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IRRIGATION MANAGEMENT WITH REMOTE SENSING

FINAL TECHNICAL REPORT
FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
GREENBELT, MD 20771

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ACKNOWLEDGEMENTS

1. INTRODUCTION

Importance

The United States possesses some of the most productive agricultural lands in the world. Indeed, the millions of hectares of land in agricultural production in the U.S. are an important natural resource. Maintenance of the quality and quantity of agricultural land, as a renewable resource, is important if we are to maintain or improve our future balance of payments picture. In 1980, the United States exported over $40 billion worth of agricultural products. Since overall U.S. exports in 1980 totaled just over $200 billion, the portion which agriculture contributes is significant. It is even more significant when one realizes that agriculture consistently produces trade surpluses. In 1980 we exported over $21 billion more agricultural products than we imported. Non-agricultural export categories showed a trade deficit of $44.8 billion. So with our agricultural surplus our total foreign trade deficit for 1980 narrowed to $22.6 billion.

United States agriculture today is beset by a growing number of problems ranging from expansion of urban areas to dwindling water supplies. In 1972, the U.S. Department of Agriculture reported that during the 1960's some 295,000 hectares of land were urbanized each year; recreational land uses increased annually by some 410,000 hectares while transportation related land uses expanded at an annual rate of 55,000 hectares (USDA, 1972). Recent figures indicate this trend has continued and has intensified.

In addition to the problems of land conversion, U.S. agriculture is faced with water problems as well. Conservation of water resources is not just a U.S. problem; it is a truly world-wide problem. Competition for water is increasing everywhere between agricultural, urban, industrial, and

recreational users. In many areas of the globe demands for water are approaching or, in some cases, exceeding supplies. The major user of water in the world is irrigated agriculture.

In the United States, agricultural irrigation accounts for over 80 percent of the water consumed (GAO report RED-76-116, 1976). Ninety percent of irrigated agriculture in the United States is in 17 western states where over 20 million hectares (50 million acres) are irrigated (Bureau of Reclamation, 1976). From declining groundwater tables in high plains aquifers to the need for new transportation, delivery, and drainage systems in Sun Belt states, water availability is an increasing problem. Efficient use of available water resources is becoming increasingly important. This is particularly true in southwestern Sun Belt states where commercial irrigation agriculture is practiced on a large scale. In the future, as population in these states continues to rise and the costs of new irrigation projects also rise while construction of approved projects are slowed by the need to satisfy environmental legislation, competition for available water supplies will become even more intense.

Because of the increasingly competitive demands placed on available water resources, irrigation agriculture must be made more efficient. Irrigation agriculture must move toward more optimum use of its share of our increasingly short water resource. The need for work in this area is even more important if we believe the 1976 Government Accounting Office (GAO) report which stated that "over half of the water delivered to farms is wasted through overwatering which can limit crop production, increase farming costs, and contribute to water pollution" (U.S. Gov't. 1976). This same GAO study cited a number of instances in which additional lands could have been put into production if irrigation water had not been used

excessively on lands already under production. It is our belief based
on the research presented herein, that remote sensing can make a contri-
bution toward more efficient use of available water resources and for
services provided in monitoring water allocation.

Background

The U.S. Bureau of Reclamation (USBR) is responsible for planning,
constructing, operating, and maintaining facilities for storing and
delivering water supplies for irrigation in the western U.S., and thus
has an interest in promoting efficient irrigation management. In 1976,
USBR delivered over 26 million acre-feet of water to 3.6 million hectares
(20 percent of the irrigated land in the western U.S.).

In 1970, USBR began developing the Irrigation Management Services
(IMS) to assist irrigators toward more efficient use of water through
irrigation scheduling. IMS provides two levels of scheduling assistance
to the farmer - the "Irrigation Guide", and the "Field Irrigation Schedule".
The Irrigation Guide gives irrigation intervals, based on daily estimated
evapotranspiration (ET) rates and average water-holding capacity of major
soils, for principal crops in an area. The Field Irrigation Schedule
provides the farmer with up-to-date soil moisture status for each of his
fields in the program. The schedule provides recommended irrigation dates
and amounts of water to be applied. One field technician is currently
required for every 800 to 1600 hectares served by this program.

In 1977, 63,516 hectares (156,884 acres) were served at the field
level and approximately 35,000 hectares (87,000 acres) served at the guide
level. When combined with ancillary services provided by IMS, a total
of 142,000 hectares (350,000 acres) were involved in irrigation scheduling.

The field-level service is based on a procedure that uses daily estimates of ET, soil moisture, effective precipitation, and applied irrigation water to compute daily soil-water depletion (Jensen, 1968). By projecting the ET rate into the future, the date at which soil-water depletion reaches its maximum allowable value, is determined.

Actual daily ET for a given crop is estimated from potential ET (calculated using meteorological data and a modification of the Penman (1963) combination equation) and a crop coefficient Kc, defined as

$$Kc = ET/ETp$$

where ET is actual evapotranspiration and ETp is potential ET. The crop coefficient is influenced by percent ground cover, leaf area index (LAI), growth stage, and soil moisture (Ritchie and Burnett, 1971; Kanemasu and Powers, 1974), all of which have potential for measurement using remote sensing.

Crop coefficient curves used by IMS are developed from experimental data and represent ET of crops in a full and healthy population. Field evaluations of crop growth are used to estimate crop coefficients from experimental curves such as those shown in Fig. 1. ET rates estimated using experimental curves require an adjustment because crops growing under experimental conditions generally are not representative of crops growing under normal irrigated conditions. Field measurements of soil moisture are currently used to adjust Kc for the effects of soil moisture (Buchheim and Ploss, 1977). At present, only tedious ground sampling procedures are available to acquire these necessary inputs.

Spectral information acquired on a repetitive basis can potentially provide inputs into the IMS program. Visible and reflective infrared wavelengths can be used to evaluate vegetation parameters (LAI, percent cover, etc.) which affect Kc (Kanemasu et al., 1974; Kanemasu et al.,
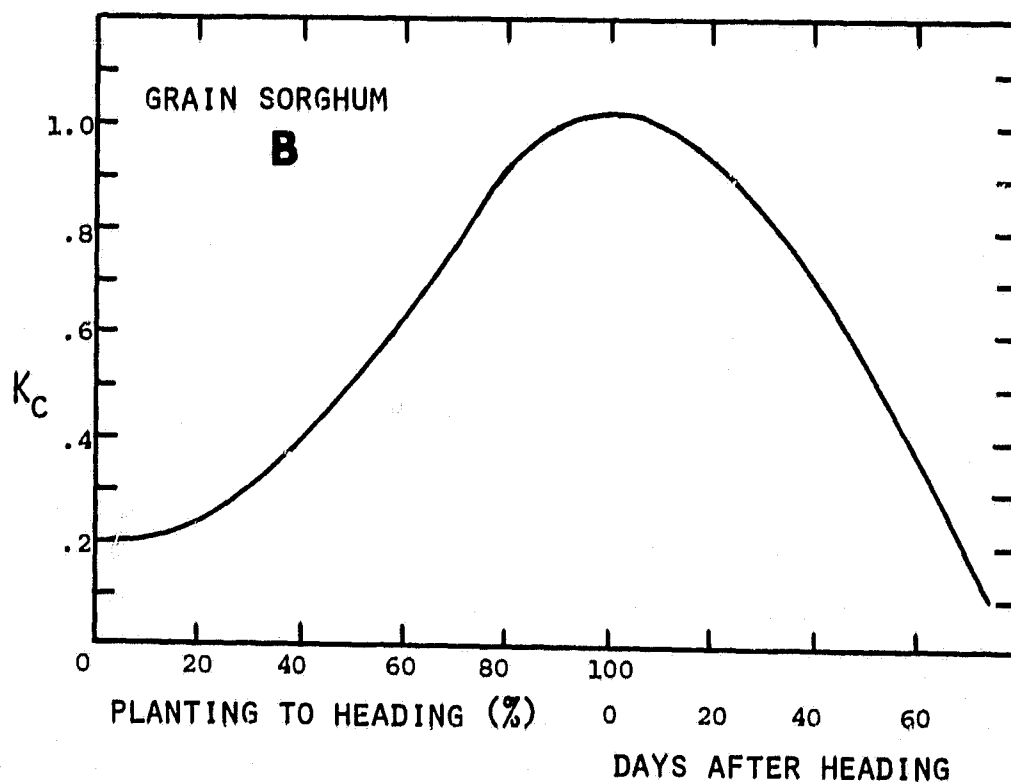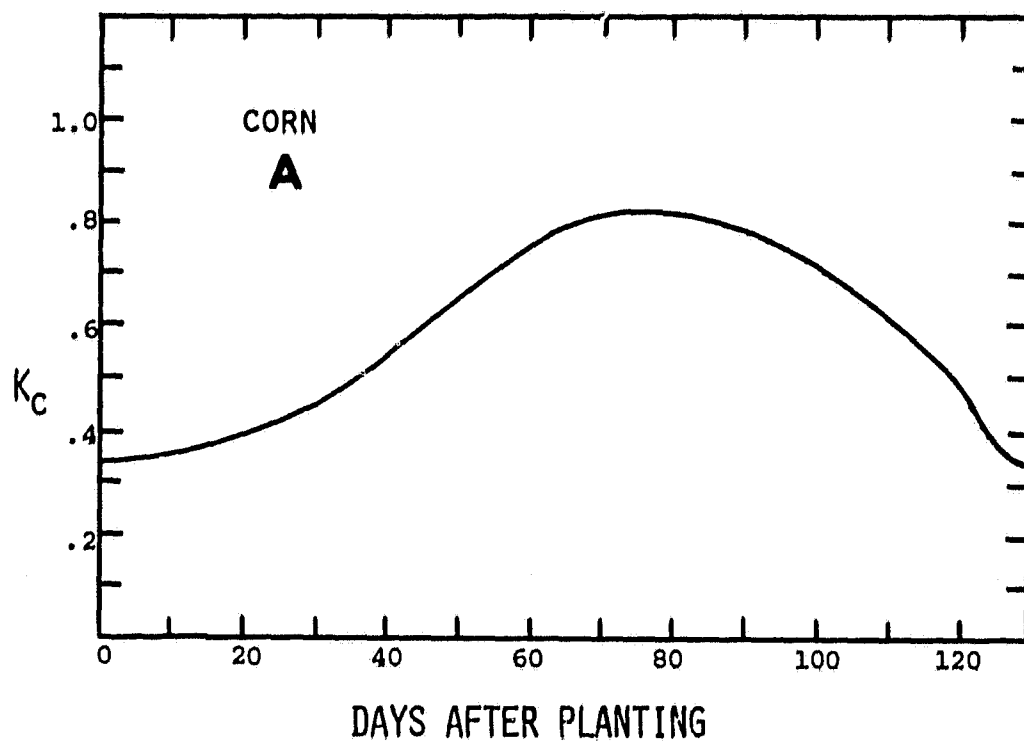
Fig. 1. Typical experimental crop coefficient curves for corn (A), and grain sorghum (B) (after Denmead and Shaw, 1959; and Jensen, 1968).

1977; Wiegand et al., 1977; Tucker, 1979). Thermal infrared and microwave wavelengths can be used to evaluate near surface soil moisture as summarized by the NASA/USDA Soil Moisture Workshop (Heilman et al., 1978). All of the remote sensing approaches have certain rudimentary details available in the literature, but for an operational system for all crop growth/soil moisture conditions, a detailed evaluation must be conducted.

The Remote Sensing Section of USBR has a computer-interactive image analysis system that can be integrated into an operational system of irrigation scheduling. In addition, IMS has an already established information dissemination network to rapidly transfer information to the individual farmer. Both these aspects are critical to the actual implementation and use of any developed procedures.

A grant was established 1 April 1980 with the long term objective of testing the utility of thermal and reflective data for predicting crop coefficients and soil moisture as inputs into the U.S. Bureau of Reclamation irrigation scheduling program. The grant proposal was in response to RTOP 677-22-23 entitled Irrigation Scheduling.

A ground study utilizing hand-held radiometers was to be conducted at the Navajo Indian Irrigation Project near Farmington, New Mexico in conjunction with ongoing USBR measurements including lysimetric measurements of evapotranspiration. The Remote Sensing Institute (RSI) was to collect visible, near IR and thermal IR measurements to be analyzed and evaluated in terms of the ground measurements which included percent crop canopy cover obtained by RSI. Results were to be used to recommend future action regarding the use of satellite data in irrigation management.

2. RESEARCH PROGRAM

Introduction

RSI conducted a field measurement program during the summer of 1980. Measurements were made with two visible/near IR hand-held radiometers and a hand-held thermal radiometer. Soil moisture and lysimetric measurements were collected by USBR personnel and forwarded to RSI along with meteorological data.

Field Measurements

The study was conducted on the Navajo Indian Irrigation Project near Farmington, New Mexico, in conjunction with a Bureau of Reclamation water use study. The test site consisted of four alfalfa plots with lysimeters that were irrigated with a line source sprinkler. The line source linearly decreases the amount of water applied as the distance from the source increases. With the configuration of the system, plot 1 was over-irrigated, plot 2 received optimum applications, and plots 3 and 4 were under-irrigated.

Radiances from each plot were measured with Mark II three-band and EXOTECH four-band radiometers in the mid-morning (1000-1100 MDT) and early afternoon (1300-1400 MDT). Radiances were converted to reflectances using radiance measurements of reference panels coated with 3-M white Nextel paint and $BaSo_4$. Panel radiances were measured before and after each plot measurement. Radiometric temperatures of the plots were measured with a PRT-5 within the same time frame. Radiances of bare soil were also measured.

Surface soil water contents (0-4 cm) were determined gravimetrically on samples collected at the same time as the spectral measurements. Percent canopy cover was determined using 35mm color slides (photographed from a vertical position) projected on a random dot grid. All measurements began after the second cutting of alfalfa in early July 1980 and

continued to maximum canopy cover.

USBR personnel collected profile soil moisture (neutron attenuation method) and lysimetric measurements of actual evapotranspiration. The collected meteorological data included maximum and minimum air and dew point temperatures, solar radiation, wind speed, and pan evaporation. USBR calculated potential ET using the Penman equation which was calibrated for the climatic conditions at Farmington.

Preliminary Results

The scheduling procedure used by the Irrigation Management Service (IMS) of USBR requires estimates of the crop coefficient which is the ratio of actual to potential ET. We evaluated the relationship between Mark II spectral measurements and the crop coefficient.

Best relationships were obtained with the perpendicular vegetation index (PVI) of Richardson and Wiegand (1977) using channels 1 (0.63-0.69μm) and 2 (0.76-0.90μm). The soil background line was

channel 1 = 1.03 channel 2 - 0.05

with an r^2 of 0.89.

Figures 2, 3 and 4 show the relationships between PVI, the percent cover, and the crop coefficient. A PVI based on channel 2 and 3 (1.55-1.75μm) did not improve the results.

These results demonstrate the potential for using spectral measurements to estimate the crop coefficient. Inclusion of a liquid water absorption channel does not appear to offer a significant benefit.

The Appendix is a paper submitted for publication which resulted from this project. The paper, "Evaluating the Crop Coefficient Using Spectral Reflectance," submitted to the Agronomy Journal, is the culmination of the Mark II Radiometer data analysis activities.
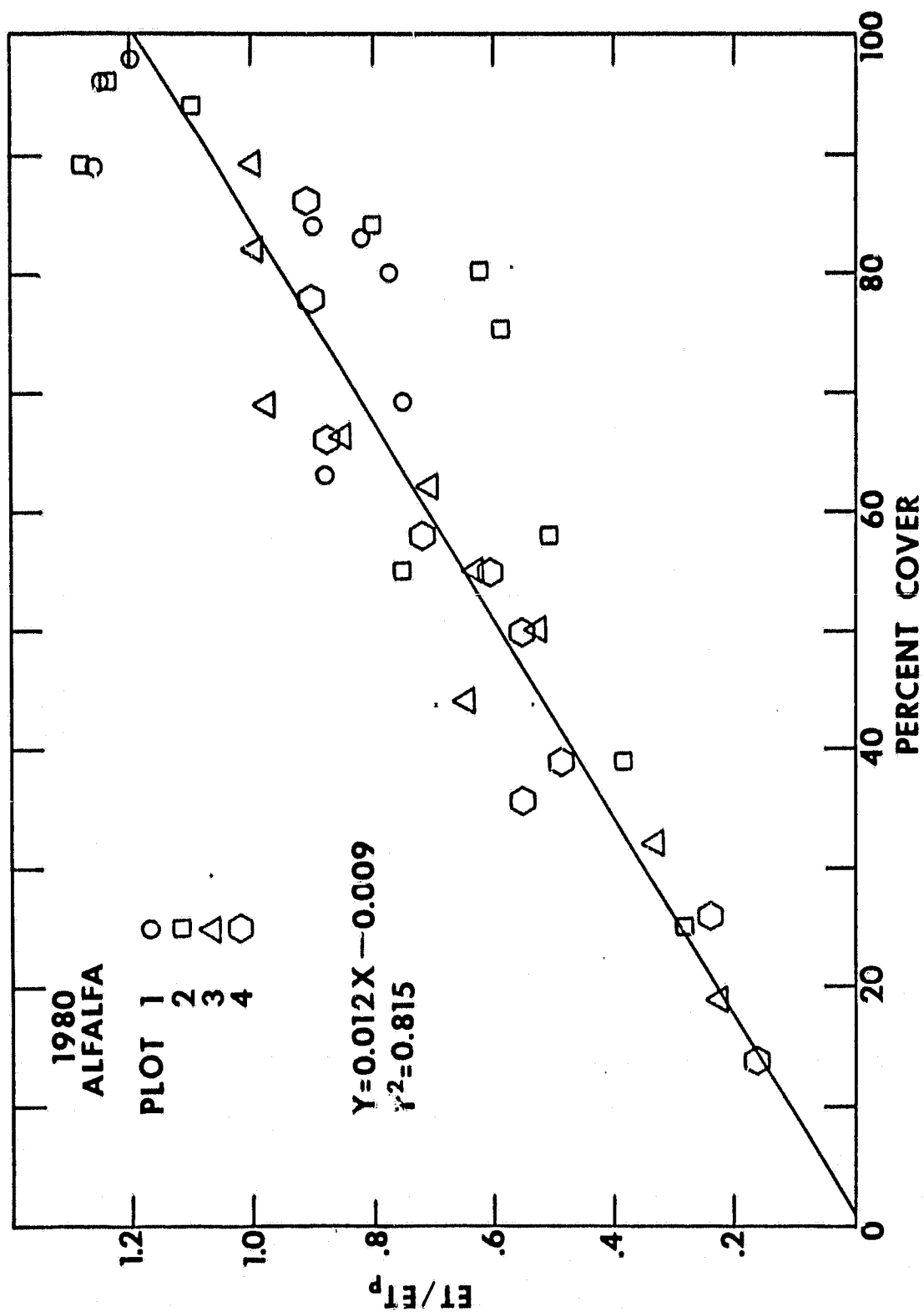
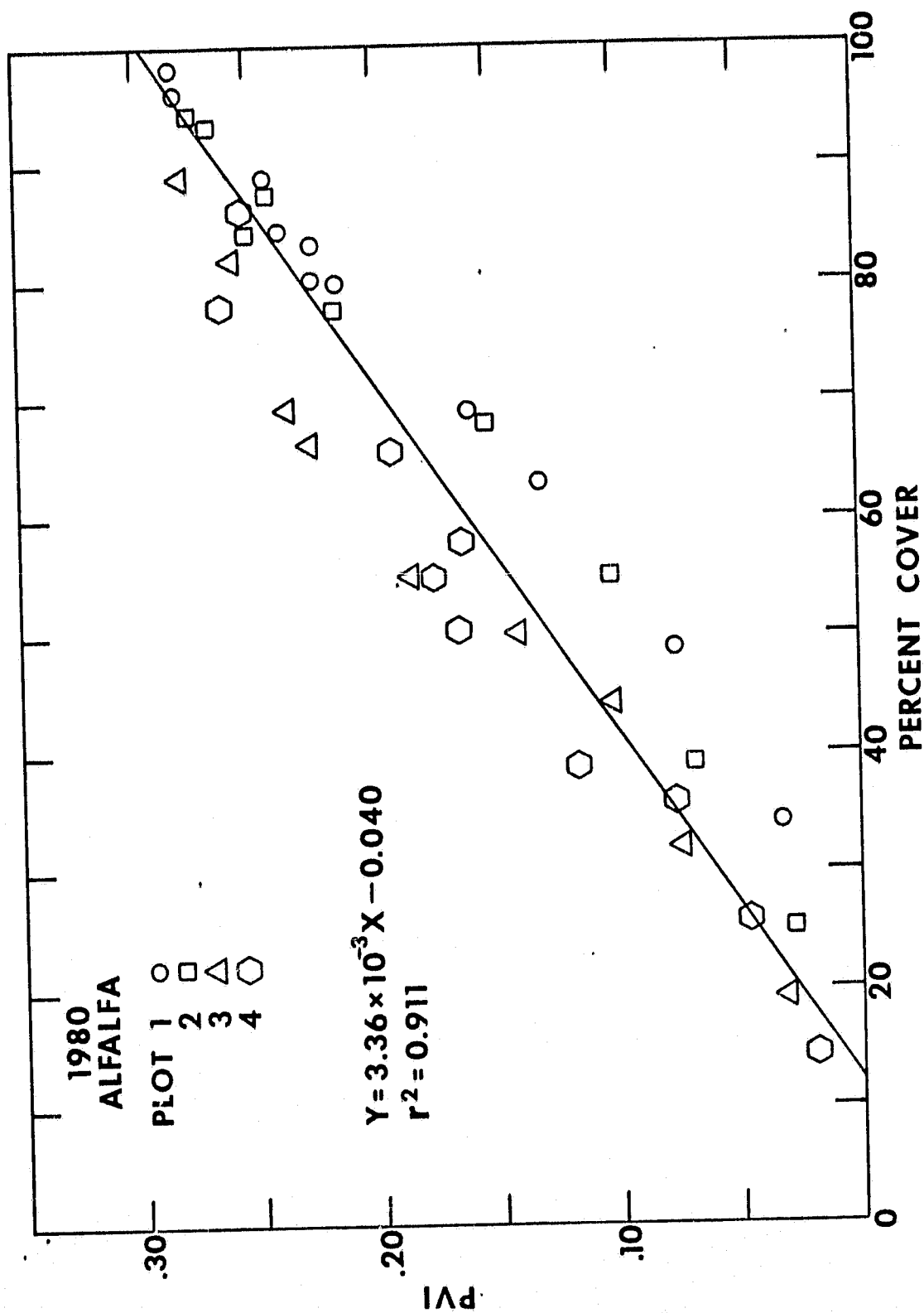Figure 2. Relationship of the crop coefficient K_c (ET/ETp) to percent cover for 1980 alfalfa plots.

Figure 3. The relationship of the spectral vegetation index PVI and percent cover for the alfalfa plots.
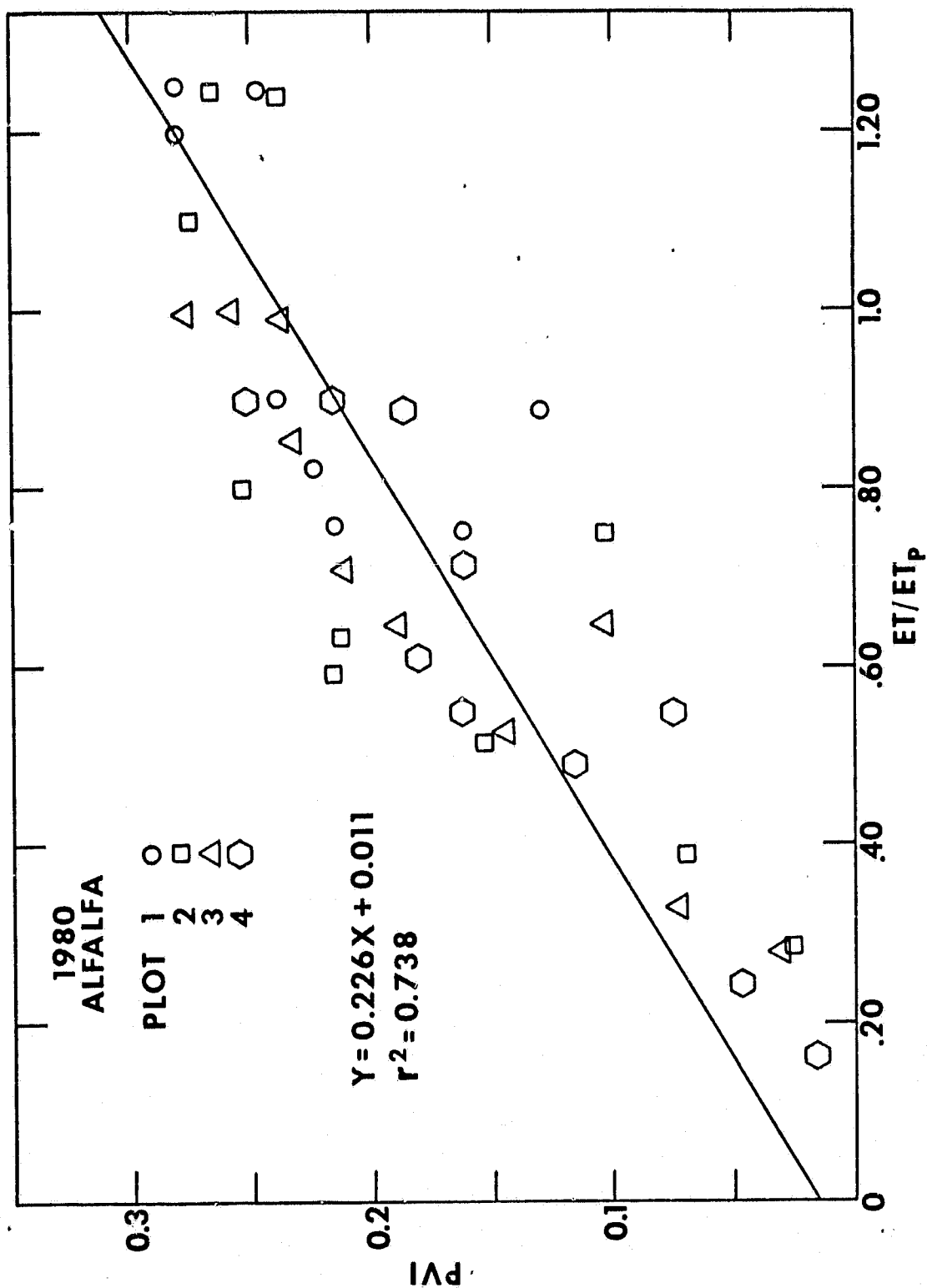
Figure 4. The relationship of PVI and K_c for the alfalfa plots.

3. FOLLOW-UP TO THE RESEARCH PROGRAM

The Navajo Indian Irrigation Project

The Navajo Indian Project near Farmington, New Mexico, which encompasses the study area, is not presently an operational program--it is a consumptive water use study. The long term plan at the location is for 105,000 acres to eventually be under irrigation management. Two aspects being considered in this large scale irrigation management program are:

1) water diversion requirements within the main water conveyance system, and

2) on-farm scheduling for water.

Although on-farm scheduling is being discussed, only water diversion requirements are presently being addressed. There is one turn-out from the main system per farm. The water diversion program now assumes that after water is delivered to the turn-out in response to a water order from the farmer to the irrigation district that those farm fields were irrigated. It further assumes that another official water order will come a certain number of days later. There is no more detailed interaction between the district and the farmer than the water order.

On-farm scheduling would require a much more extensive interaction. The water district, through computerized modeling of on-farm water usage could more accurately determine its scheduling, but would require more information about the individual farms and their usage. Computerized modeling would require many inputs--crop type and acreage, soil moisture and others. Present discussions with the Bureau of Indian Affairs and the Navajo Indian Irrigation Project personnel about on-farm scheduling do not include modeling and concern using neutron probes to obtain soil

moisture data.

The possibilities for interfacing remotely sensed crop coefficient data into an on-farm scheduling service were discussed with Jerry Buchheim and Bob Hanson, Bureau of Reclamation, Denver. The results of the research effort were presented, illustrating the potential for estimating crop coefficient from Landsat-type spectral data. The Bureau's information needs toward development of on-farm scheduling include crop inventory techniques and consumptive water use monitoring through the growing season. Proposed application projects utilizing remote sensing must be submitted through the cooperating irrigation district and require a monetary contribution by the district in order to obtain Bureau approval. The idea of a demonstration project was appealing and it was agreed that future cooperation toward such a project was desirable.

Truck-mounted Radiometer System

The remotely sensed data utilized in the crop coefficient estimation portion of the grant effort were acquired with hand-held radiometers. RSI was given the opportunity to upgrade considerably it's capabilities for multispectral measurements on the ground and has done so with a little help from this grant although it was not one of the stated objectives of the project. RSI was designated by NASA as one of a few institutions which best could take advantage of the new LARS/Barnes modular multi-band radiometer in on-going NASA-sponsored projects.

RSI purchased a 3/4 ton pickup. LARS/Purdue manufactured a boom and mounting platform and a separate reference panel platform for the RSI truck under one of their NASA contracts through the Johnson Space Center. RSI utilized some travel funds from this NASA Grant to transport the truck to and from Purdue for the installation of the boom and platforms.
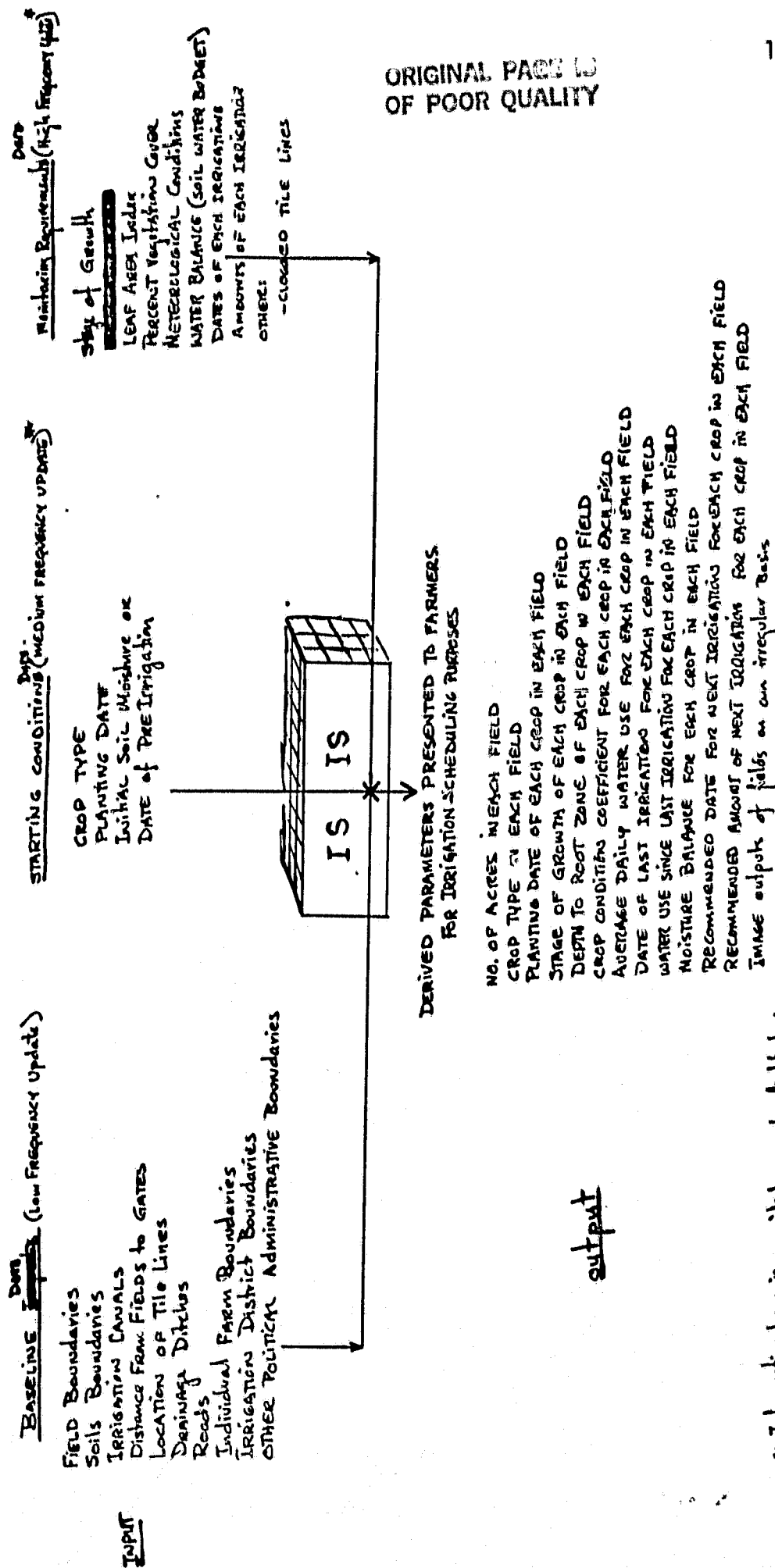
The LARS/Barnes Radiometer has not been received at RSI yet, although the other elements of the data system have. Therefore, no actual measurements are available with which to illustrate this new capability. The system will be utilized in South Dakota during the 1982 growing season as the primary data acquisition system on one or more experiments concerning remote sensing of cultivated crop parameters.

4. A LOOK TO THE FUTURE

An outgrowth of the review of source material and analyses of the data acquired is the realization of the potential for developing a remote sensing assisted Irrigation Scheduling Information System (ISIS). Such a system would contain data gathered from a variety of sources depicting information for regions of differing sizes all registered to a common cartographic base with a uniform scale (See figure 5). Different data planes could be input to the system at regular or irregular intervals. ISIS is conceived of as a flexible system which assumes a high degree of user interaction and indeed cannot adequately function without user participation. That is, any remote sensing assisted irrigation scheduling information system can only work if individual irrigators (farmers) fully cooperate. Individual farmers therefore must gain an understanding of and an appreciation for the fact that the data they supply must be accurate and timely in order to insure that the information produced by the system is useful to them in terms of optimum scheduling. ISIS should not necessarily be considered an isolated system but could, and probably should, be considered more as an integral part of a larger farm management information system such as the Agnet system developed at the University of Nebraska.

Paralleling the Agnet systems concept it is envisioned that ISIS be comprised of a central computing facility with terminal links to

Irrigation Scheduling Information System
ISIS

BASELINE DATA (Low Frequency Update)

INPUT

FIELD Boundaries
Soils Boundaries
Irrigation Canals
Distance From Fields to Gates
Location of Tile Lines
Drainage Ditches
Roads
Individual Farm Boundaries
Irrigation District Boundaries
Other Political Administrative Boundaries

STARTING CONDITIONS Data (MEDIUM FREQUENCY UPDATE)*

CROP TYPE
PLANTING DATE
Initial Soil Moisture or
Date of Pre Irrigation

Monitoring Requirements Data (High Frequency Update)*

Stage of Growth
LEAF AREA Index
Percent vegetation cover
Meteorological Conditions
WATER BALANCE (SOIL WATER BUDGET)
DATES OF EACH IRRIGATION
Amounts of Each Irrigation
other:
— Clogged Tile Lines

DERIVED PARAMETERS PRESENTED TO FARMERS.
FOR IRRIGATION SCHEDULING PURPOSES

output

NO. OF ACRES IN EACH FIELD
CROP TYPE IN EACH FIELD
PLANTING DATE OF EACH CROP IN EACH FIELD
STAGE OF GROWTH OF EACH CROP IN EACH FIELD
DEPTH TO ROOT ZONE OF EACH CROP IN EACH FIELD
CROP CONDITION COEFFICIENT FOR EACH CROP IN EACH FIELD
AVERAGE DAILY WATER USE FOR EACH CROP IN EACH FIELD
DATE OF LAST IRRIGATION FOR EACH CROP IN EACH FIELD
WATER USE SINCE LAST IRRIGATION FOR EACH CROP IN EACH FIELD
MOISTURE BALANCE FOR EACH CROP IN EACH FIELD
RECOMMENDED DATE FOR NEXT IRRIGATION FOR EACH CROP IN EACH FIELD
RECOMMENDED AMOUNT OF NEXT IRRIGATION FOR EACH CROP IN EACH FIELD
IMAGE output of fields on an irregular Basis

* Information here is provided on a by field basis

Figure — Conceptual Diagram of the input output parameters of a Irrigation scheduling geographic
information system.

farm agents' offices and eventually to individual cooperating irrigated farmsteads. Table 1 shows the information which would be held in each separate location and that which would be shared by both computers.

TABLE 1

INFORMATION RESIDENT ON ISIS COMPUTERS

Farmer Computer	Shared Information	Central Computer
Field Boundaries	Crop Type	Leaf Area Index
Soils	Planting Dates	% Vegetation Cover
Farm Boundaries	Initial Soil moisture; or	Meteorological Conditions
Location of Tile	Date of Pre-irrigation	Water Budget Calculation
Lines	Irrigation Canals	Crop Condition Calculation
	Gates	
	Drainage Ditches	
	Irrigation District Boundaries	
	Other Political Administrative Boundaries	
	Stage of Growth	
	Date of Last Irrigation	
	Amount of Last Irrigation	

By distributing information storage in this manner and implementing coded access procedures, security of individual farmer information could be maintained. Such a network also means that the farm computers could be small and the access time and costs minimized by having the image processing and modelling routines which require more computing power and frequent updates residing on a larger central computer (possibly in a regional Bureau of Reclamation office).

The ISIS concept, as presented herein, is not intended to replace the current operational Bureau of Reclamation irrigation scheduling procedures described in the background section of this report. We do, however believe that implementation of a cooperative research program with the Bureau to prove the effectiveness of an ISIS type concept could provide significant benefits. We believe that an irrigation scheduling in-

formation system could facilitate the work of Bureau field-level personnel. But the real beneficiaries of such a system would be the farmers (irrigators). By tapping into the geobased information potentially available from an ISIS type system, the individual farmer could fine tune (in essence, customize) his irrigation procedures for each of his fields. Such a system can improve irrigation efficiency and potentially save water while maintaining and hopefully increasing yield through improved management and/or bringing new lands into production.

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APPENDIX

"Evaluating the Crop Coefficient Using Spectral Reflectance"

a paper submitted to the Agronomy Journal

EVALUATING THE CROP COEFFICIENT USING SPECTRAL REFLECTANCE[1]

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ABSTRACT

A field study was conducted in four differentially irrigated plots of alfalfa (Medicago sativa L.) planted in Shiprock sandy loam to assess spectral reflectance for estimating the crop coefficient (K_c), the ratio of actual to potential evapotranspiration (ET). A bidirectional reflectance factor was measured using a three-channel (0.63 to 0.69 μm, 0.76 to 0.90 μm, and 1.55 to 1.75 μm) hand-held radiometer, and was used to calculate a perpendicular vegetation index (PVI). Actual ET was determined by the water balance method in non-weighing lysimeters, and potential ET was calculated using Penman's equation.

Significant linear relationships were found between PVI, and percent cover ($r^2 = 0.911$), and between K_c and percent cover ($r^2 = 0.815$). In addition, the position of the PVI intersection on the soil background line changed as a result of soil moisture increases following irrigation, even at high percent cover. Thus, once experimental relationships between K_c and crop growth are established, a mean K_c can be determined from spectral estimates of stage of development and the soil background component of PVI can be used to adjust the mean K_c for increased evaporation following irrigation because the ratio of actual to potential evapotranspiration will approach 1 when the soil surface is wet.

INTRODUCTION

Most irrigation scheduling models have an evapotranspiration (ET) component to calculate soil water depletion. A common method of estimating ET is to relate it to potential evapotranspiration (ET_p) using a dimensionless crop coefficient K_c, defined by the equation

$$K_c = ET/ET_p. \qquad [1]$$

The scheduling models may differ in the method used to determine K_c and ET_p.

The crop coefficient increases from a low value at emergence to a maximum at full cover. However, significant fluctuations in the ET/ET_p ratios can occur due to increased evaporation from the soil surface following rainfall or irrigation. K_c will approach 1 when the soil surface is wet, regardless of crop stage of development. In addition, K_c can be increased by advection, or decreased when soil moisture becomes limiting.

Experimental crop coefficients have been determined for a number of different crops, and are usually expressed as a function of growth parameters such as percent cover, leaf area index, or growth stage (Denmead and Shaw, 1959; Fritschen and Shaw, 1961; Grimes et al., 1969; Jensen, 1968; Jensen et al., 1970; Kanemasu and Powers, 1974). Use of the experimental data for scheduling irrigation on a field-by-field basis is difficult since fields of the same crop species are seldom at the same stage of development. In addition, the experimental relationships do not account for increased evaporation following irrigation.

1 Because K_c is closely related to crop growth, it should be

2 possible to use spectral reflectance to derive a crop growth parameter

3 for defining a crop coefficient curve. Development of remote sensing

4 techniques to estimate K_c would be particularly beneficial for large

5 irrigation projects where manpower limitations preclude frequent field

6 observations necessary to accurately determine K_c and ET.

7 We conducted a field investigation in differentially irrigated

8 plots of alfalfa (Medicago sativa L.) to assess the use of spectral

9 reflectance for estimating the crop coefficient, and for adjusting the

10 crop coefficient to account for increased soil evaporation following

11 irrigation or rainfall.

12

13 MATERIALS AND METHODS

14

15 Experiments were conducted on the Navajo Indian Irrigation Pro-

16 ject (NIIP) near Farmington, New Mexico. Average annual rainfall of

17 the area is 176.3 mm.

18 The research site consisted of four 1.8 x 1.8 x 1.8 m lysimeters

19 in a field of Shiprock sandy loam (coarse-loamy, mixed mesic Typic

20 Haplargid). Lysimeters were installed so that tops of the walls

21 were 15 cm below the soil surface. Each lysimeter contained two neu-

22 tron probe access tubes. Lysimeters were drained with perforated pipe

23 and ceramic cup suction systems. Alfalfa (Medicago sativa L.) was

24 planted in the 32-ha field in late July 1979.

25 The field was irrigated with a line source sprinkler system

26 (Hanks et al., 1976) that produced a continuously decreasing irriga-

27 tion pattern at right angles outward from the line source. The

lysimeters (designated plots 1 through 4) were 1.5, 4.5, 7.5, and 10.5 m, respectively, from the line source. The plots were irrigated twice during the study (Table 1).

Spectral radiances were measured with a hand-held 15 degree field-of-view radiometer (Tucker et al., 1981) in three wavelength bands (0.63 to 0.69 μm, 0.76 to 0.90 μm, and 1.55 to 1.75 μm) at a height of 1.5 m above the canopy. Data were acquired between 1000 and 1200 MDT following the first alfalfa cutting (7 July, 1980). On each date, six measurements were made per plot and averaged for analyses. Bare soil radiances were also measured in a similar manner on a plot adjacent to the alfalfa.

A panel coated with highly reflecting barium sulfate was used for determining the bidirectional reflectance factor (Silva, 1978), defined as

$$BRF(\lambda) = \frac{R_s(\lambda)}{R_r(\lambda)} \cdot \rho_r(\lambda) \qquad [3]$$

where $BRF(\lambda)$ is the bidirectional reflectance factor at a specific wavelength interval λ, $R_s(\lambda)$ is the radiance of the scene, $R_r(\lambda)$ is the radiance of the reference panel, and $\rho_r(\lambda)$ is the reflectance of the reference panel at λ. Radiance of the reference panel was measured immediately before radiance of each plot was measured.

The BRF's were used to calculate a perpendicular vegetation index (PVI) (Richardson and Wiegand, 1977), defined as

$$PVI = [(Rg1 - Rp_1)^2 + (Rg2 - Rp2)^2]^{1/2} \qquad [4]$$

where Rp1 and Rp2 are composite BRF's (vegetation plus soil background) measured in radiometer channels 1 (0.63 to 0.69 μm) and 2

(0.76 to 0.90 μm), respectively, and Rg1 and Rg2 are soil background BRF's corresponding to the vegetation points (Fig. 1). The PVI references canopy reflectance to a soil background line determined from regression analysis of the bare soil reflectance measurements. The soil background line for the Shiprock sandy loam was

$$BRF1 = 1.03 \, BRF2 - 0.05 \qquad (r^2 = 0.89) \qquad [5]$$

where BRF1 and 2 are bare soil bidirectional reflectance factors in channels 1 and 2, respectively. Soil line intersection coordinates, determined using the method outlined by Richardson and Wiegand (1977), were

$$Rg1 = -0.024 + 0.515 \, Rp1 + 0.500 \, Rp2 \qquad [6]$$

and

$$Rg2 = 0.025 + 0.500 \, Rp1 + 0.486 \, Rp2 \qquad [7]$$

from which PVI (Eq. 4) was calculated.

PVI can also be calculated using radiance. However, since radiance is proportional to irradiance, a PVI based on radiance will change with sun angle (Richardson, 1981). This can be overcome by normalizing the data to a constant sun angle (Jackson et al., 1980).

Percent cover of the plots was determined using 35 mm color slides of the plots (photographed from a vertical position approximately 1 m above the plots) projected on a random dot grid. Figure 2 shows changes in percent cover of the plots during the study. Surface soil water content (0 to 4-cm layer) was determined gravimetrically on samples collected at the time of the spectral measurements. Profile soil water content was determined using the neutron attenuation method. Meteorological data collected at the site included daily

maximum and minimum air temperature, relative humidity, precipitation, daily solar radiation, and windspeed at 2 m.

Actual ET was calculated using the water balance equation

$$ET = I + P - D - \Delta SWC \qquad [8]$$

where I and P are irrigation and precipitation amounts, respectively, D is drainage, and ΔSWC is the change in soil water content from the previous measurement. Daily ET_p was calculated using the Penman (1953) equation

$$ET_p(ly) = \frac{\Delta}{\Delta + \gamma}(Rn-G) + \frac{\gamma}{\Delta + \gamma}(15.36)(1.0+0.01W)(e_s - e_d) \qquad [9]$$

where Δ is the slope of the saturation vapor pressure-air temperature curve, γ is the psychrometric constant, $R_n(ly)$ is net radiation, $G(ly)$ is soil heat flux, $e_s(mb)$ is the mean saturation vapor pressure, $e_d(mb)$ is the mean dewpoint temperature, and $W(miles)$ is the wind run.

RESULTS AND DISCUSSION

The relationship between K_c (defined as ET/ET_p) and percent cover for the four alfalfa plots is shown in Fig. 3. As expected, K_c increased with canopy cover. The data in Fig. 3 include both wet and dry soil surface conditions (see Fig. 6B), as well as advection (K_c greater than 1). The linear relationship ($r^2=0.815$) in Fig. 3 can be thought of as a mean crop coefficient curve for the conditions encountered during the study.

A logical role for remote sensing in estimating K_c is to use spectral reflectance to estimate a growth parameter, such as percent

cover, and then relate the spectral estimates of growth to K_c using an established relationship such as that of Fig. 3. Although radiance or spectral reflectance in properly selected wavebands usually correlate with crop growth, radiance ratios and vegetation index models provide better day-to-day comparisons of spectral data (Richardson and Wiegand, 1977). Since soil background reflectance can significantly affect reflectance measurements of a crop canopy, we chose to use the perpendicular vegetation index (PVI) of Richardson and Wiegand (1977) in our analyses. The PVI reduces the effect of the soil background by referencing canopy reflectance to a soil background line. A complete discussion of vegetation index models can be found in Richardson and Wiegand (1977) and Wiegand et al. (1979).

A simple model can be used to illustrate the behavior of spectral reflectance in radiometer channels 1 (0.63 to 0.69 μm) and 2(0.76 to 0.90 μm), and PVI as a crop canopy grows. Composite bidirectional reflectance (vegetation plus soil background) can be approximated by the equations

$$Rp1 = fvRv1 + (1-fv)Rg1 \qquad [10]$$

and

$$Rp2 = fvRp2 + (1-fv)Rg2 \qquad [11]$$

where Rp1 and Rp2 are composite BRF's in channels 1 and 2, fv is percent cover expressed as a fraction, Rv1 and Rv2 are vegetation BRF's in channels 1 and 2, and Rg1 and Rg2 are the corresponding soil background BRF's.

Composite BRF's were calculated for wet and dry soil backgrounds (11.5 and 1.0 percent gravimetric water content, respectively) using the following values representative of alfalfa and Shiprock sandy

loam: Rv1 = 0.08, Rv2 = 0.50, Rg1 wet = 0.20, Rg1 dry = 0.30, Rg2 wet = 0.25, and Rg2 dry = 0.35. It was assumed that the soil background was sunlit.

As shown in Fig. 4, composite red reflectance (Rp1) decreases and near infrared reflectance (Rp2) increases as percent cover increases. The coordinates (Rp1, Rp2) converge to a single point at full cover. The area within the triangle in Fig. 4 represents the range of possible composite reflectances, assuming that all soil seen by the radiometer is sunlit. For a given percent cover, PVI is identical for wet and dry soil backgrounds (Table 2).

In reality, a radiometer will see both shaded and sunlit soil. The result will be composite reflectances which are lower than those shown in Fig. 4 for the wet and dry soil backgrounds, but values of PVI will remain about the same, as shown in Table 3.

Actual values of PVI were linearly related ($r^2 = 0.911$) to percent cover of the alfalfa plots (Fig. 5). This compares with an r^2 of 0.861 when a channel 2/1 radiance ratio was compared with percent cover. Inclusion of channel 3 (1.55 to 1.75 μm), a liquid water absorption band, in the analyses did not significantly improve the results.

Although PVI can be used to estimate percent cover and thus a mean K_c, it cannot be used as an index to adjust K_c for increased evaporation following irrigation since the magnitude of PVI is related only to canopy growth. However, the intersection coordinates (Rg1, Rg2) on the soil background line, which are used to calculate PVI, are related to soil reflectance. Thus, the position of the intersection on the soil line may be an indicator of irrigation or rainfall since

wet soil reflectance is less than for a dry soil. As a means of describing the the soil line intersection, we defined a parameter D as

$$D = [(Rg1 - a_0)^2 + (Rg2)^2]^{1/2}$$ [12]

where a_0 is the y-intercept of the soil background line. As shown in Fig. 1, D is the distance along the soil line from the y-intercept of the soil line to the intersection coordinates (Rg1, Rg2).

D and surface soil water content during the study are shown in Fig. 6. Irrigations occurred on 15 and 22 July (Table 1). On the first measurement days following the irrigations, D had decreased from the value on the previous day on which spectral measurements were made. The reductions in D ranged from 4.5 to 13.9 percent on 17 July, and from 5.1 to 9.4 percent on 23 July. D then increased as the soil surface dried (Fig. 6). D was sensitive to increases in surface soil water content, even at high percent cover. Percent cover on 23 July was as high as 90 percent. Differences in D between consecutive measurement dates were significantly correlated (r = 0.75**) with corresponding differences in surface soil water content. Thus, a decrease in D from its value on the previous observation date may be used as an indicator of irrigation or rainfall so that K_c can be adjusted to 1 account for increased evaporation.

This study has demonstrated a potential use of spectral reflectance for evaluating the crop coefficient. Once experimental relationships between the crop coefficient and stage of development are established, repetitive reflectance measurements from aircraft or satellites could be used to estimate the stage of development of individual fields. Use of reflectance for evaluating crop growth has

been demonstrated for a variety of crops (Aase and Siddoway, 1980; Heilman et al., 1977; Tucker et al., 1979; Tucker, 1979; Wiegand et al., 1979). If frequent observations are available, the soil line intersection coordinates of PVI could be used as an indicator of when to adjust the crop coefficient to account for effects of irrigation or rainfall.

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    tions for evapotranspiration and crop modeling. Agron. J. 71:
    336-342.

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LIST OF FIGURES

Table 1. Timing and amounts of water applied to the differentially irrigated plots of alfalfa.

Date	Plot No.	Amount of applied water (mm)
15 July	1	98
	2	70
	3	50
	4	38
22 July	1	72
	2	55
	3	43
	4	30

Table 2. Simulated values of composite reflectance and PVI for wet and dry soil backgrounds (11.5 and 1.0 percent gravimetric water content, respectively).

Percent Cover	Rp1		Rp2		PVI	
	Wet	Dry	Wet	Dry	Wet	Dry
20	0.18	0.26	0.30	0.38	0.057	0.059
40	0.15	0.21	0.35	0.41	0.110	0.111
60	0.13	0.17	0.40	0.44	0.163	0.163
80	0.10	0.12	0.45	0.47	0.216	0.216
100	0.08	0.08	0.50	0.50	0.267	0.267

Table 3. Measured composite reflectances for observed values of percent cover comparable to those in Table 2, and associated values of PVI.

Plot No.	Observed percent cover	Surface soil water content (% by weight)	Rp1	Rp2	PVI
3	19	1.1	0.17	0.26	0.033
4	39	3.7	0.13	0.34	0.119
2	58	3.9	0.10	0.36	0.154
1	80	3.5	0.11	0.43	0.218
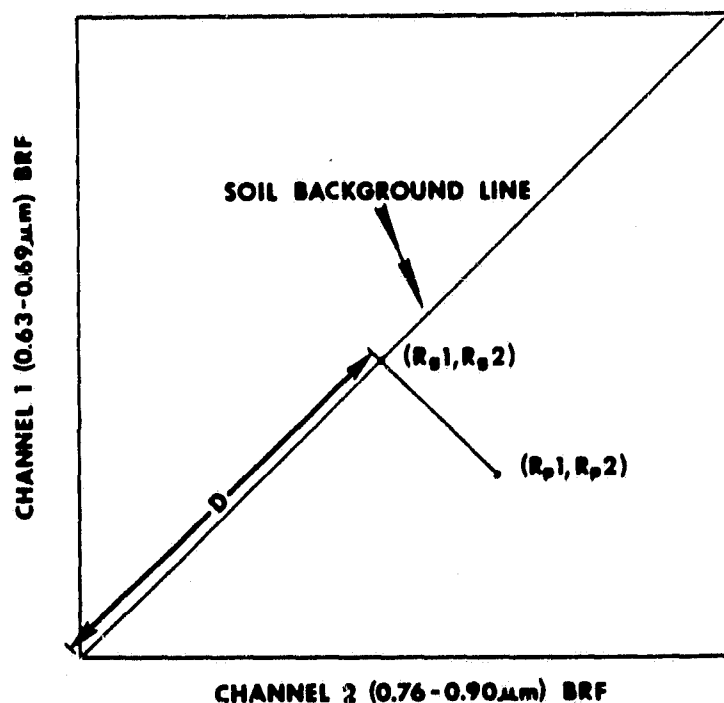
Fig. 1.   A diagram illustrating the perpendicular vegetation index
(PVI) of Richardson and Wiegand (1977).   A perpendicular
from the bidirectional reflectance (BRF) coordinates of the
plant canopy (Rp1, Rp2) intersects the soil background line
at coordinates (Rg1, Rg2).   The position of Rg1 and Rg2
depends on the reflectance of the soil beneath the crop.   D·
is the distance along the soil line from the y-intercept of
the soil line to the PVI intersection coordinates (Rg1, Rg2).
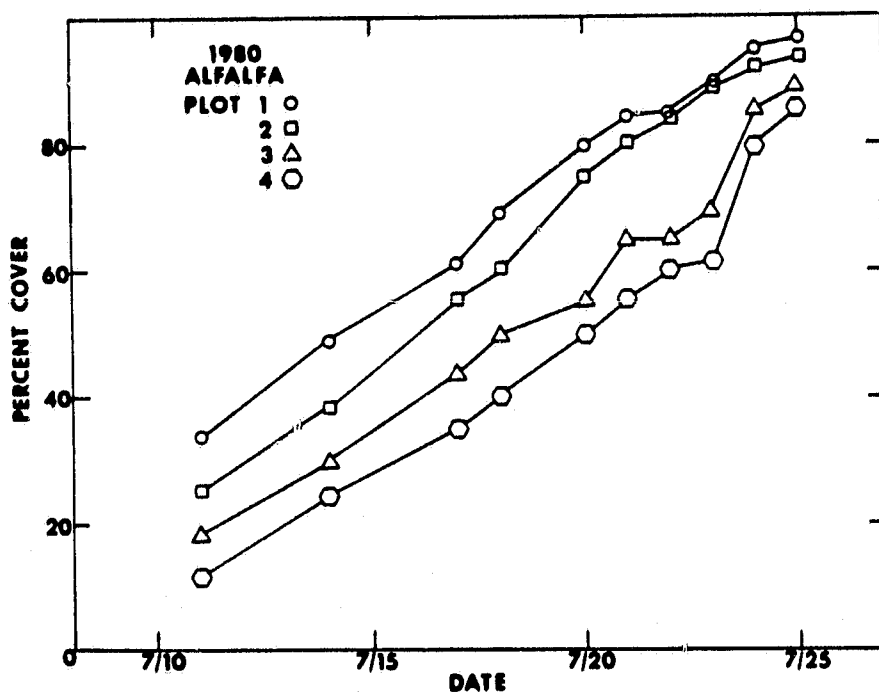
Fig. 2.   Changes in percent cover of the alfalfa plots during the
study.   A linearly decreasing amount of irrigation water was
applied to the plots with plot 1 receiving the most water,
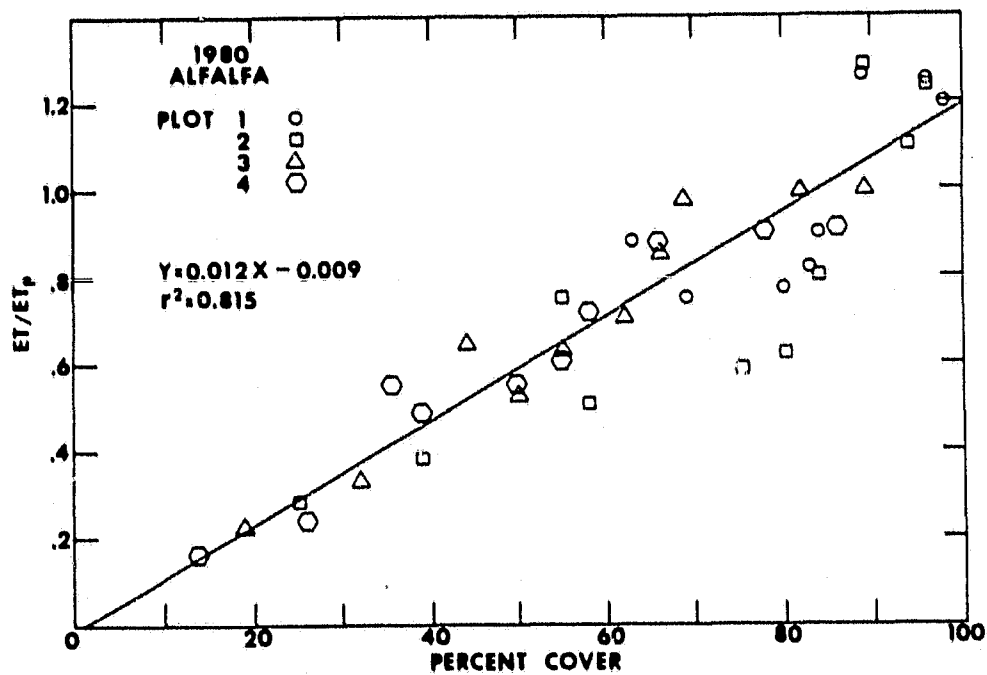and plot 4 the least.

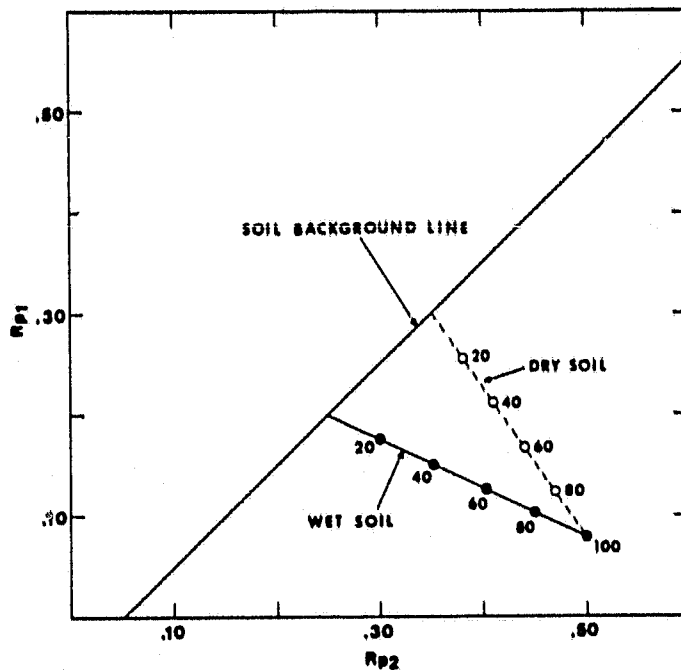Fig. 3. Relationship between the crop coefficient (ET/ET$_p$) and
percent cover of the alfalfa plots.

Fig. 4. Calculated bidirectional reflectance factors (Rp1 and Rp2)
in radiometer channels 1 (0.63 to 0.69 μm) and 2(0.76 to 0.90
μm), respectively, for a wet and a dry soil background.
Numbers adjacent to the data points denote percent cover.
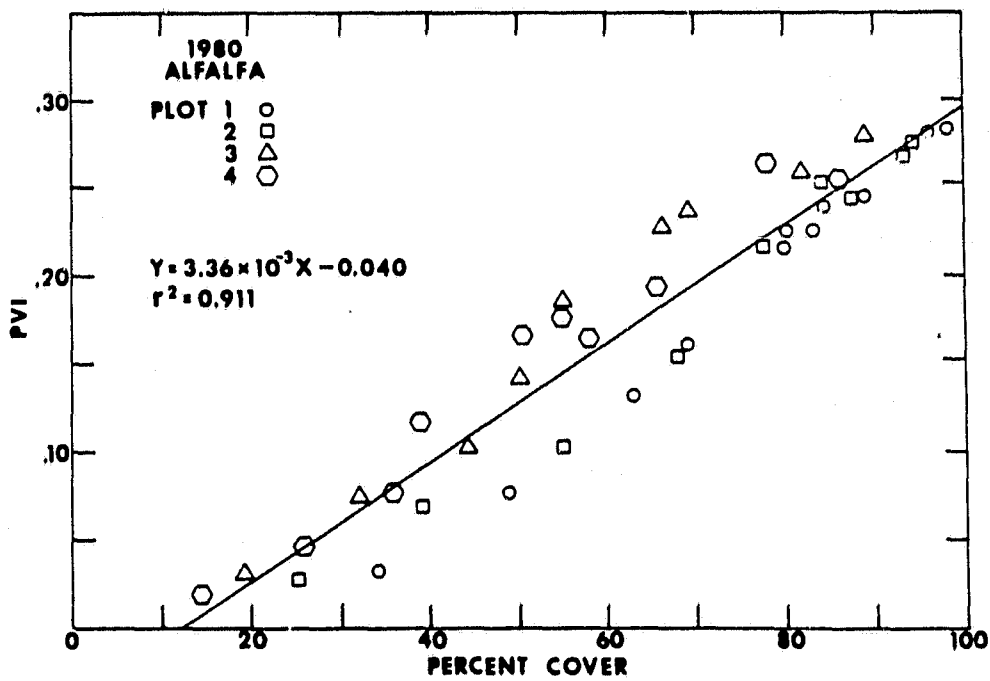
Fig. 5.   Relationship between PVI and percent cover of the alfalfa
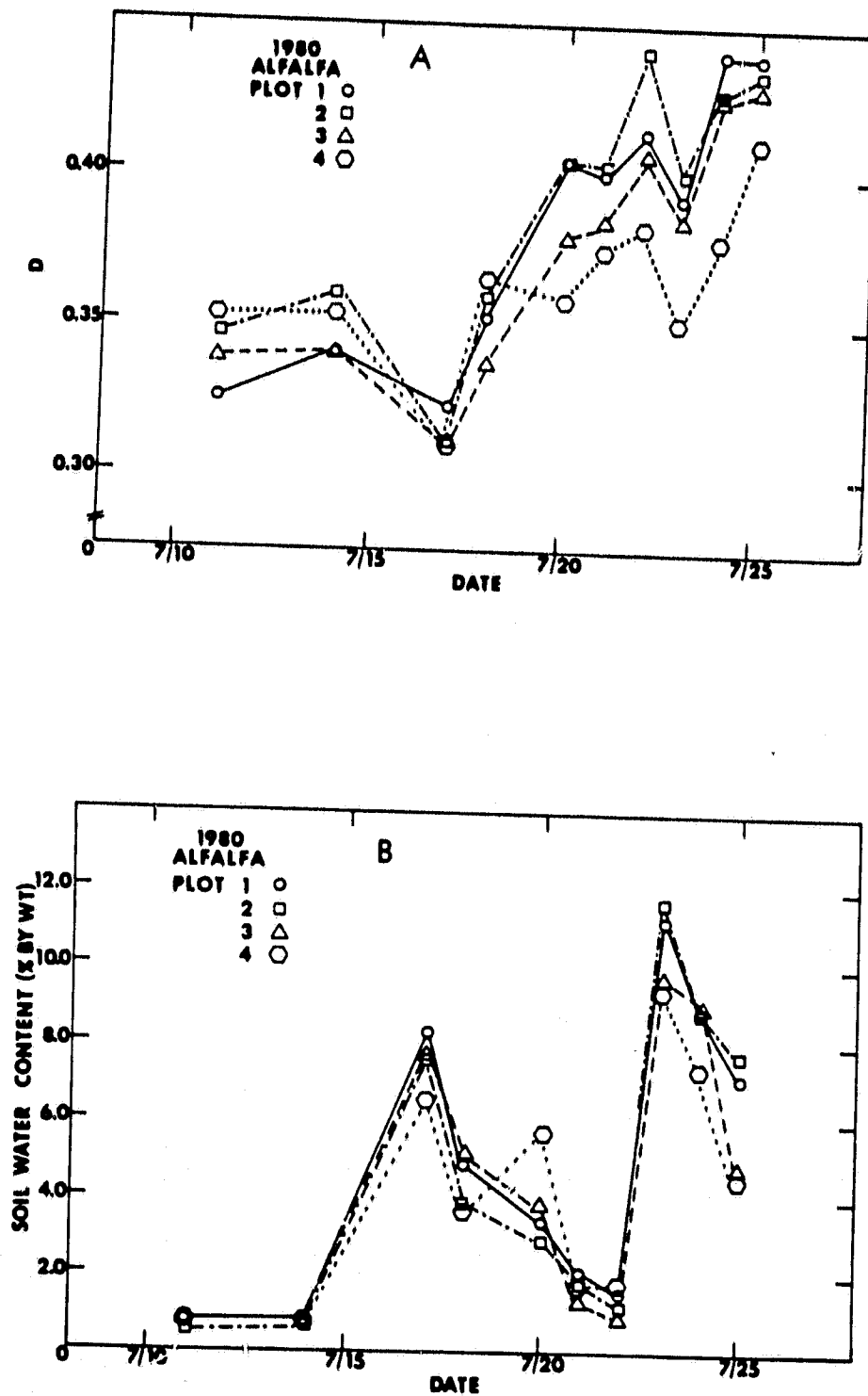   plots.

Fig. 6. Comparison of D, the distance from the y-intercept of the
soil background line to intersection coordinates Rg1, Rg2,
(A) and soil water content in the 0 to 4-cm layer (B).