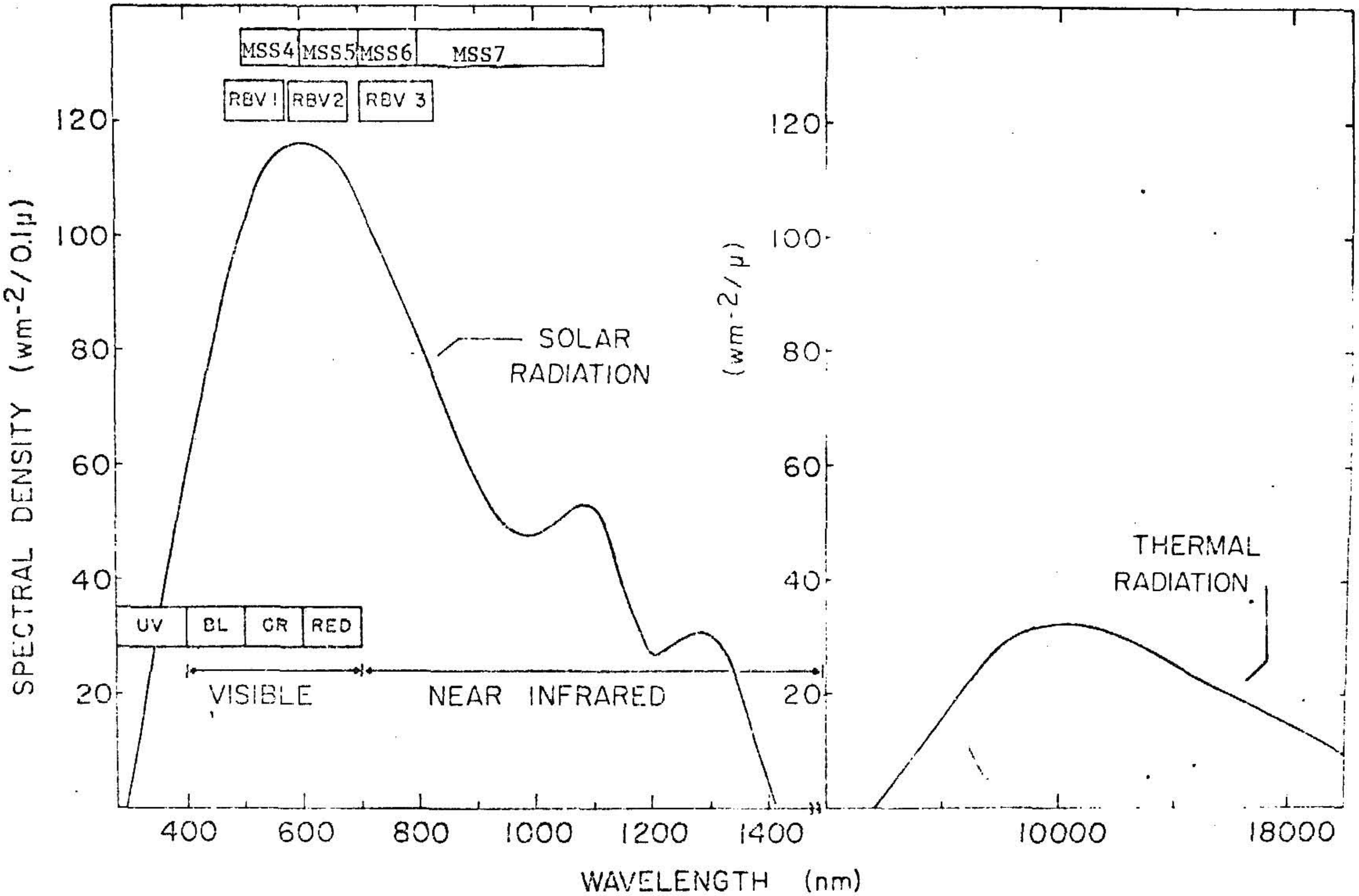

Fig. 3. Energy Emitted in the Solar and Thermal Spectrum.

fiber. The MSS image covers 185 km square with 4 images per area. The imagery is relayed to ground stations and then is processed into photographs at Goddard Space Flight Center in Greenbelt, Maryland. The resolution capability reveals surface features at a scale of 1:250,000 and information at a scale of 1:30000. Further details of the equipment aboard the ERTS-1 satellite are given by NASA Earth Resources Technology Satellite Data Users Handbook (1972).

Methods of Procedure

The research was conducted on winter wheat fields approximately 30 kilometers northwest of Garden City, Kansas. Two soil moisture treatments, one dryland wheat field (A) located 38° 9.6' North latitude and 101° 5.9' West longitude and one irrigated field (B) 38° 8.5' North latitude and 101° 4.9' West longitude, were used with approximately 60 hectares in each. Field B was irrigated by a center pivot sprinkler system. The two fields were located within 3 km of each other. The area's normal annual precipitation is 43.6 cm with about 70 percent of the precipitation during September through June.

The two fields were located on Ulyssess-Richfield silt loam with an average organic matter of 1.5 percent and soil pH of 6.9. The exchangeable potassium was in excess of 560 kg per hectare. Available phosphorus in field A was 117 kg per hectare and in field B was 64 kg per hectare. Particle size analyses revealed that both field's soils contained an average of 50 percent silt and 20 percent clay.

Field A had been in fallow the previous year. Scout wheat was planted at a seeding rate of 29 kg per hectare on September 15, 1972. The grain drill used had a 25.4 cm spacing between rows. By May 24, 1973, the wheat was completely headed and was harvested on July 5.

Since field B had been in wheat the previous season, the field was preirrigated. Anhydrous ammonia at a rate of 90 kg of nitrogen per hectare was applied to the field. On September 22, 1972, Eagle wheat was seeded at a rate of 50 kg per hectare with a row spacing of 30.48 cm. According to Variety Tests with Fall-Planted Small Grains (1971), Eagle wheat was a selection of Scout with nearly identical vegetative characteristics. Water was applied with the center pivot irrigation system on May 23 (3.05 cm) and June 2 (3.05 cm). Harvest of the wheat was completed on July 5.

Data Collection

Both fields A and B were divided into four square equally sized plots with a sampling area in the center of each plot. An additional sampling area was also set up in two of the plots in field A where the corners had been double drilled. This gave a total of six sampling areas in field A and four in field B. By the use of random sampling techniques, the areas were broken down into one meter squares, where the leaf area index and soil moisture were measured.

The soil samples were gathered at the surface and at intervals of 0 to 15, 15 to 30, 30 to 60, 60 to 91, 91 to 121, 121 to 152 and 152 to 182 cm with a soil sampling tube. The samples were later dried in an oven at 105°C until they reached a constant weight. Then the soil moistures were calculated.

The leaf area was determined by measuring the length and breadth of each leaf from randomly selected plants in the one square meter and using the following equation (Teare and Peterson, 1971):

$$LA = -0.64 + 0.813\ X \qquad (1)$$

where:

LA = leaf area (cm^2)

X = product of length times breadth of leaf (cm^2).

The leaf area index is the total leaf area divided by the land surface area. Both soil moisture and leaf area index data were obtained within one day of the flights over.

The meteorological data were from the Garden City Experiment Station. These data included maximum and minimum temperatures, dew point temperatures and wind run. Also the field capacity, permanent wilting point and bulk density for Ulyssess-Richfield silt loam were obtained from the experiment station. This information was determined by laboratory measurements and may not describe the test fields accurately. Solar radiation was obtained from the Dodge City Weather Service while rainfall readings were taken near the research area.

Data Analysis

Using a negative transparency from ERTS-1, the general area of fields (A and B) was located. Then the specific fields were found by the use of computer printed gray scales. From the gray scales the coordinates were located and the numerical values were stripped off the magnetic tapes. To prevent any overlapping outside of the research area, one row of data points around the edge of the fields was eliminated. The mean and standard deviation of the remaining data of the four bands were calculated (Tables 1 and 2). Also the mean and standard deviation of point by point ratios were determined (Tables 1 and 2). Stepwise Deletion Multiple Regression (1973) was used to evaluate the relationship between reflectance, soil moisture and leaf area index.

The meteorological data, as well as the soil moistures on March 22, were used in the computer model of evapotranspiration (Appendix, Table 11) developed by Jensen et al. (1971). The original wheat crop coefficient

Table 1. ERTS-1 Data for Field A.

Date		MSS4	MSS5	MSS6	MSS7	MSS4/5	MSS4/7	MSS5/7
9/22/72	Mean	34.75	37.89	38.64	19.55	0.918	1.779	1.939
	S.D.*	1.41	1.90	2.18	0.86	0.040	0.068	0.080
3/22/73	Mean	33.26	32.29	45.87	25.25	1.031	1.318	1.280
	S.D.*	1.28	1.58	1.74	0.69	0.040	0.055	0.069
5/14/73	Mean	29.74	24.50	48.11	28.08	1.218	1.064	0.877
	S.D.*	1.69	2.12	1.79	1.66	0.066	0.101	0.104
6/1/73	Mean	33.43	29.48	52.32	29.87	1.138	1.121	0.990
	S.D.*	1.72	2.42	1.84	1.04	0.062	0.083	0.104
6/19/73	Mean	41.14	49.33	55.26	28.70	0.835	1.436	1.722
	S.D.*	1.62	2.07	1.49	0.92	0.033	0.074	0.090
7/7/73	Mean	59.46	78.53	77.68	36.36	0.758	1.636	2.161
	S.D.*	2.14	4.25	2.72	1.49	0.030	0.061	0.115

*Standard deviation.

Table 2. ERTS-1 Data for Field B.

Date		MSS4	MSS5	MSS6	MSS7	MSS4/5	MSS4/7	MSS5/7
9/22/72	Mean	37.05	40.41	40.96	20.78	0.919	1.786	1.947
	S.D.*	1.62	2.54	2.37	1.02	0.038	0.094	0.128
3/22/73	Mean	33.54	32.99	41.47	22.57	1.019	1.488	1.463
	S.D.*	1.09	1.91	2.15	0.96	0.049	0.073	0.088
5/14/73	Mean	27.63	19.22	56.66	36.78	1.454	0.760	0.532
	S.D.*	1.60	2.68	3.56	3.18	0.132	0.109	0.129
6/1/73	Mean	26.93	20.03	48.66	31.61	1.355	0.858	0.638
	S.D.*	1.32	2.23	3.43	2.54	0.111	0.083	0.094
6/19/73	Mean	36.68	37.94	52.00	29.97	0.971	1.227	1.270
	S.D.*	1.21	3.11	2.05	1.56	0.060	0.079	0.131
7/7/73	Mean	54.46	73.87	77.48	38.24	0.739	1.425	1.932
	S.D.*	2.30	4.37	3.39	1.31	0.033	0.060	0.100

*Standard deviation.

curves were evaluated first. Then curves developed by regression analysis from the leaf area index data were used as the crop coefficient curves. From the computer model, soil moisture depletions were predicted.

RESULTS

Prediction of Vegetative Growth

ERTS-1 passes over any location on the Earth's surface once every 18 days at the same time of day, but some dates had high percentages of cloud cover. Neither aerial nor ground data were collected on those days (Table 3). These data (Table 4) were used as a means for determining vegetative growth with Stepwise Deletion Multiple Regression (1973). The July 7 data were not used because of the alteration of the natural vegetative growth by harvesting the wheat. The wheat threshed straw provided a stubble mulch compared to the uncut wheat. The equations that best describe vegetative growth were:

$$LAI = 2.92MSS4/5 - 2.63 \quad , \quad R^2 = 0.95 \qquad (2)$$

$$LAI = -0.065MSS5 + 2.66 \quad , \quad R^2 = 0.86 \qquad (3)$$

$$LAI = -1.22MSS5/7 + 2.08 \quad , \quad R^2 = 0.85 \qquad (4)$$

where

LAI = Leaf area index

MSS4/5 = Ratio of band 4 to band 5

MSS5 = Band 5

MSS5/7 = Ratio of band 5 to band 7

R^2 = Regression coefficient.

For the predicted values of leaf area index to have meaning, it is necessary that a minimum or maximum value of MSS4/5, MSS5 and MSS5/7 be set so that the predicted leaf area index is never negative.

The general trend from equation 2 indicates that as the ratio of band 4 to band 5 increases the leaf area index increases linearly. This

Table 3. Weather Conditions at Flight Time Over Test Fields.

Date	Weather Condition	Data Acquired*
September 4, 1972	Cloudy	
September 22, 1972	Clear	X
October 10, 1972	Partly Cloudy	
October 28, 1972	Cloudy	
November 15, 1972	Cloudy	
December 3, 1972	Partly Cloudy	
December 21, 1972	Partly Cloudy	
January 8, 1973	Cloudy	
January 26, 1973	Cloudy	
February 13, 1973	Rain	
March 3, 1973	Foggy	
March 21, 1973	Clear	X
April 8, 1973	Heavy Snow	
April 26, 1973	Rain	
May 14, 1973	Clear	X
June 1, 1973	Clear	X
June 19, 1973	Clear	X
July 7, 1973	Clear	X

*Indicates both ERTS-1 and field data taken.

Table 4. Leaf Area Index Data for Fields A and B.

Date	Field A Mean	Field A Standard Deviation	Field B Mean	Field B Standard Deviation
9/22/72	0.00	0.00	0.00	0.00
12/21/72	0.33	0.00	0.12	0.07
3/22/73	0.37	0.10	0.44	0.07
5/14/73	0.97	0.26	1.53	0.39
6/1/73	0.89	0.25	1.23	0.36
6/18/73	0.00	0.00	0.00	0.00
7/7/73	0.00	0.00	0.00	0.00

means that reflectance due to plant growth in band 4 increases faster than band 5 since the vegetation reflects less radiation in band 5. Equation 2 (Fig. 4) best describes leaf area index because of its high regression coefficient. The ratio appears to have cancelled any soil moisture variations.

Equation 3 shows a linear relationship between leaf area index and band 5. From the equation it appears soil moisture is not significant in band 5. Of the three equations presented, an error in band data would have the least effect on leaf area index as represented by the low coefficient of the band in equation 3. Equation 4 uses the ratio of band 5 and band 7 to evaluate leaf area index with no significant variation from soil moisture. The reflectance due to vegetation of band 7 increases at a much faster rate than band 5 as plant growth continues, causing a decrease in the ratio.

Prediction of Soil Moisture

The Stepwise Deletion Multiple Regression (1973) was used to help interpret the aerial and ground truth data available (Tables 5 and 6). The information for field B on March 22 was eliminated since rain fell before the soil moisture could be measured. Again the July 7 data were not used due to the stubble mulch caused by harvesting the wheat crop. The equations determined were:

$$SM2 = 164.44 - 4.00MSS4 - 24.08LAI \quad , \quad R^2 = 0.93 \qquad (5)$$

$$SM2 = 80.70 - 1.41MSS6 + 10.00LAI \quad , \quad R^2 = 0.80 \qquad (6)$$

$$SM2 = 77.92 - 2.56MSS7 + 20.36LAI \quad , \quad R^2 = 0.79 \qquad (7)$$

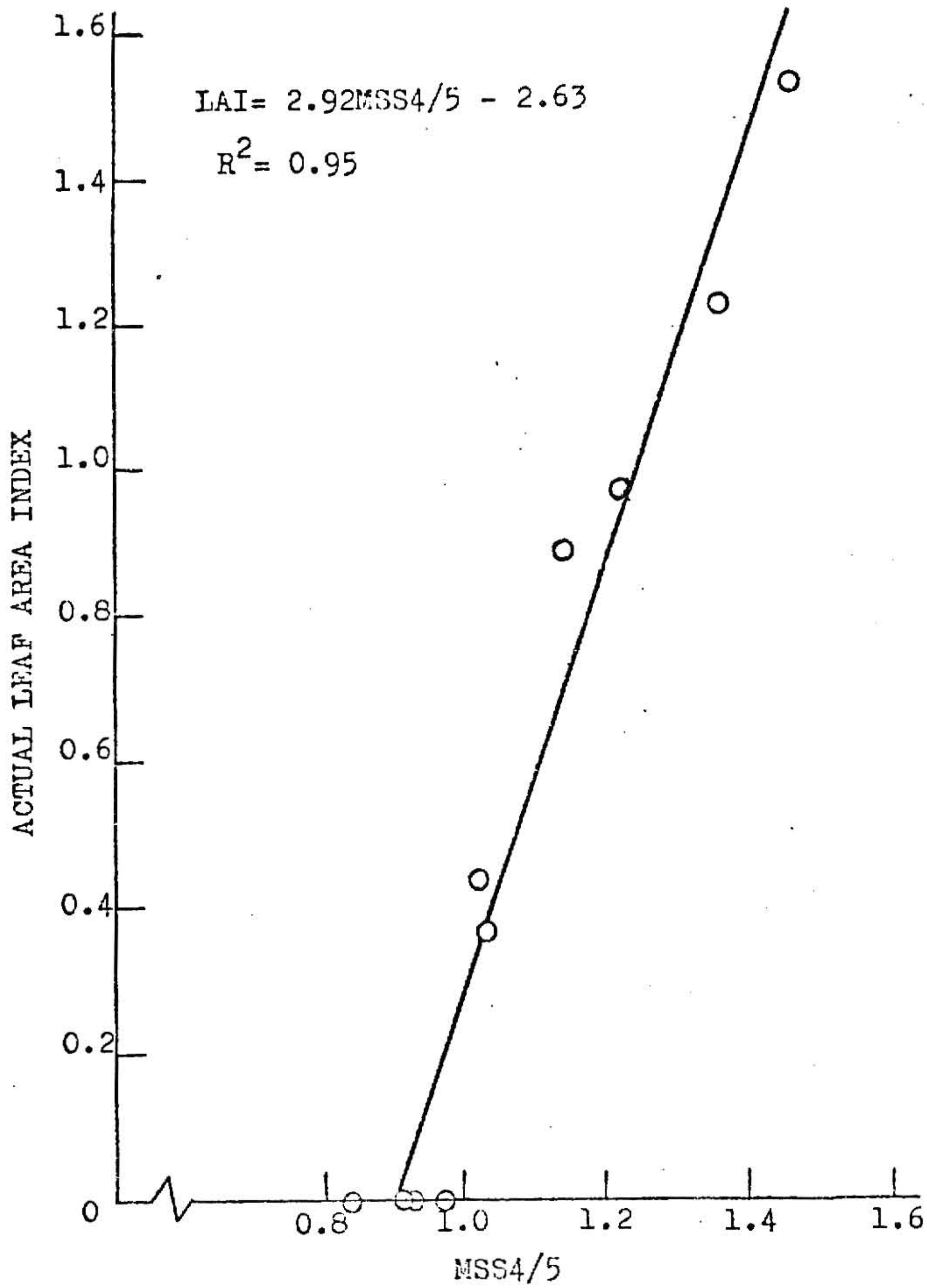

Fig. 4. Prediction of Leaf Area Index.

Table 5. Soil Moisture Percentages[†] for Field A.

Date		Soil Moisture at Increments (cm)							
		Surface	0-15	15-30	30-61	61-91	91-122	122-152	152-183
9/22/72	Mean	10.43	22.97	23.70	21.35	17.65	14.35	12.85	13.55
	S.D.*	2.18	0.99	2.58	0.93	3.10	1.87	0.75	0.97
12/21/72	Mean	34.30	30.40	27.70	26.50	24.30	21.10	15.70	13.80
	S.D.*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3/22/73	Mean	8.13	22.98	25.42	23.82	20.70	16.63	14.62	14.98
	S.D.*	2.59	1.27	1.81	1.26	2.02	2.70	2.61	2.61
5/14/73	Mean	3.82	16.92	17.20	19.12	20.35	20.03	18.52	16.45
	S.D.*	0.75	1.87	1.61	1.15	1.61	1.52	1.99	2.40
6/1/73	Mean	2.87	11.12	13.45	15.22	15.72	15.95	16.38	15.97
	S.D.*	0.84	1.50	0.63	1.22	2.04	2.19	2.00	2.28
6/19/73	Mean	0.85	6.35	9.80	11.12	10.13	11.08	12.47	13.32
	S.D.*	0.44	0.73	1.55	1.31	1.68	1.41	2.06	2.01
7/7/73	Mean	1.77	15.65	11.45	12.92	14.15	15.20	16.33	17.33
	S.D.*	0.21	1.73	0.89	0.39	1.00	2.30	2.65	2.51

[†]Soil moisture percentages on dry weight basis

*Standard deviation

Table 6. Soil Moisture Percentages[†] for Field B.

Date		Soil Moisture at Increments (cm)							
		Surface	0-15	15-30	30-61	61-91	91-122	122-152	152-183
9/22/72	Mean	8.35	22.40	20.75	16.93	13.43	13.00	14.70	16.05
	S.D.*	1.81	1.30	0.34	2.99	2.81	4.13	3.62	2.40
12/21/72	Mean	16.28	30.10	26.27	24.90	19.25	14.83	15.70	16.70
	S.D.*	3.71	5.60	2.11	3.19	2.83	3.41	2.75	2.88
3/22/73	Mean	19.00	27.05	23.97	24.15	20.02	14.78	15.00	15.97
	S.D.*	6.44	4.11	1.68	4.16	3.49	4.56	3.43	3.18
5/14/73	Mean	5.58	21.20	16.33	18.15	18.38	17.73	16.70	16.90
	S.D.*	0.93	3.27	2.06	3.53	3.85	3.75	3.85	2.58
6/1/73	Mean	25.10	25.47	18.93	15.48	13.88	13.68	15.55	16.62
	S.D.*	12.43	4.10	5.16	3.70	2.85	2.40	4.12	2.81
6/19/73	Mean	2.28	9.63	9.23	11.98	10.78	11.18	11.48	13.50
	S.D.*	1.13	2.19	1.73	3.88	3.02	1.72	1.68	1.91
7/7/73	Mean	2.60	17.20	9.40	11.43	11.10	10.50	10.38	13.15
	S.D.*	1.25	1.81	2.23	1.53	0.67	1.39	1.27	1.64

[†]Soil moisture percentages on dry weight basis.

*Standard deviation.

where:

SM2 = Soil moisture dry weight at 0 to 15 cm (%)

LAI = Leaf area index

MSS4 = Band 4

MSS6 = Band 6

MSS7 = Band 7

MSS4/5 = Ratio of band 4 to band 5

R^2 = Regression coefficient.

The soil moisture equation 5 indicates that an increase in leaf area index, with soil moisture remaining constant, decreases the reflectance in band 4. This could be caused by the reflectance of the soil being greater than the plant reflectance. Thus as the leaf area increased, more surface was covered by the plant canopy causing a decrease in reflectance monitored. The fact that soil moisture increases absorption is reaffirmed by equations 5, 6 and 7. Equation 5 is the best equation due to its high regression coefficient.

Equations 6 and 7 indicate that the reflectance of the plant is greater than the reflectance of the soil. An error in band reading or leaf area index would cause the least change in soil moisture in equation 6 due to the small coefficients.

Upon substituting equation 2 into equation 5, soil moisture at 0 to 15 cm depth became:

$$SM2 = 101.11 - 4.00MSS4 - 70.31MSS4/5 \quad (8)$$

Table 7 and Fig. 5 show a comparison of soil moisture predicted by equation 8 with the measured soil moisture. Equation 8 was developed for soil factors pretaining to the fields. Different soil factors would require a new equation to be developed for soil moisture. These factors include soil type, organic matter, particle size and cultural practices.

Table 7. Predicted Soil Moisture Percentages at 0 to 15 cm from ERTS-1 Data.

Date	Field A				Field B			
	MSS4	MSS4/5	Predicted[a] SM2	Actual SM2	MSS4	MSS4/5	Predicted[a] SM2	Actual SM2
9/22/72	34.75	0.918	24.24	22.97	37.05	0.919	14.80	22.40
3/22/73	33.26	1.031	22.25	22.98	33.54	1.019	21.85	27.05[b]
5/14/73	29.74	1.218	23.09	16.92	27.63	1.454	14.91	21.20
6/1/73	33.43	1.138	13.86	11.12	26.93	1.355	24.69	25.47
6/19/73	41.14	0.835	-----[c]	6.35	36.68	0.971	12.66	9.63

[a]Calculated by SM2 = 101.11 - 4.00MSS4 - 70.31MSS4/5.

[b]Precipitation fell after ERTS-1 flight but before measurement.

[c]A negative value is predicted which has no meaning.

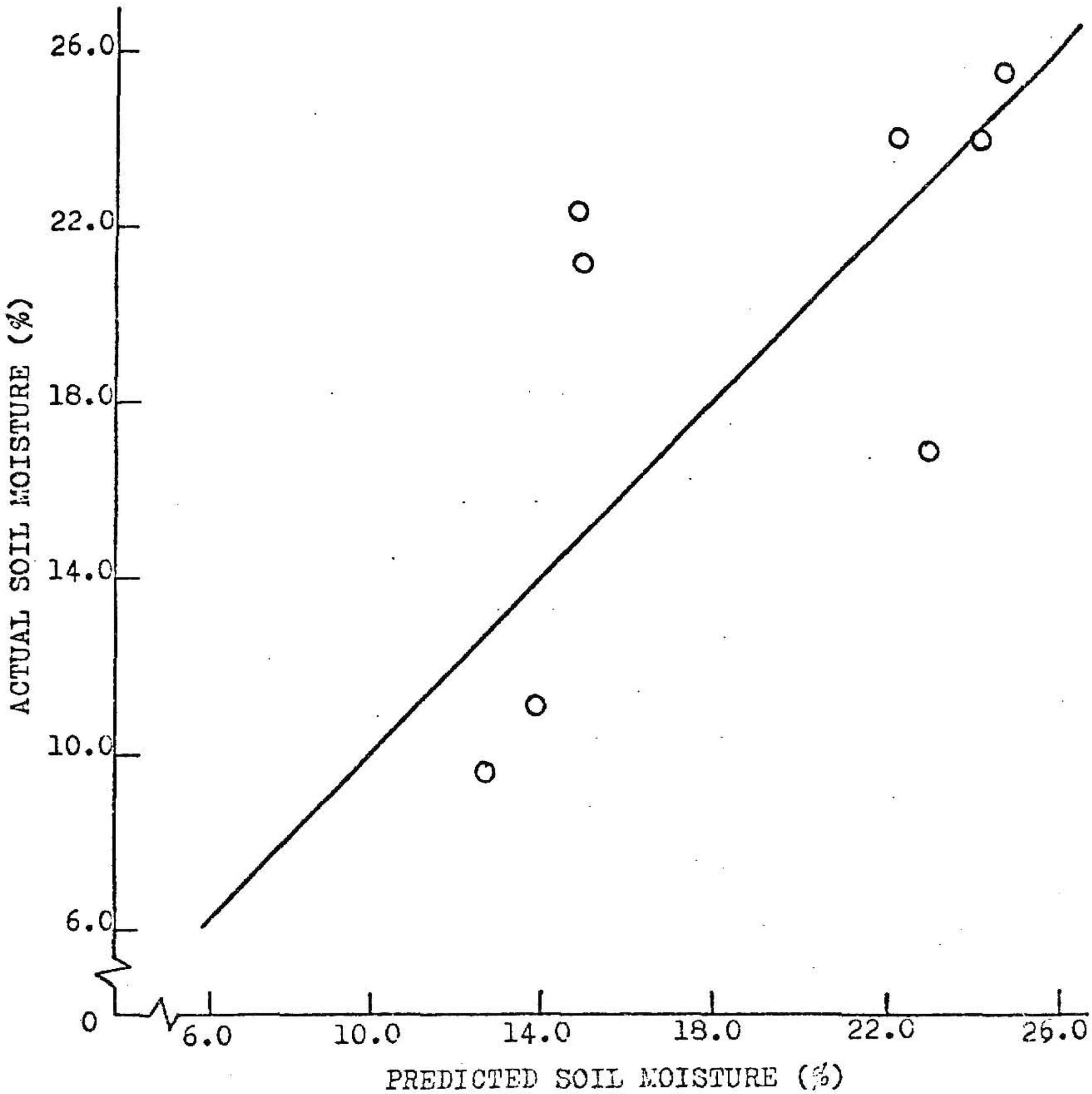

Fig. 5. Actual and Predicted Soil Moisture Percentages at 0 to 15 cm.

Soil Moisture Model

The original wheat crop coefficient curve developed by Jensen et al. (1971) was:

$$Y = 0.233 - 0.0114X + 0.000484X^2 - 0.00000289X^3 \quad (9)$$

$$Y = 1.022 + 0.00853D - 0.000726D^2 + 0.00000444D^3 \quad (10)$$

where:

Y = Wheat crop coefficient

X = Percent of crop cover

D = Days after 100 percent crop cover.

Equations 9 and 10 in conjunction with climatic data (Table 8) and soil moisture information (Tables 5, 6 and 9), were used in the computer model developed by Jensen et al. (1971). The soil moisture depletion for both fields in most cases was overestimated (Table 10).

Regression analysis of leaf area index data for field A (Fig. 6) was used as the new winter wheat crop coefficient curve (Fig. 7). The equations of the curve were:

$$Y = 0.005 + 0.0165X - 0.000467X^2 + 0.00000402X^3 \quad (11)$$

$$Y = 0.998 - 0.00297D - 0.000747D^2 \quad (12)$$

where:

Y = Wheat crop coefficient

X = Percent of crop cover

D = Days after 100 percent crop cover.

Fig. 8 and Table 10 represent the results from the computer model with equations 11 and 12 on dryland (Field A) compared to the actual measured values. The actual soil moisture values compared very closely with predicted values of the model until near maturity of the wheat crop on June 19. At

Table 8. Climatic Data.

Month	Day	Minimum Temp. (°F)	Maximum Temp. (°F)	Solar Radiation (cal/cm^2 day)	Dew Point Temp. (°F)	Wind Run (miles/day)	Rainfall (inches)
March	20	28	52	561.5	28	144	
	21	31	53	492.6	36	113	
	22	39	56	505.9	36	327	
	23	39	63	33.8	39	157	1.10
	24	36	49	108.2	36	167	
	25	35	40	90.2	35	415	
	26	35	42	468.6	35	284	
	27	35	55	205.5	35	127	.70
	28	42	51	163.4	42	200	
	29	32	50	91.1	32	160	
	30	32	39	47.7	32	166	1.00
	31	32	37	214.9	32	325	
April	1	30	45	588.5	30	239	
	2	30	58	428.7	34	79	
	3	31	54	429.0	32	187	
	4	31	48	642.3	31	274	
	5	22	54	634.0	30	163	
	6	31	63	627.3	28	164	
	7	37	70	44.7	35	124	0.25
	8	24	37	381.6	24	378	
	9	17	33	596.2	17	262	
	10	19	35	664.7	19	192	
	11	26	53	625.2	37	123	
	12	31	64	400.6	38	68	
	13	37	62	595.8	40	102	
	14	46	66	470.8	57	273	
	15	58	78	216.5	58	387	
	16	25	61	642.3	31	220	
	17	35	60	652.1	39	158	
	18	46	76	643.9	48	209	
	19	45	77	596.8	42	336	
	20	36	60	693.4	23	219	
	21	38	72	672.7	37	259	
	22	36	65	612.9	38	98	
	23	33	67	655.0	42	78	
	24	46	73	162.5	50	117	0.80
	25	44	57	107.9	45	115	
	26	34	48	221.9	36	181	
	27	31	48	200.5	36	122	
	28	38	66	666.9	43	153	
	29	45	82	635.9	45	167	
	30	49	78	368.8	49	134	

Table 8. Continued.

Month	Day	Minimum Temp. (°F)	Maximum Temp. (°F)	Solar Radiation (cal/cm^2 day)	Dew Point Temp. (°F)	Wind Run (miles/day)	Rainfall (inches)
May	1	44	73	156.6	45	176	
	2	35	46	633.8	37	178	
	3	32	58	704.2	36	90	
	4	40	71	688.0	41	165	
	5	50	79	503.6	45	319	
	6	47	79	702.9	47	207	
	7	48	77	520.8	50	185	1.25
	8	42	68	682.7	44	160	
	9	48	79	706.0	45	109	
	10	44	77	698.4	45	106	
	11	50	77	681.7	48	140	
	12	46	70	674.5	40	144	
	13	42	68	672.1	37	67	
	14	38	65	728.4	42	59	
	15	38	66	727.4	38	84	
	16	45	78	718.4	39	123	
	17	42	71	568.8	42	127	
	18	48	88	708.2	46	77	
	19	54	87	705.3	49	102	
	20	54	84	633.4	52	109	
	21	57	86	689.5	61	201	
	22	51	85	611.9	50	148	
	23	51	68	672.9	53	79	
	24	54	80	738.7	50	79	
	25	47	72	641.0	47	143	
	26	55	80	488.7	56	249	
	27	46	68	107.2	37	266	
	28	50	53	624.3	48	490	
	29	40	73	674.8	42	208	
	30	46	70	406.9	44	125	
	31	42	62	751.1	44	43	
June	1	48	77	623.8	60	133	
	2	57	82	659.7	56	247	
	3	53	86	645.8	53	192	
	4	53	80	599.6	54	94	
	5	47	68	667.5	48	133	
	6	50	79	736.5	46	70	
	7	51	88	729.0	49	78	
	8	56	94	719.4	53	87	
	9	57	97	739.9	56	98	
	10	60	92	734.1	58	182	
	11	62	90	707.2	59	277	

Table 8. Continued.

Month	Day	Minimum Temp. (°F)	Maximum Temp. (°F)	Solar Radiation (cal/cm^2 day)	Dew Point Temp. (°F)	Wind Run (miles/day)	Rainfall (inches)
June	12	64	91	498.0	60	210	
	13	64	82	627.2	66	102	
	15	59	89	737.1	52	216	
	16	57	94	743.0	46	215	
	17	53	84	740.3	49	121	
	18	48	95	757.4	32	239	
	19	54	78	695.6	35	170	
	20	45	79	738.7	41	113	
	21	52	85	683.0	54	85	
	22	55	86	725.5	51	62	
	23	57	91	723.3	51	84	
	24	64	98	729.4	46	126	
	25	61	98	663.5	49	186	
	26	63	101	701.2	51	130	
	27	62	102	690.7	50	156	
	28	63	93	594.5	61	106	0.90
	29	64	87	646.0	66	97	
	30	65	88	647.8	68	82	
July	1	66	94	668.4	68	146	
	2	70	102	613.5	63	197	
	3	67	92	639.6	63	75	
	4	66	102	661.3	65	160	
	5	62	95	702.4	62	94	
	6	65	97	715.1	62	102	
	7	68	101	714.1	64	170	

Table 9. Soil Moisture Information.*

Depth (cm)	Field Capacity (%)	Permanent Wilting Point (%)	Bulk Density (gm/cm^3)
0-30	28.5	14.5	1.29
30-61	28.0	14.0	1.37
61-91	27.5	13.5	1.39
91-122	27.0	13.0	1.16
122-152	26.5	12.5	1.16
152-183	26.0	12.0	1.16

*Obtained from the Garden City Experiment Station.

Table 10. Soil Moisture Depletion Using the Model Developed by Jensen *et al.*

	Field A (cm)			Field B (cm)			
Date	Actual[a]	Jensen[b]	Revised 1[c]	Actual[a]	Jensen[b]	Revised 1[c]	Revised 2[d]
3/21/73	17.65			19.28			
5/14/73	19.84	25.07	19.35	23.44	26.14	20.80	26.52
6/1/73	27.74	31.24	27.86	27.15	29.24	26.56	32.66
6/19/73	37.52	32.16	34.65	37.77	27.61	31.52	37.90
7/7/73	28.68	31.29	34.51	34.21	26.75	31.70	38.07

[a] Actual field measurements of soil moisture depletion.

[b] Original wheat crop coefficient suggested by Jensen *et al.*

[c] Wheat crop coefficient using leaf area index of Field A.

[d] Wheat crop coefficient using leaf area index of Field B.

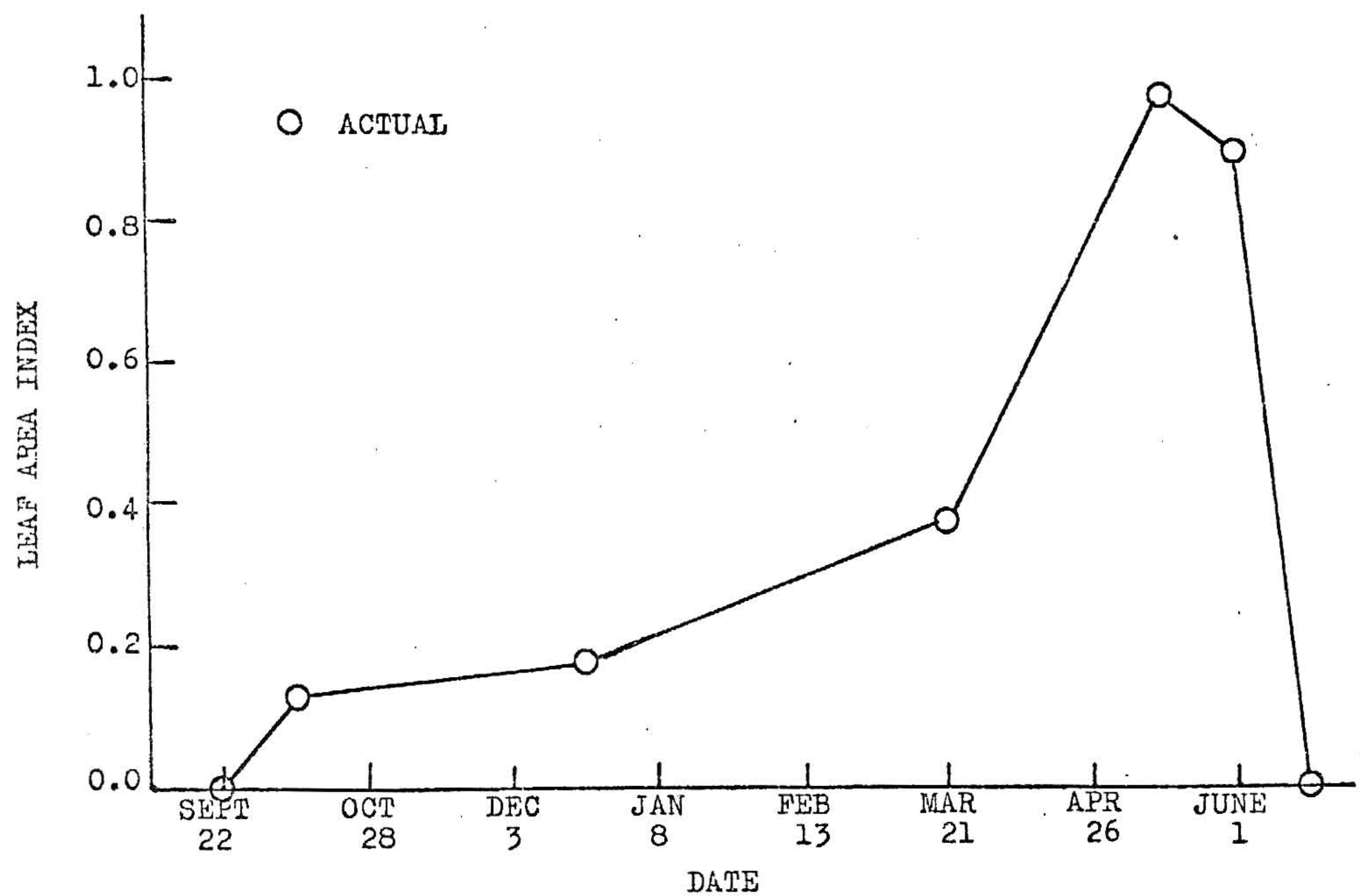

Fig. 6. Measured Leaf Area Index from Field A.

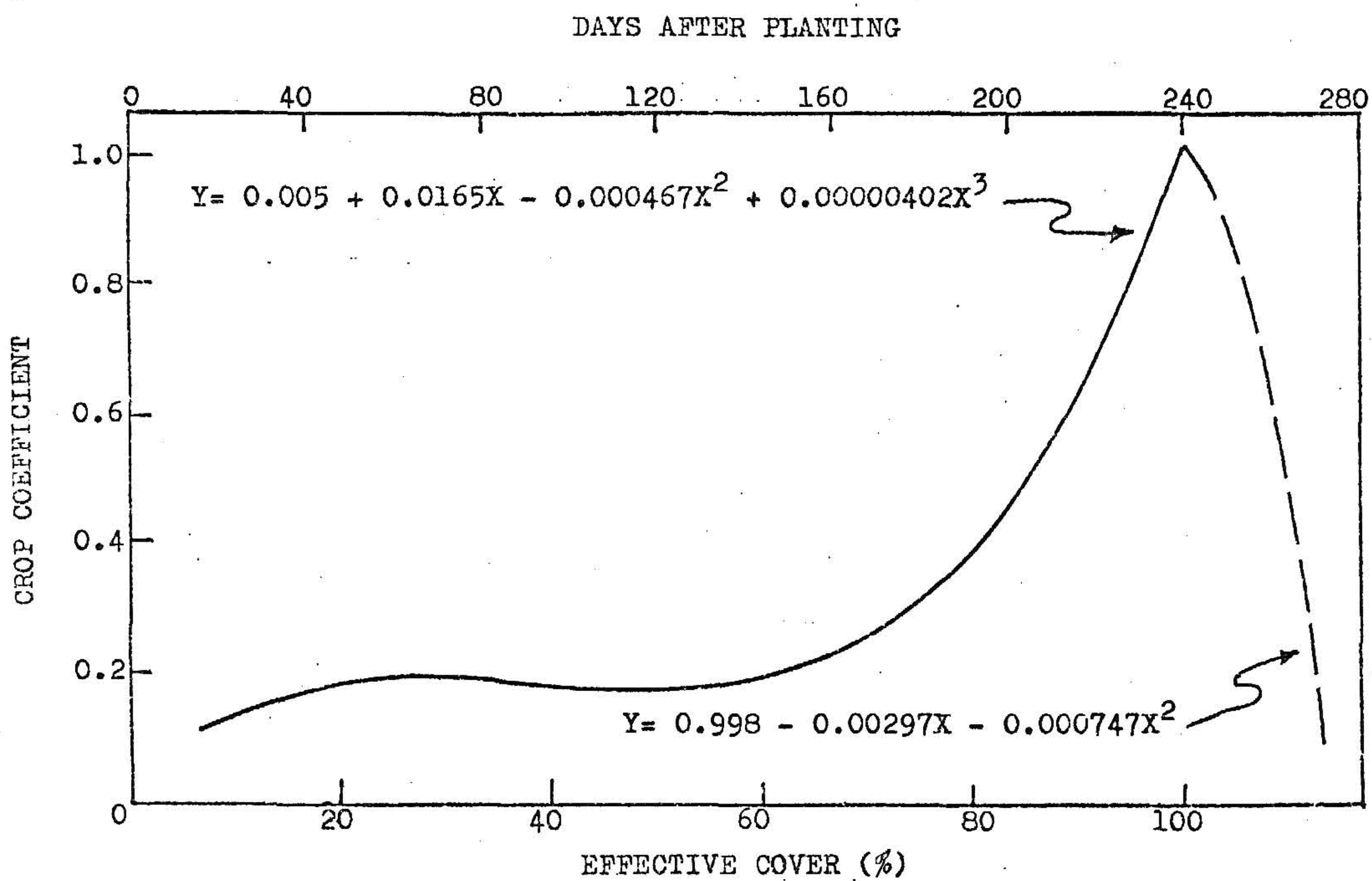

Fig. 7. Winter Wheat Crop Coefficient.

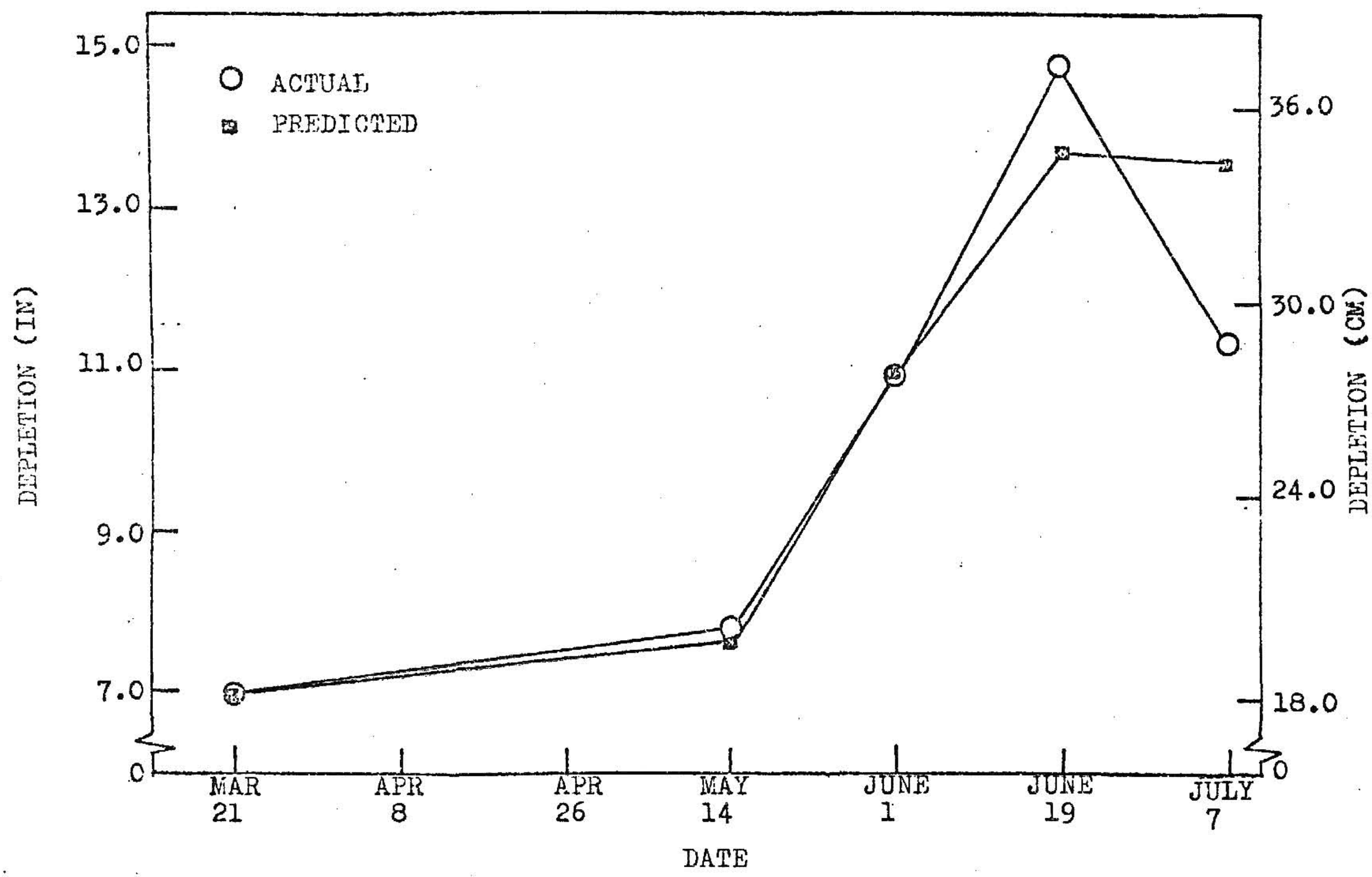

Fig. 8. Soil Moisture Depletion Measured and Predicted for Field A.

this date soil moisture depletion was underestimated, but still the difference in values were insignificant compared to the available moisture. After the June 19 date, comparison became difficult due to the discrepancy of actual soil moisture increasing 8.84 cm while rainfall only totaled 2.29 cm.

Fig. 9 and Table 10 show the results of the irrigated Field (B) using equations 11 and 12. The computer model consistently underestimates the evapotranspiration. For the time period up to June 1, the differences were not significant in relation to the available soil moisture, which included an irrigation on May 23 of 3.05 cm. By June 19 the two had considerably different values with another unexplained increase of 3.56 cm in soil moisture and only 2.29 cm of rainfall.

Regression analysis was used to develop a third wheat crop coefficient curve from the leaf area index of Field B (Fig. 10). The equations for the curve were:

$$Y = 0.0109X - 0.000288X^2 + 0.00000333X^3 \qquad (13)$$

$$Y = 1.52 - 0.000834D^2 \qquad (14)$$

where:

Y = Wheat crop coefficient

X = Percent of crop cover

D = Days after 100 percent crop cover.

The computer model's results using equations 13 and 14 indicate that the soil moisture depletion was overestimated meaning the crop coefficient used was too large.

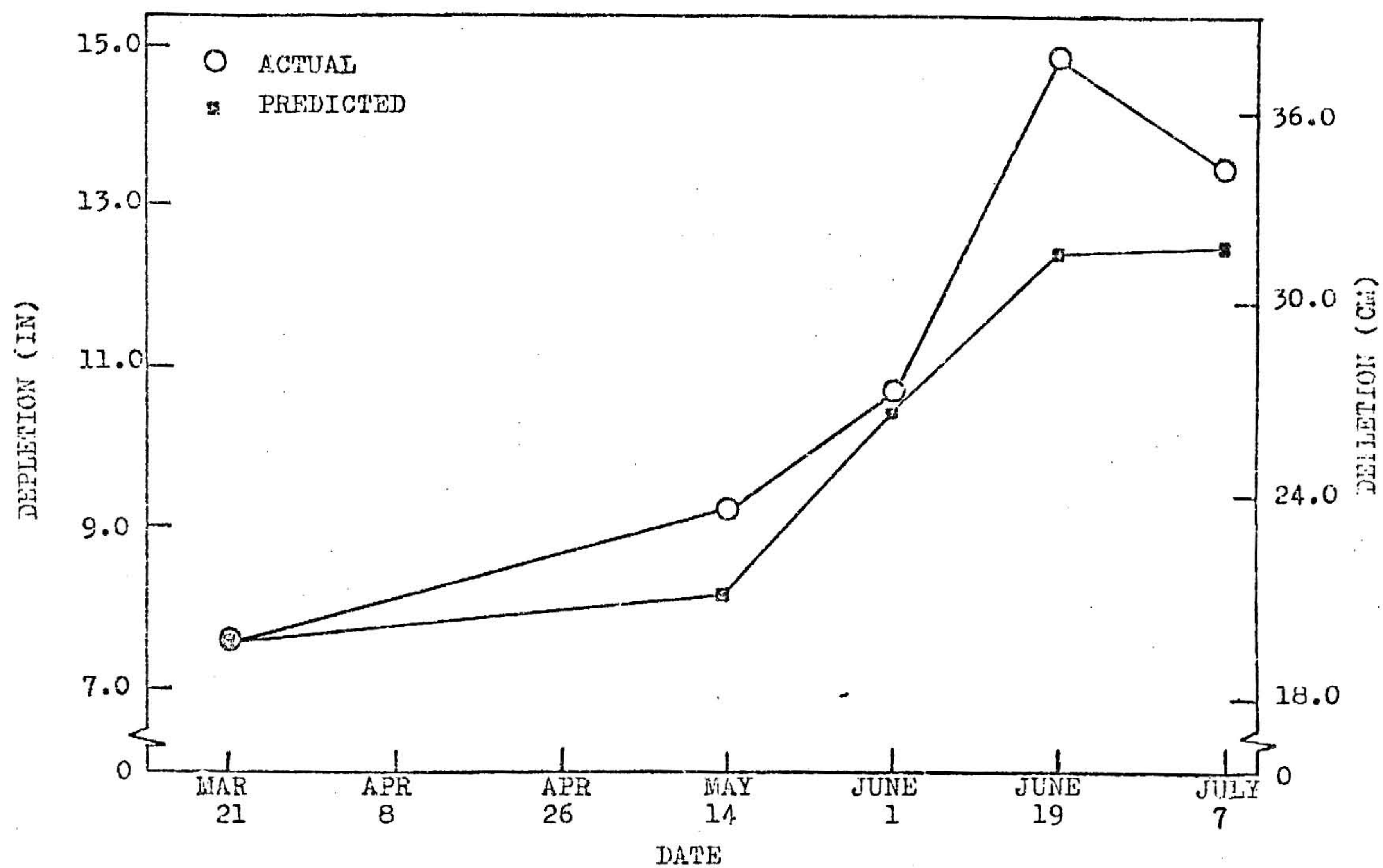

Fig. 9. Soil Moisture Depletion Measured and Predicted for Field B.

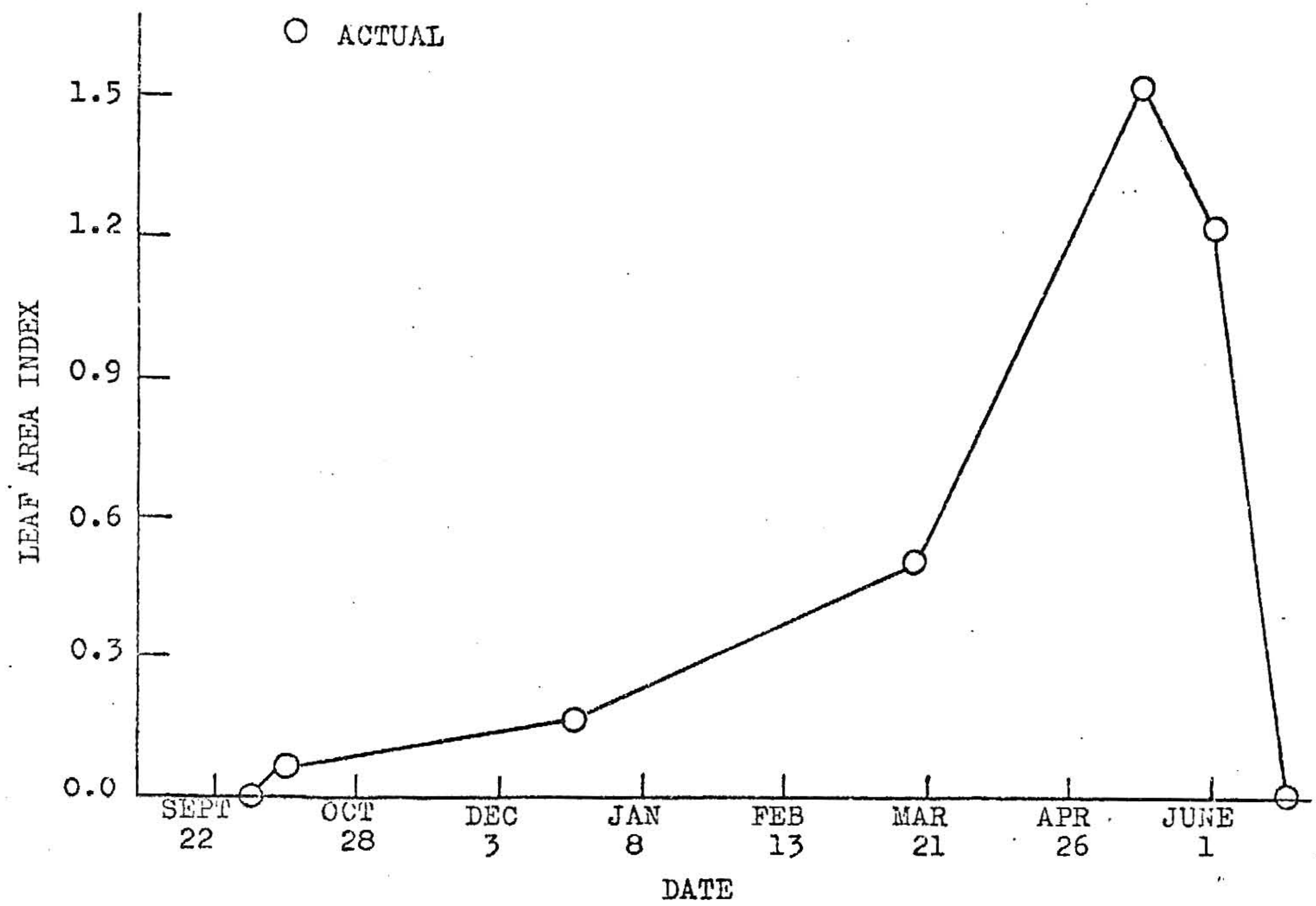

Fig. 10. Measured Leaf Area Index from Field B.

DISCUSSION

The computer model of irrigation scheduling developed by Jensen et al., (1971) uses a crop coefficient which represents the effects of the resistance of the water movement from the soil to the evaporating surfaces, the resistance of the diffusion of water vapor from the surfaces to the atmosphere and the amount of available energy compared to the reference crop. The model predicts percent effective cover by assuming that it is equal to days after planting divided by the days from planting to heading for small grains. This proves to be a poor assumption for winter wheat.

An alternative to this method of crop coefficient determination would be the direct use of wheat vegetative growth or more specifically leaf area index. If a leaf area index versus the crop coefficient curve was developed, vegetative growth would then indicate a specific value for the crop coefficient at a certain point in time. This would eliminate problems due to seasonal variation of weather conditions such as an early fall or late spring.

From this study it appears that a further step can be taken to utilize remote sensing. The winter wheat leaf area index has been described, with high correlation, by reflectance readings. These readings could be used as a direct input into a computer model instead of the original percent of effective cover.

If remote sensing data were available within hours after flight over an area, the following procedure might occur. Data direct from the remote sensing device would be fed into the computer containing an irrigation scheduling model. Meteorological data and a weather forecast for the prediction period would be the other inputs. From a leaf area index curve averaged over many years and the value from the remote sensor, the growth of the crop could be estimated for the prediction period. Knowing the growth or water use, the computer model would then be able to predict the irrigation requirement necessary. This process could be handled by one manager for large areas of irrigated wheat land.

CONCLUSIONS

Results from this study indicate:

1. Vegetative growth was best predicted by a linear relationship between leaf area index and the ratio of band 4 to band 5. All significant soil moisture effects were cancelled by the ratio.
2. Soil moisture at a depth of 0 to 15 cm, with specific soil factors, was predicted by band 4 and leaf area index with a high regression coefficient.
3. Vegetative growth, measured by leaf area index, was one of the necessary inputs in evaluating the winter wheat crop coefficient from March to maturity.

SUMMARY

A realization that wise resource management is necessary comes at a time when resource use is greater than ever before and the population is still increasing. With the use of remote sensing large quantities of data are available for resource management. These large quantities of data have led to the development of automatic recognition techniques in agriculture. Earth Resources Technology Satellite program provides a system for developing and demonstrating the techniques for efficient resource management.

With the large amount of irrigated land in the world, excess irrigation applications means large quantities of water needlessly lost. This valuable resource could be better utilized through the use of irrigation scheduling. Irrigation scheduling predicts the consumptive use (evapotranspiration). The actual evapotranspiration is dependent upon potential evapotranspiration and a crop coefficient which may be predicted by the plant's actual growth. The plant's growth can be determined by reflection of solar radiation from the plant canopy.

The objectives of this study were to evaluate reflectance for prediction of soil moisture and vegetative growth; and to determine the feasibility of using the plant's actual growth for use in determining the winter wheat crop coefficient curve and using it in a computer model developed by Jensen _et al_. (1971).

The study was conducted on winter wheat fields located northwest of Garden City, Kansas. Two soil moisture treatments were used, one dryland wheat field and one irrigated wheat field. Both fields were on Ulyssess-Richfield silt loam.

ERTS-1 satellite passes over any location on the Earth's surface once every 18 days at the same time of day. The satellite contains a line scanning device (Multispectral Scanner) that operates in two bands of the visible region and two in the near infrared region. Band 4 includes the spectrum between 0.5 and 0.6 μ, band 5 between 0.6 and 0.7 μ, band 6 between 0.7 and 0.8 μ and band 7 between 0.8 and 1.1 μ.

The ground truth data were gathered within one day of the aerial flights by ERTS-1. The ground truth data included soil moisture at various depths, leaf area index measurements and rainfall readings. The meteorological data were from the Garden City Experiment Station with the exception of solar radiation which was obtained from the Dodge City Weather Service.

Stepwise Deletion Multiple Regression (1973) was used to formulate equations with the use of reflectance data for vegetative growth and soil moisture. The equation that best described the relationship between reflectance and vegetative growth was:

$$LAI = 2.92MSS4/5 - 2.63 \quad , \quad R^2 = 0.95 \qquad (2)$$

where:

LAI = Leaf area index

MSS4/5 = Ratio of band 4 to band 5

R^2 = Regression coefficient

Soil moisture at a depth of 0 to 15 cm was best predicted by;

$$SM2 = 101.11 - 4.00MSS4 - 70.31MSS4/5 \qquad (8)$$

where:

SM2 = Soil moisture dry weight at 0 to 15 cm (%)

MSS4 = Band 4

MSS4/5 = Ratio of band 4 to band 5.

The best winter wheat crop coefficient curve was developed by regression analysis on the leaf area index data of the dryland field (A). The crop coefficient curve was:

$$Y = 0.005 + 0.0165X - 0.000467X^2 - 0.00000402X^3 \quad (11)$$

$$Y = 0.998 - 0.00297D - 0.000747D^2 \quad (12)$$

where:

Y = Wheat crop coefficient

X = Percent of crop cover

D = Days after 100 percent crop cover.

Meteorological data, starting soil moistures and crop coefficient curve were used in the computer model by Jensen et al. (1971). From results obtained, vegetative growth provides a feasible method for evaluating the winter wheat crop coefficient from at least March through maturity. Within the limits specified by Jensen et al. (1971), the model and modified coefficient proved to be a good estimator of soil moisture.

SUGGESTIONS FOR FUTURE RESEARCH

The research on evapotranspiration modeling and determining the crop coefficient by leaf area index should be expanded to include other crops and the whole growing season as well as increasing the number of test fields. More frequent sampling of soil moisture and leaf area index may be helpful. The neutron probe method for determining soil moisture measurement would provide a more representative indication due to the increased area of sampling. Continued research in using remote sensing for predicting vegetative growth with an emphasis on its use as an input in evaluating the crop coefficient in an evapotranspiration model may prove beneficial.

Additional research in the area of detecting soil moistures at depths greater than 15 cm with thermal energy could prove productive.

REFERENCES

Allen, W. H. and J. I. Sewell. 1973. Remote sensing of fallow soil moisture by photography and infrared line scanner. Transactions ASAE. 16(4): 700-706.

Angstrom, A. 1925. The albedo of various surfaces of the ground. Geografiska Annaler. (7):323.

Ashburn, E. V. and R. G. Weldon. 1956. Reflectance of Spectral Diffuse Desert Surfaces. Optical Society of America Journal. (46):583.

Bauer, Kenneth G. and John A. Dutton. 1962. Albedo variations measured from an airplane over several types of surfaces. Journal of Geophysical Research. 67(6):2367-2376.

Bhangoo, M. S. 1956. Fractionation of total supplies of nitrogen, phosphorus and potassium in certain Kansas surface soils and subsoils and their effect on the yield and composition of wheat. Kansas State University Library. Manhattan, Kansas.

Bolaria, T. S. 1956. Cold hardiness, growth and yield of winter wheat as influenced by mineral nutrients. Kansas State University Library. Manhattan, Kansas.

Bowers, S. A. 1971. Reflection of radiant energy from soils. Kansas State University Library. Manhattan, Kansas.

Carlson, Richard E. 1971. Remote detection of moisture stress: Field and laboratory experiments. Iowa State University Library. Ames, Iowa.

Cole, F. W. 1970. Introduction to meteorology. New York. John Wiley and Sons, Inc.

Coulson, L. 1966. Effects of reflection properties of natural surfaces in aerial reconnaissance. Applied Optics. (5):905-917.

David, W. P. 1969. Remote sensing of crop water deficits and its potential applications. Texas A&M University Remote Sensing Center Technical Report RSC-06.

Earing, Dianne L. and I. William Ginsberg. 1969. A spectral discrimination technique for agricultural applications. Sixth International Symposium on Remote Sensing of Environment Proceedings.

Economic Research Service. 1965. Agricultural application of remote sensing--The potential from space platforms. U.S. Dept. of Agri. Bulletin 328.

Fritschen, L. J. 1967. Net and solar radiation relations over irrigated field crops. Agri. Meteorology. (4):55-62.

Frits, Sigmund. 1948. The albedo of the ground and atmosphere. Meteorological Society Bulletin. (29):303.

Fry, A. W. and Alfred S. Gray. 1970. Sprinkler irrigation handbook. Glendora, California. Rain Bird Sprinkler Mfg. Corporation.

Gates, David M. 1965. Characteristics of soil and vegetated surfaces to reflected and emitted radiation. Third Symposium on Remote Sensing of Environment Proceedings.

Gates, David M. and R. J. Hanks. 1967. Plant factors affecting evapotranspiration. Irrigation of Agricultural Lands. American Society of Agronomy Monograph No. 11.

Geiger, Rudolf. 1965. The climate near the ground. Cambridge, Massachusetts. Harvard University Press.

George, Theodore A. 1970. Unmanned spacecraft for surveying earth's resources. Princeton University Conference on Aerospace Methods for Revealing and Evaluating Earth's Resources.

Heermann, D. F. and H. R. Gardner. 1970. Evapotranspiration model for dryland crops for the Great Plains. Evapotranspiration in the Great Plains Seminar.

Hoffer, Roger M., Roger A. Holmes and J. Ralph Shay. 1966. Vegetative, soil and photographic factors affecting tone in agricultural remote multispectral sensing. Fourth Symposium on Remote Sensing of Environment Proceedings.

Interpretation of remote multispectral imagery of agricultural crops. 1967. Purdue University Agri. Exp. Sta. Bulletin 831.

Isralsen, Orson W. and Vaughn E. Hansen. 1967. Irrigation principles and practices. New York. John Wiley and Sons, Inc.

Jensen, M. E. 1968. Water consumption by agricultural plants. Water Deficits and Plant Growth. (2):1-22.

___________ and J. L. Wright. 1970. Irrigation-oriented et models for the Great Plains. Evapotranspiration in the Great Plains Seminar.

_______________________ and B. J. Pratt. 1971. Estimating soil moisture depletion from climate, crop and soil data. Transactions of ASAE. 14(5):954-959.

Kanemasu, E. T. 1973. Energy from solar and thermal radiation. (Private Communication).

Kohnke, Helmut. 1968. Soil physics. New York. McGraw-Hill Book Company.

Kondrat'yev, K. Y. 1965. Actinomentry NASATT F9712. National Aeronautics and Space Administration, Washington, D.C.

Lowry, W. P. 1969. Weather and life. New York. Academic Press.

Luxmoore, R. J., R. J. Millington and H. Marcellos. 1971. Soybean canopy structure and some radiant energy relations. Agronomy Journal. (63):111-114.

Monteith, J. L. 1959. The reflection of short-wave radiation by vegetation. Quarterly Journal of the Royal Meteorological Society. (85):386-392.

__________ and G. Szeicz. 1961. The radiation balance of bare soil and vegetation. Royal Meteorological Society of London (87):159-170.

Myers, Victor I. and William A. Allen. 1968. Electrical sensing as non-destructive testing and measuring techniques in agriculture. Applied Optics. (7):1819.

Myers, V. I., C. L. Wiegand, M. D. Heilman and J. R. Thomas. 1966. Remote sensing in soil and water conservation research. Southern Plains Branch Soil and Water Conservation Research Div. Agri. Research Service U.S. Dept. of Agri.

NASA Earth Resources Technology Satellite Data Users Handbook. 1972. Goddard Space Flight Center Document 71SD4249.

Nicodemus, F. E. 1965. Directional reflectance and emissivitiy of an opaque surface. Applied Optics. (4):767-773.

Penman, H. L. 1963. Vegetation and hydrology. Commonwealth Bureau of Soils Technical Communication No. 53.

__________, D. E. Angus and C. H. M. Van Bavel. 1967. Microclimatic factors affecting evaporation and transpiration. Irrigation of Agricultural Lands. American Society of Agronomy Monograph No. 11.

Remote multispectral sensing in agriculture. 1967. Purdue University Agri. Exp. Sta. Bulletin 844.

Remote multispectral sensing in agriculture. 1970. Purdue University Agri. Expt. Sta. and Purdue University Bulletin 873.

Remote Sensing. 1970. Washington, D.C. National Academy of Sciences.

Rijks, D. A. 1967. Water use by irrigated cotton in Sudan. I. Reflection of short-wave radiation. Journal of Applied Ecology. (4):561-568.

Ritchie, J. T. 1971. Dryland evaporative flux in a subhumid climate: I. Micrometeorological influences. Agronomy Journal. (63):51-55.

__________. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resources Research. 8(5):1204-1213.

__________ and Earl Burnett. 1971. Dry land evaporative flux in a sub humid climate: II. Plant influences. Agronomy Journal (63):56-62.

Savage, R. G. 1949. Moisture determinations in hay yield. Sci. Agri. (29):305-329.

Sewell, John I., William H. Allen and Robert S. Pile. 1971. Visible and near infrared remote-sensing of soil moisture levels. Transactions ASAE. 14(6):1163-1166.

Sinclair, T. R., R. M. Hoffer and M. M. Schreiber. 1971. Reflectance and internal structure of leaves from several crops during a growing season. Agronomy Journal. (63):863-868.

__________, M. M. Schreiber and R. M. Hoffer. 1973. Diffuse reflectance hypothesis for the pathway of solar radiation through leaves. Agronomy Journal 65(2):276-283.

Stanhill, G., G. J. Hofstede and J. D. Kalma. 1966. Radiation balance of natural and agricutlrual vegetation. Quarterly Journal of the Royal Meteorological Society. (92):128-140.

__________, J. H. Cox and S. Moreshet. 1968. The effect of crop and climate factors on the radiation balance of an irrigated maize crop. Journal of Applied Ecology. (5):707-720.

Stepwise deletion multiple regression (STEPDEL) description 4. 1973. Kansas State University Statistical Laboratory. Manhattan, Kansas.

Teare, I. D. and C. J. Peterson. 1971. Surface area of chlorophyll-containing tissue of the inflorescence of triticum aestivum l. Crop Science. 2(5):627-628.

Variety tests with fall-planted small grains. 1971. Kansas State University Agri. Exp. Sta. Report 180.

Werner, Hal D., Fred A. Schmer, Maurice L. Horton and Fred A. Waltz. 1971. Application of remote sensing techniques to monitoring soil moisture. Seventh International Symposium on Remote Sensing of Environment Proceedings.

Winkler, Erhard M. 1966. Moisture measurements in glacial soils from airphotos. Ecology. 47(1):156-158.

APPENDIX

Table 11. Computer Model of Evapotranspiration by Jensen et al.

```
$JOB              JK,TIME=(5),PAGES=20
      REAL METH1,IRR
C**   "IRRIGATE" WITH 1971 REVISIONS BY PRATT, JENSEN & HEERMANN
C********     PLUS  KSU MODIFICATIONS FOR IBM 360/50
C** MAIN PROGRAM
      COMMON A(4,5), CTR(4),TXR(4),ND(4,30).
     1X(13,4,30),DESC(5),DATE(4),CROP(3),AIRA(2),FORC(15),
     2N(4),NOB(4),RSO(4),MONDAY(4),W1(5,100),C(8,8),RREG(4,30),R(30)
      COMMON /NEW/  M(4),MON(13),IP,NCP,NDE,NOP,B(4,6),ETAP(4),TP(4),
     1DT1(4),DT2(4),FCT(4),ETP5
      DIMENSION CW(4)
      DATA METH1 /'RREG'/
C     READ NUMBER OF REGIONS
C** READ CROP COEFFICIENTS BEFORE EFFECTIVE COVER, C(1,1) TO C(8,4)
C** II=CROP NO.   JJ=NO. OF TERM IN POLYNOMIAL EQUATION
   16 FORMAT (5X,F15.3,3E20.3)
   17 FORMAT(1H ,4F15.8)
      DO 18 II=1,8
   15 READ(5,16)(C(II,JJ),JJ=1,4)
   18 WRITE(6,17)(C(II,JJ),JJ=1,4)
C** READ CROP COEFFICIENTS AFTER EFFECTIVE COVER, C(1,5) TO C(8,8)
      DO 21 II=1,8
   20 READ (5,16) (C(II,JJ),JJ=5,8)
   21 WRITE(6,17)(C(II,JJ),JJ=5,8)
      READ (5,1) NREG,RNRD
    1 FORMAT  (5X,I5,1X,A4)
C     READ REGIONAL DATA
      DO 2 I=1,NREG
      READ (5,3) (A(I,J), J=1,5), CTR(I),TXR(I),CW(I)
    3 FORMAT(5X,5A4,3F7.3)
      READ (5,103)  ETAP(I),TP(I),DT1(I),DT2(I)
  103 FORMAT  (5X,F5.2,3F5.0)
    2 READ (5,104)  (B(I,J),J=1,6)
  104 FORMAT  (5X,6E10.2)
C     READ CLIMATIC DATA - NUM. OF DAYS PLUS THREE PREVIOUS DAYS
      DO 7 I=1,NREG
      READ(5,11)N(I),NOB(I), FCT (I),RSO(I)
   11 FORMAT (5X,2I5,F5.2 ,F5.0)
      K=N(I) +3
C** IF RNRD=METH1 THEN RAIN IS READ BY REGION RATHER THAN BY FARM
C** I=REGION.   K=NO OF DAY.  K=4 IS FIRST DAY OF ANALYSIS PERIOD.
C**  K=1 IS FIRST DAY OF THREE PREVIOUS DAYS.
      IF (RNRD.EQ.METH1) GO TO 12
      DO 4 J=1,K
    4 READ( 5,5) ND(I,J),X (1,I,J),X (2,I,J),X(3,I,J),X(4,I,J),X(5,I,J)
      GO TO 7
   12 DO 9 J=1,K
    8 READ (5,25) ND(I,J),X(1,I,J),X(2,I,J),X(3,I,J),X(4,I,J),X(5,I,J)
     1,RREG(I,J)
    7 CONTINUE
   25 FORMAT  (5X,I5,6F5.0)
      WRITE(6,9)
    9 FORMAT(1H1)
    5 FORMAT(5X,I5,5F5.0)
      DO 6  I=1,NREG
      K=N(I)+3
 2989 FORMAT(1H ,4F15.8)
      WRITE(6,2989)C(1,1),C(1,2),C(1,3),C(1,4)
      CALL EVAP (I,K)
      WRITE(6,2989)C(1,1),C(1,2),C(1,3),C(1,4)
```

Table 11. Continued.

```
      CALL VAPOR(I,K,CW)
      WRITE(6,2389)C(1,1),C(1,2),C(1,3),C(1,4)
    6 CALL PRINTR(I,K)
      WRITE(6,2389)C(1,1),C(1,2),C(1,3),C(1,4)
      CALL FARMS(NREG,METH1,RNRD)
      WRITE(6,2389)C(1,1),C(1,2),C(1,3),C(1,4)
      CALL PRINTS(NREG,METH1,RNRD)
      WRITE(6,2389)C(1,1),C(1,2),C(1,3),C(1,4)
  999 STOP
      END

      SUBROUTINE FARMS (NREG,METH1,RNRD)
C    SUBROUTINE TO CALCULATE IRRIGATION DATES
      REAL METH1,IRR
      COMMON A(4,5), CTR(4),TXP(4),ND(4,30),
     1X(15,4,30),DESC(5),DATE(4),CROP(3),AIRR(2),FORC(15),
     2N(4),NOB(4),RSH(4),MODAY(4),W1(5,100),C(8,8),PREG(4,30),R(30)
      COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
     1DT1(4),DT2(4),FCT(4),ETP5
      DIMENSION DPAKSU(6),AIRKSU(6),NXDKSU(6)
      DIMENSION D(8),       SUMR(30),ET(30),DPL(30),D1(8)
      DIMENSION  ETRSET(8,30),ETSET(8,30),AKC11(8,30),AKCSET(8,30),
     1RSET(4,8,30),AETFLD(8),CROPST (8,3 ), DPLSET(8,30)
C    D ARRAY -LOWER LIMIT FOR CROP COEFFS.
C    D1ARRAY-UPPER LIMIT FOR CROP COEFFS.
      DATA D1/1.1,1.1,1.1,1.1,1.1,1.1,1.0,0.87/
      DATA NCROPS/8/,D/7*0.1,.87/
      DATA    SUMR,ET,DPL/30*0.0,30*0.0,30*0.0/
C    READ DATE
      READ( 5,14) (DATE(K),K=1,4)
      N4=1
      F=0.9
      DO 100 I=1,NREG
      WRITE(6 ,13)(A(I,J),J=1,5)
   13 FORMAT(1H1,' REGION:   ',5A4,//)
   14 FORMAT(5X,15A4)
      READ( 5,10)LL
   10 FORMAT(25X,I5)
      M=N(I) +3
      NN=N(I)
      DO 100 L=1,LL
      READ(5 ,10)NFN
      READ(5 ,14)(DESC(K),K=1,5)
      WRITE(6 ,15)(DESC(K),K=1,5),(DATE(K),K=1,4)
   15 FORMAT('1FARM:',5A4,3X,'DATE OF COMPUTATION: ',4A4,/)
      WRITE (6,16)
   16 FORMAT   ('0',T11,'|',T18,'|***** SOIL MOISTURE DEPLETION ******|--
     1---- IRRIGATIONS -------| INCHES |',/,' ',T11,'|',T18,'|',T28,'|',
     2          T37,'|',T48,'|',T55,'|',T64,               '|    IF    | WITH
     3  |    TO    |',/,
     4 ' CROP-FLD | COEF | TO DATE | TYPE-D | OPTIMUM   | RATE |  LAST','
     5  | RAIN=0 |   RAIN   | APPLY   | REG FM FLD')
   24 DO 110 NF=1,NFN
      IF(RNRD.EQ.METH1) GO TO 1
      GO TO 2
    1 DO 26 J=1,M
   26 R(J)=PREG(I,J)
    2 READ(5,17)NCR,CROP(1),CROP(2),CROP(3),NDP,NDE,NDH,E,AVM
   17 FORMAT(5X,I2,2A4,A2,3I5,2F5.2)
      IF (RNRD.EQ.METH1) GO TO 23
```

Table 11. Continued.

```
          READ(5,18)(AIRR(J),J=1,2),DPA,N5,(R(J),J=4,M )
       18 FORMAT (5X,2A3,F4.1,I4,10F4.2/20F4.2)
          READ(5,19) DPL(NF),SUMR(NF),(R(J),J=1,3)
       19 FORMAT(5F10.2)
          GOTO 22
       23 READ (5,20)(AIRR(J),J=1,2),DPA,N5,IRR
       20 FORMAT   (5X,2A3,F4.1,I4,F4.1)
          READ  (5,19) DPL(NF),SUMR(NF)
          IF (N5.GE.1)  R(N5+3)=R(N5+3)+IRR
       22 CONTINUE
          AKC=0.0
          AKC1=0.0
          PCT=0.0
          DT=0.0
C
C**  J=4 REPRESENTS FIRST DAY OF THE PERIOD FOR WHICH ANALYSIS IS BEING
C**  RUN
          DO 98 J=4,M
          ET(J)=0.0
          ETR=0.0
          RX= R(J)
          SUMR(NF)= SUMR(NF)+R(J)
          IF(J-N5-3)76,75,76
C** DPL AND SUMR ARE SET TO ZERO ON THE DAY OF IRRIGATION
       75 DPL(NF)=0.0
          SUMR(NF)=0.0
          GO TO 99
       76 IF(NDB(I)-NDP)109,176,176
      176 IF(NDB(I)-NDH)29,29,109
       29 IF(NDB(I)+J-4-NDE) 30,30,31
       30 PCT=100.0*(NDB(I)+J-4-NDP)/(NDE-NDP)
          AKC1=C(NCR,1)+C(NCR,2)*PCT+C(NCR,3)*PCT**2+C(NCR,4)*PCT**3
          IF(AKC1-D1(NCR))231,232,232
      232 AKC1=D1(NCR)
      231 AV=(1.0-DPL(NF)/AVM)*100.0
          IF(AV)130,131,131
      130 AV=0.0
      131 AV3=1.0+AV
          AKC=AKC1*ALOG(AV3)/ALOG(101.0)
          GO TO 32
       31 DT=NDB(I)+J-4-NDE
          PCT=100.
          AV=(1.0-DPL(NF)/AVM)*100.0
          AKC1=C(NCR,5)+C(NCR,6)*DT+C(NCR,7)*DT**2+C(NCR,8)*DT**3
          IF(AKC1-D(NCR))88,235,235
      235 IF(AKC1-D1(NCR))242,241,241
      241 AKC1=D1(NCR)
          GO TO 242
       88 AKC1=D(NCR)
      242 IF(AV)233,234,234
      233 AV=0.0
      234 AV3=1.0+AV
          AKC=AKC1*ALOG(AV3)/ALOG(101.0)
       32 ET(J)=AKC*X(16,I,J)
          IF(AKC-F) 38,121,121
       38 IF(R(J-1))42,42,43
       43 ETR=0.8*(F-AKC)*X(16,I,J)
          R(J-1)=R(J-1)-ETR
          IF(R(J-1))49,121,121
       49 R(J-2)=R(J-2)+R(J-1)
```

Table 11. Continued.

```
          R(J-1)=0.0
       45 IF(R(J-2))46,121,121
       46 R(J-3)=R(J-3)+R(J-2)
          R(J-2)=0.0
       40 IF(R(J-3))53,121,121
       53 ETR=ETR+R(J-3)
          R(J-3)=0.0
          GO TO 121
       42 IF(R(J-2))44,44,47
       47 ETR=0.5*(F-AKC)*X(16,I,J)
          R(J-2)=R(J-2)-ETR
          GO TO 45
       44 IF(R(J-3))121,121,48
       48 ETR=0.3*(F-AKC)*X(16,I,J)
          R(J-3)=R(J-3)-ETR
          GO TO 40
      121 IF(ETR)50,51,51
       50 ETR=0.0
       51 ET(J)=ET(J)+ETR
       91 DPL(NF)=DPL(NF)+ET(J)-RX
          IF(DPL(NF))115,99,99
      115 DPL(NF)=0.0
       99 CONTINUE
          ETRSET(NF,J)=ETR
          ETSET(NF,J)=ET(J)
          AKC11(NF,J)=AKC1
          AKCSET(NF,J)=AKC
          DO 890 NM=1,4
      890 RSET(NM,NF,J)=R(J-NM+1)
          DPLSET(NF,J)=DPL(NF)
       98 CONTINUE
          SUMET=0.0
          DO 57 J=4,M
       57 SUMET=SUMET + ET(J)
          RDIF=M-3
          AET=SUMET/RDIF
          AETFLD(NF)=AET
          DO 880 J=1,3
      880 CROPST(NF,J)=CROP(J)
          MBD=NDB(I)+N(I)
          IF (NDB(I)+N(I)+3-NDE)  250,250,255
      250 PCT=100.0*(NDB(I)+N(I)+2-NDP)/(NDE-NDP)
          AKC5 = C(NCR,1)+C(NCR,2)*PCT+C(NCR,3)*PCT**2+C(NCR,4)*PCT**3
          GO TO 260
      255 DT=NDB(I)+N(I)+3-NDE
          PCT=100.0
          AKC5 = C(NCR,5)+C(NCR,6)*DT+C(NCR,7)*DT**2+C(NCR,8)*DT**3
      260 IF  (AKC5 .LT. D(NCR)) AKC5=D(NCR)
          IF (AKC5 .GT. D1(NCR)) AKC5=D1(NCR)
          AJJ5=NDB(I)+N(I)+3
          IF (AJJ5 .GT. TP(I)) GO TO 7034
          DLT=DT1(I)
          GO TO 7341
     7034 DLT=DT2(I)
     7341 ETP5=  (ETAP(I)/(EXP(((AJJ5-TP(I))/DLT)**2)))*FCT(I)
          ETA5 = AKC5*ETP5
          DPLA = DPL(NF)
C**        SUBSCRIPT  J=1 IS 20%D  --  J=2 IS 30%D  --  J=3 IS 40%D
C**            J=4 IS 50%D  --  J=5 IS 60%D
          NPCT=100.0*(NDB(I)+N(I)+2-NDP)/(NDE+33.-NDP)
```

Table 11. Continued.

```
      IF(NPCT-100)248,248,249
  249 NPCT=100.0
  248 CONTINUE
                                      DO 108 J=1,5
                                      RJJ=J+1
      DPAKSU(J)=NPCT*AVM*RJJ*.001
                                      IPC=(J+1)*10
      AVW=DPAKSU(J)-DPL(NF)
      CALL SCHED (MBD,AVW,NCH,NXD,NXDP,I,DPLA,AVM,D,D1)
      CALL DATEE (NXD,IX,IY,NDH)
      CALL DATEE (NXDP,JX,JY,NDH)
   59 IF (DPAKSU(J) - DPL(NF)) 60,61,61
   60 AIR = DPL(NF)/E
      GO TO 63
   61 AIR = DPAKSU(J)/E
   63 IF (J .GT. 1) GO TO 65
      WRITE (6,64)  CROP,AKC5,DPL(NF),DPAKSU(J),ETA5,AIRR,MON(IX),IY,MON
     1   (JX),JY,AIR,    I,L,NF
   64 FORMAT  ('0',2A4,A2,F5.2,F9.2,5X,'20% D',2F9.2,' | ',2A3,2(2X,A4,I
     23),' | ',F4.1,I7,2I4)
      GO TO 108
   65 WRITE (6,68)  IPC,DPAKSU(J),ETA5,AIRR,MON(IX),IY,MON(JX),JY,AIR
   68 FORMAT  (' ',T31,I2,'% D',2F9.2,' | ',2A3,2(2X,A4,I3),
     1    ' | ',F4.1,I7,2I4)
  108 CONTINUE
  109 CONTINUE
      W1(1,N4)=DPL(NF)
      W1(2,N4)=SUMR(NF)
      W1(3,N4)=R(M-2)
      W1(4,N4)=R(M-1)
      W1(5,N4)=R(M)
      N4=N4+1
  110 CONTINUE
      WK = (NDB(I) + N(I) - 53)/7
      PP = 14.*(B(I,1)+B(I,2)*WK+  B(I,3)*WK**2+  B(I,4)*WK**3 +
     1     B(I,5)*WK**4 + B(I,6)*WK**5)
      IF (PP .LT. 0.0) PP=0.0
      WRITE (6,163) PP,I,L
  163 FORMAT  ('OPROBABLE RAIN NEXT TWO WEEKS=',F5.2,2X,'INCHES',30X,2I2
     1   )
      WRITE  (6,801)
  801 FORMAT  ('-***TABLE OF DAILY VALUES***')
      DO 830 NF=1,NFN
      WRITE  (6,803)(CROPST(NF,K),K=1,3)
  803 FORMAT  ('0',2A4,A2,/,
     1          'O  DAY       ETR        ET        SO     AKC1      AKC',         '
     2    RX      R(J-1)   R(J-2)   R(J-3)     DPL',/)
      DO 820 J=4,M
      WRITE  (6,802) ND(I,J),ETRSET(NF,J),ETSET(NF,J),X(16,I,J),
     1AKC11(NF,J),AKCSET(NF,J),(RSET(MM,NF,J),MM=1,4),DPLSET(NF,J)
  802 FORMAT  (' ',I5,2X,F8.4,F6.3,8F8.2)
  820 CONTINUE
      WRITE (6,821) AETFLD(NF)
  821 FORMAT  (13X,'AET=',F7.3)
  830 CONTINUE
  100 CONTINUE
C
C**  NDB(1)= NO. OF FIELDS FOR WHICH ANALYSIS WAS RUN   .
      NDB(1)=N4-1
   81 RETURN
```

Table 11. Continued.

```
      END
      SUBROUTINE EVAP(I,K)
C     SUBROUTINE TO CALCULATE EVAPOTRANSPIRATION POTENTIAL
      REAL METH1
      COMMON A(4,5), CTR(4),TXP(4),ND(4,30),
     1X(16,4,30),DESC(5),DATE(4),CROP(3),AIRR(2),FORC(15),
     2N(4),NDB(4),RSO(4),MODAY(4),W1(5,100),C(8,8),RREG(4,30),R(30)
      DO 10 J=4,K
      X(6,I,J)= (X(1,I,J) + X(2,I,J))/2.0
   15 X(7,I,J)=  CTR(I)*( X(6,I,J)-TXR(I)) *X(3,I,J)* 0.000673
   10 CONTINUE
      RETURN
      END

      SUBROUTINE VAPOR(I,K,CW)
C     SUBROUTINE TO CALCULATE HEAT FLUX,ED POTENTIAL, NET RADIATION
      REAL METH1
      COMMON A(4,5), CTR(4),TXP(4),ND(4,30),
     1X(16,4,30),DESC(5),DATE(4),CROP(3),AIRR(2),FORC(15),
     2N(4),NDB(4),RSO(4),MODAY(4),W1(5,100),C(8,8),RREG(4,30),R(30)
      COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
     1DT1(4),DT2(4),FCT(4),ETP5
      DIMENSION CW(4)
      DO 30 J=4,K
      IF(X(4,I,J).EQ.0)GOTO 35
      X(8,I,J)= X(5,I,J)/24.0
      VPS1= -0.6959+0.2946*X(2,I,J)-0.005195*X(2,I,J)**2+0.000089*
     1X(2,I,J)**3
      VPS2= -0.6959+0.2946*X(1,I,J)-0.005195*X(1,I,J)**2+0.000089*
     1X(1,I,J)**3
      X(9,I,J) = (VPS1+VPS2)/2.0
      X(10,I,J)=-0.6959+ 0.2946*X(4,I,J)-0.005195*X(4,I,J)**2 +
     10.000089* X(4,I,J)**3
      X(11,I,J )=(X(6,I,J)-(X(1,I,J-1)+X(2,I,J-1)+X(1,I,J-2)+X(2,I,J
     1-2)+X(1,I,J-3)+X(2,I,J-3))/6.0)*5
      T1= 0.041 + 0.0125*X(6,I,J)-4.534*X(6,I,J)**2/10**5
      T2= 0.959 -0.0125*X(6,I,J)+4.534*X(6,I,J)**2/10**5
      X(12,I,J)= ((X(1,I,J)-32)/1.8 + 273)/100.0
      X(13,I,J)= ((X(2,I,J)-32)/1.8 + 273)/100.0
      Y= X(10,I,J)
      JJ=NDB(I) + J - 4
      EMT=0.325+0.045*SIN(30*(JJ/30.-1.5)*3.1416/180.)
      X(14,I,J)= (EMT -0.044*SQRT(Y))*11.71*(X(13,I,J)**4+X(12,I,J)
     1**4)*0.5
      X(15,I,J)= 0.77*X(3,I,J)-(1.22* X(3,I,J)/RSO(I)-0.18)*X(14,I,J)
   30 X(16,I,J)=(T1*(X(15,I,J)-X(11,I,J))+T2*15.36*(.75+CW(I)*
     1X(5,I,J))*(X(9,I,J)-X(10,I,J)))*0.000673
      AJJ5=NDB(I)+N(I)+3
      IF (AJJ5 .GT. TP(I)) GO TO 34
      DLT=DT1(I)
      GO TO 341
   34 DLT=DT2(I)
  341 ETP5=  (ETAP(I)/(EXP(((AJJ5-TP(I))/DLT)**2)))*FCT(I)
   35 RETURN
      END

      SUBROUTINE PRINTR(I,K)
C     SUBROUTINE TO PRINT REGIONAL DATA
      REAL METH1
```

Table 11. Continued.

```
          COMMON A(4,5), CTR(4),TXR(4),ND(4,30),
         1X(16,4,30),DESC(5),DATE(4),CROP(3),AIRR(2),FORC(15),
         2N(4),NDR(4),RSO(4),MODAY(4),W1(5,100),C(8,8),RREG(4,30),R(30)
          COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
         1DT1(4),DT2(4),FCT(4),ETP5
          JJ=NDB(I)
          CALL DATEE (JJ,MN,NID,336)
          WRITE(6,10) (A(I,J),J=1,5),MON(MN),NID
       10 FORMAT(1H-,5X,'REGION:',5A4,5X,'BEGINNING DATE=',A4,I3)
          WRITE(6,15)
       15 FORMAT(1H-,'   DAY   TAVG     RS    UA      VPS     VPD     RN       G
         1    ETP       EO')
          WRITE(6,27)
       27 FORMAT(1H )
          DO 20 J=4,K
          WRITE(6,25)ND(I,J),X(6,I,J),X(3,I,J),X(8,I,J),X(9,I,J),X(10,I,J)
         1,X(15,I,J),X(11,I,J),X(7,I,J),X(16,I,J)
       20 CONTINUE
       35 WRITE(6,40)    ETP5
       40 FORMAT(1H ,'FORECAST :  POTENTIAL ET NEXT 5 DAYS=',F5.2)
       25 FORMAT(1H ,I5,F7.1,F6.0,F6.1,F7.1,F8.1,F7.0,F8.1,2F7.2)
          RETURN
          END

          SUBROUTINE ETAVG(II,ETA,MBD,I,D,D1,AVM,DPL)
          COMMON A(4,5), CTR(4),TXR(4),ND(4,30),
         1X(16,4,30),DESC(5),DATE(4),CROP(3),AIRR(2),FORC(15),
         2N(4),ND3(4),RSD(4),MODAY(4),W1(5,100),C(8,8),RREG(4,30),R(30)
          COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
         1DT1(4),DT2(4),FCT(4),ETP5
          DIMENSION D(8),D1(8)
          AI=II
          AV=(1.0-DPL/AVM)*100.
          IF (AV .GT. 0.0) GO TO 300
          AV=0.0
      300 AV3=1+AV
        5 IF (II .GT. NDE) GO TO 2
          AP=NDP
          AE=NDE
          PCT=100.*(AI-AP)/(AE-AP)
          AKC1=C(NCR,1)+C(NCR,2)*PCT+C(NCR,3)*PCT**2+C(NCR,4)*PCT**3
          GO TO 1
        2 DT=II-NDE
          AKC1=C(NCR,5)+C(NCR,6)*DT+C(NCR,7)*DT**2+C(NCR,8)*DT**3
        1 IF (AKC1 .LT. D(NCR)) AKC1=D(NCR)
          IF (AKC1 .GT. D1(NCR)) AKC1=D1(NCR)
          IF(II .GT. TP(I)) GO TO 7
          DLT=DT1(I)
          GO TO 8
        7 DLT=DT2(I)
        8 AKC=AKC1*ALOG(AV3)/ALOG(101.0)
          ETA=AKC * (ETAP(I)/(EXP(((AI-TP(I))/DLT)**2)))
          IF (II-MBD .LT. 5) ETA=ETA*FCT(I)
          RETURN
          END

          SUBROUTINE DATEE (II,MN,IID,NDH)
C         CALCULATES MONTH AND DAY FROM JULIAN DAY
          DIMENSION NND (12)
          DATA NND/0,31,60,91,121,152,182,213,244,274,305,335/
```

Table 11. Continued.

```
      DO 10 J=2,12
      IF (II .LE. NND(J)) GO TO 12
   10 CONTINUE
      J=13
   12 MN=J-1
      IID = II-NND(J-1)
      IF (II .LT. NDH) GO TO 14
      MN=13
      IID = 0
   14 RETURN
      END

      BLOCK DATA
      COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
     1DT1(4),DT2(4),FCT(4),ETP5
      DATA MON  /'JAN','FEB','MAR','APR','MAY','JUN','JUL','AUG','SEP',
     1  'OCT','NOV','DEC','NONE'/
      END

      SUBROUTINE SCHED(MBD,AVW,NDH,NXD,NXDP,I,DPL,AVM,D,D1)
      COMMON A(4,5), CTR(4),TXR(4),ND(4,30),
     1X(16,4,30),DESC(5),DATE(4),CROP(3),AIRR(2),FORC(15),
     2N(4),NDB(4),RSD(4),MODAY(4),W1(5,100),C(8,3),RREG(4,30),F(30)
      COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
     1DT1(4),DT2(4),FCT(4),ETP5
      DIMENSION D(8),D1(8)
C     CHECK TO SEE IF THE FIELD NEEDS IRRIGATING AT BEGINNING OF DAY
      IF (AVW.LE.0.0) GO TO 10
      BD=MBD
C     CALCULATING ESTIMATED DATE OF IRRIGATION WITHOUT PROB PRECIP
      DO 1 II=MBD,NDH
      CALL ETAVG (II,ETA,MBD,I,D,D1,AVM,DPL)
      AVW=AVW-ETA
      IF (AVW.LE.0.0) GO TO 2
    1 CONTINUE
C     IF AN IRRIGATION IS NOT REQUIRED BEFORE HARVEST
      GO TO 12
    2 NXD=II
      NXDP=NXD
C     CHECK IF RAINFALL PROBABILITY IS TO BE USED
C     B(I,1)=0 IF RAINFALL PROBABILITY IS NOT DESIRED
      IF (ABS(B(I,1)) .LT. 0.00001) GO TO 11
C     DETERMINE NUMBER OF DAYS FOR EXPECTED PRECIPITATION
      WK=(MBD-53)/7
   16 AI=II
      T=AI-BD
      BD=BD+T
      IF (T .LE. 14. )  GO TO 15
      BD=BD-T+14.
      T=14.
   15 AVW=AVW+PAMT(T,WK,I)
      L=II+1
      DO 3 II=L,NDH
      CALL ETAVG(II,ETA,MBD,I,D,D1,AVM,DPL)
      AVW=AVW-ETA
      IF (AVW .LE. 0.0 )  GO TO 4
    3 CONTINUE
C     IRRIGATION NOT REQUIRED BEFORE HARVEST
      GO TO 13
C      CHECKING IF EACH EXTENDED IRRIGATION DATE USING PROBABILITIES
```

Table 11. Continued.

```
      DO 10 J=2,12
      IF (II .LE. NMO(J)) GO TO 12
   10 CONTINUE
      J=13
   12 MN=J-1
      IID = II-NMO(J-1)
      IF (II .LT. NDH) GO TO 14
      MN=13
      IID = 0
   14 RETURN
      END

      BLOCK DATA
      COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
     1DT1(4),DT2(4),FCT(4),ETP5
      DATA MON  /'JAN','FEB','MAR','APR','MAY','JUN','JUL','AUG','SEP',
     1  'OCT','NOV','DEC','NONE'/
      END

      SUBROUTINE SCHED(MBD,AVW,NDH,NXD,NXDP,I,DPL,AVM,D,D1)
      COMMON A(4,5), CTR(4),TXR(4),ND(4,30),
     1X(16,4,30),DESC(5),DATE(4),CROP(3),AIRR(2),FORC(15),
     2N(4),NDB(4),RSD(4),MODAY(4),W1(5,100),C(8,8),RHEG(4,30),F(30)
      COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
     1DT1(4),DT2(4),FCT(4),ETP5
      DIMENSION D(8),D1(8)
C     CHECK TO SEE IF THE FIELD NEEDS IRRIGATING AT BEGINNING OF DAY
      IF (AVW.LE.0.0) GO TO 10
      BD=MBD
C     CALCULATING ESTIMATED DATE OF IRRIGATION WITHOUT PROB PRECIP
      DO 1 II=MBD,NDH
      CALL ETAVG (II,ETA,MBD,I,D,D1,AVM,DPL)
      AVW=AVW-ETA
      IF (AVW.LE.0.0) GO TO 2
    1 CONTINUE
C     IF AN IRRIGATION IS NOT REQUIRED BEFORE HARVEST
      GO TO 12
    2 NXD=II
      NXDP=NXD
C     CHECK IF RAINFALL PROBABILITY IS TO BE USED
C     B(I,1)=0 IF RAINFALL PROBABILITY IS NOT DESIRED
      IF (ABS(B(I,1)) .LT. 0.00001) GO TO 11
C     DETERMINE NUMBER OF DAYS FOR EXPECTED PRECIPITATION
      WK=(MBD-53)/7
   16 AI=II
      T=AI-BD
      BD=BD+T
      IF (T .LE. 14. )  GO TO 15
      BD=BD-T+14.
      T=14.
   15 AVW=AVW+PAMT(T,WK,I)
      L=II+1
      DO 3 II=L,NDH
      CALL ETAVG(II,ETA,MBD,I,D,D1,AVM,DPL)
      AVW=AVW-ETA
      IF (AVW .LE. 0.0 )  GO TO 4
    3 CONTINUE
C     IRRIGATION NOT REQUIRED BEFORE HARVEST
      GO TO 13
C      CHECKING IF EACH EXTENDED IRRIGATION DATE USING PROBABILITIES
```

Table 11. Continued.

```
C       OF RAIN RESULTS IN FURTHER EXTENSION OF IRRIGATION PERIOD
      4 IF (II-1 .EQ. NXDP) GO TO 11
        WK=WK+T/7
        NXDP=II
        GO TO 16
C       SITUATION WHERE FIELD NEEDS IRRIGATION AT THE BEGINNING DATE
     10 NXD=MBD
        NXDP=NXD
        GO TO 11
C       SITUATION WHERE AN IRRIGATION IS NOT REQUIRED BEFORE HARVEST
     12 NXD=NDH
     13 NXDP=NDH
     11 RETURN
        END

        FUNCTION RAMT(T,WK,I)
C  FUNCTION FOR PROBABLE PRECIPITATION
        COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
       1DT1(4),DT2(4),FCT(4),ETP5
        RAMT       =T*(B(I,1)+B(I,2)*WK+B(I,3)*WK*WK+B(I,4)*
       1     WK**3+B(I,5)*WK**4+B(I,6)*WK**5)
        RETURN
        END

        SUBROUTINE  PRINTS  (NREG,METH1,RNRD)
C SUBROUTINE TO RETAIN INFORMATION IN "SAVE" FOR NEXT RUN
        REAL METH1
        COMMON A(4,5), CTR(4),TXP(4),ND(4,30),
       1X(16,4,30),DESC(5),DATE(4),CROP(3),AIRR(2),FCAC(15),
       2N(4),NOB(4),PSD(4),MODAY(4),W1(5,100),C(8,3),RREG(4,30),F(20)
        COMMON /NEW/  W(4),MON(13),ID,NCR,NDE,NDP,B(4,6),ETAP(4),TP(4),
       1DT1(4),DT2(4),FCT(4),ETP5
        WRITE(6,11) NOB(1)
     11 FORMAT(1H1,' NO. OF FIELDS =',I5)
        DO 40 I=1,NREG
        K1=N(I)+3
        K=K1-2
        IF (RNRD.EQ.METH1) GO TO 15
        WRITE(7,10) (ND(I,J),X(1,I,J),X(2,I,J),X(3,I,J),X(4,I,J),
       1X(5,I,J),J=K,K1)
        WRITE(6,10) (ND(I,J),X(1,I,J),X(2,I,J),X(3,I,J),X(4,I,J),
       1X(5,I,J),J=K,K1)
     10 FORMAT(5X,I5,5F5.0)
        GO TO 40
     15 WRITE (7,20) (ND(I,J),X(1,I,J),X(2,I,J),X(3,I,J),X(4,I,J),X(5,I,J)
       1,RREG(I,J),J=K,K1)
        WRITE (6,20) (ND(I,J),X(1,I,J),X(2,I,J),X(3,I,J),X(4,I,J),X(5,I,J)
       1,RREG(I,J),J=K,K1)
     40 CONTINUE
     20 FORMAT  (5X,I5,5F5.0,F5.2)
        K=NOB(1)
        DO 50 J=1,K
        WRITE(7,55) W1(1,J),W1(2,J),W1(3,J),W1(4,J),W1(5,J)
        WRITE(6,55) W1(1,J),W1(2,J),W1(3,J),W1(4,J),W1(5,J)
     50 CONTINUE
     55 FORMAT(5F10.2)
        RETURN
        END

$ENTRY
```

PREDICTING SOIL MOISTURE AND WHEAT
VEGETATIVE GROWTH FROM ERTS-1 IMAGERY

by

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AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

Wise resource management techniques are necessary if the population of the Earth is to continue to expand. The Earth Resources Technology Satellite program combines remote sensing in space with efficient resource management. Water is a valuable resource needlessly lost by excessive irrigation applications. If needless loss of water is to be lessened, determination of evapotranspiration will be necessary. Actual evapotranspiration is dependent upon potential evapotranspiration and a crop coefficient. One method of predicting the crop coefficient is to use the plant's vegetative growth which may be determined by reflection from the plant canopy.

The relationship between soil moisture, vegetative growth and solar reflectance was studied. Vegetative growth was evaluated by leaf area index with the equation:

$$LAI = 2.92MSS4/5 - 2.63 \quad , \quad R^2 = 0.95$$

where:

LAI = Leaf area index

MSS4/5 = Ratio of band 4 (0.5-0.6 μ) to band 5 (0.6-0.7 μ)

R^2 = Regression coefficient.

It appears that the ratio eliminated soil moisture effects. At a depth of 0 to 15 cm soil moisture was predicted by:

$$SM2 = 101.11 - 4.00MSS4 - 70.31MSS4/5$$

where:

SM2 = Soil moisture dry weight at 0 to 15 cm (%)

MSS4 = Band 4 (0.5-0.6 μ)

MSS4/5 = Ratio of band 4 (0.5-0.6 μ) to band 5 (0.6-0.7 μ).

The equations of the wheat crop coefficient for the evapotranspiration model of Jensen and associates, developed by using leaf area index of dryland wheat, were:

$$Y = 0.005 + 0.0165X - 0.000467X^2 - 0.00000402X^3$$

$$Y = 0.998 - 0.00297D - 0.000747D^2$$

where:

Y = Wheat crop coefficient

X = Percent of crop cover

D = Days after 100 percent crop cover.

This method of evaluating the crop coefficient provided reasonable estimates of soil moisture depletion.