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HCMM Energy Budget Data As A Model Input For
Assessing Regions of High Potential Groundwater Pollution

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16. Abstract

Progress of the investigation is reported. Results to date indicated that diurnal surface soil temperature differences, estimated from simulated HCMM data and a land cover correction, were significantly correlated with depth to water table for a variety of land cover conditions. Surface temperatures at approximately 1330 local standard time, estimated from simulated HCMM data, were significantly correlated with 50-cm soil temperature. Also, diurnal surface temperature differences, estimated from simulated HCMM data, were significantly correlated with soil water content for a variety of land cover conditions.

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Sioux Falls, SD 57198

17. Key Words Suggested by Author HCMM, Thermal Inertia, Water Table, Soil Water Content, Heat Flow Model	18. Distribution Statement

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A.   Problems

HCMM Data and digital RS-18 data from the August 1978 WB-57F aircraft flight have not been received.

B.   Accomplishments

Analyses of the ground data, and model simulations are continuing. During the next reporting period, analysis of HCMM data will begin upon receipt of the data.

C.   Significant Results

1.   Detection of Flooded Areas

In early April, 1978, heavy spring runoff from snowmelt caused significant flooding along a portion of the Big Sioux River Basin in southeastern South Dakota. The flood delayed spring planting by as much as two months in some areas.

The flooded-area (primarily alluvial soils) was visible from surrounding areas on a May 15 HCMM day IR test image (Fig. 1). On May 15, the flood waters had receded but an area of anamolous residual high soil moisture remained. The soils were at or near field capacity. Soil moisture in the surrounding terrace soils was generally less. The cooler temperatures of the flooded area were primarily the result of a higher thermal inertia and more available water for surface evaporation due to the high soil moisture content.

The high soil moisture area was not visible on a HCMM day visible test image of the same scene (Fig. 2), or on Landsat imagery acquired on May 16, 1978 (Fig. 3 and 4).

1
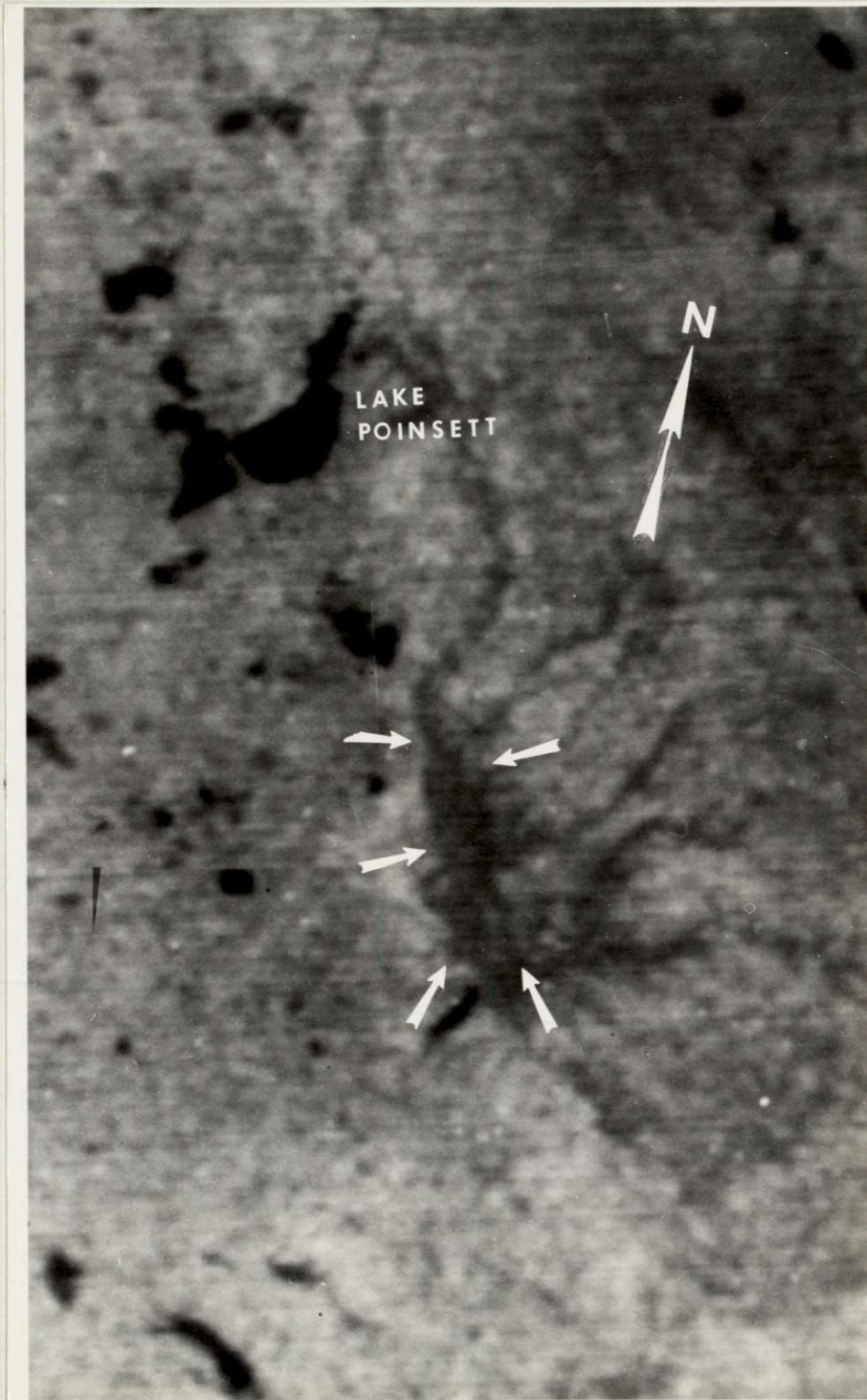
Fig. 1. Photographic enlargement of a May 15, 1978, Day IR test
image (scene I.D. A-A0029-19575) showing a high soil
moisture area (arrows) in southeastern South Dakota.
The flooding occurred in early April. (Approx. scale =
1:500,000; dark is cool).
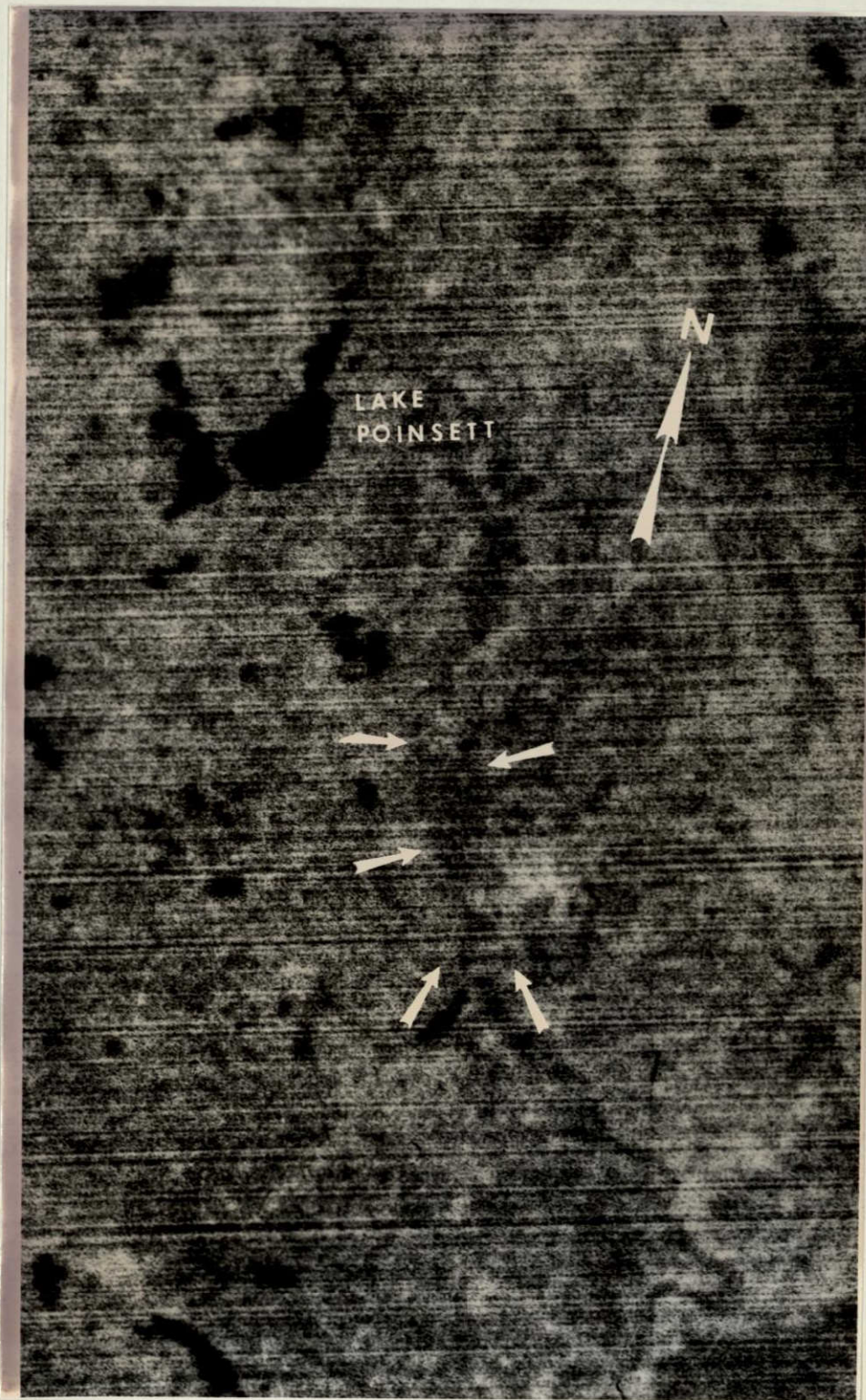
Fig. 2. Photographic enlargement of a May 15, 1978, Day Visible
test image (scene I.D. A-A0029-19575) of the same area
as Fig. 1. (Approx. scale = 1:500,000).

3
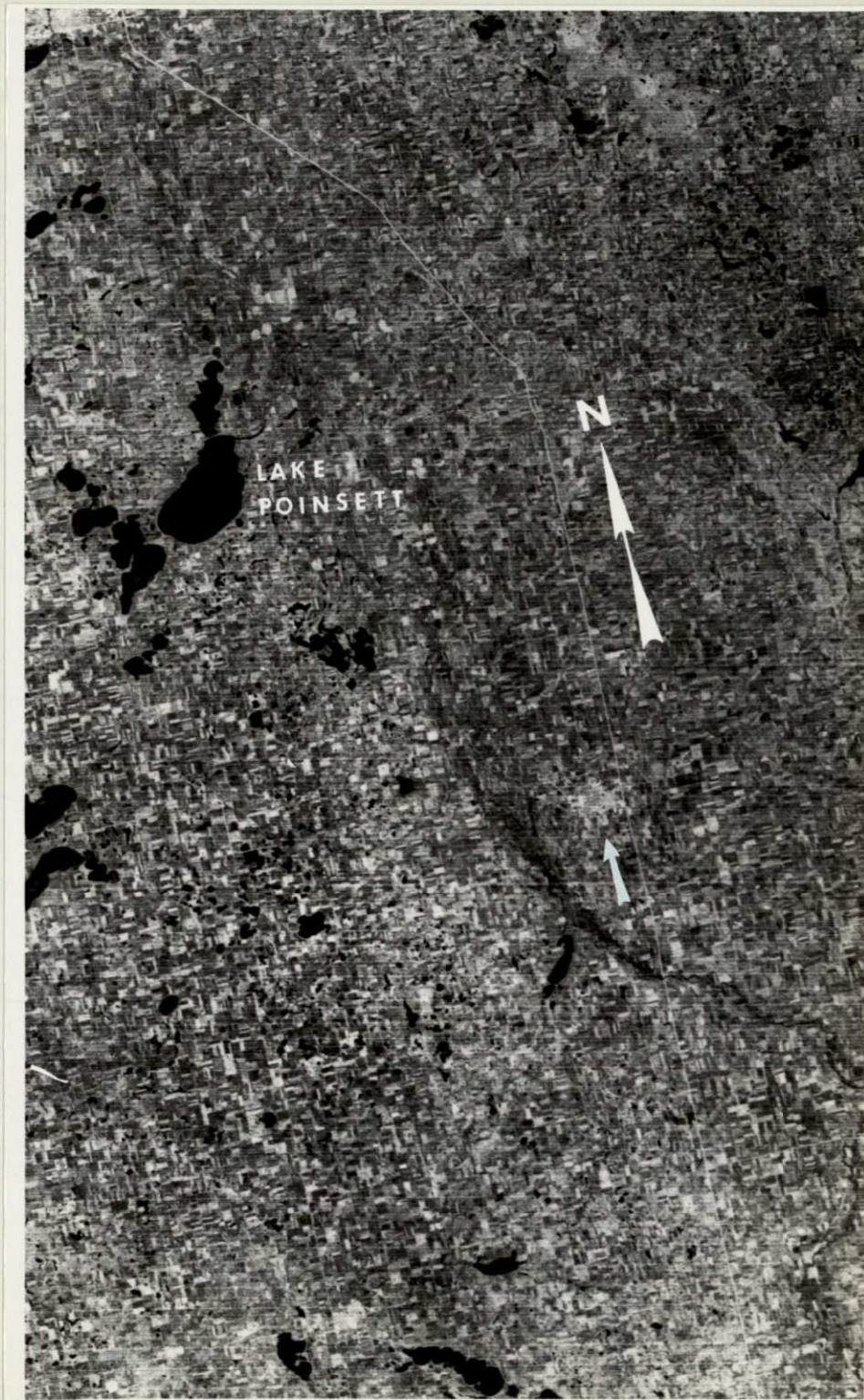
Fig. 3. Photographic enlargement of a May 16, 1978 band 5 Landsat image of the same area as Fig. 1. (Approx. scale = 1:500,000). Note the generally lower reflectance of alluvium and terraces around Brookings (arrow), but the absence of differential spectral properties identifying the lower lying alluvium from the terraces to north and east of Brookings.

LAKE
POINSETT

N
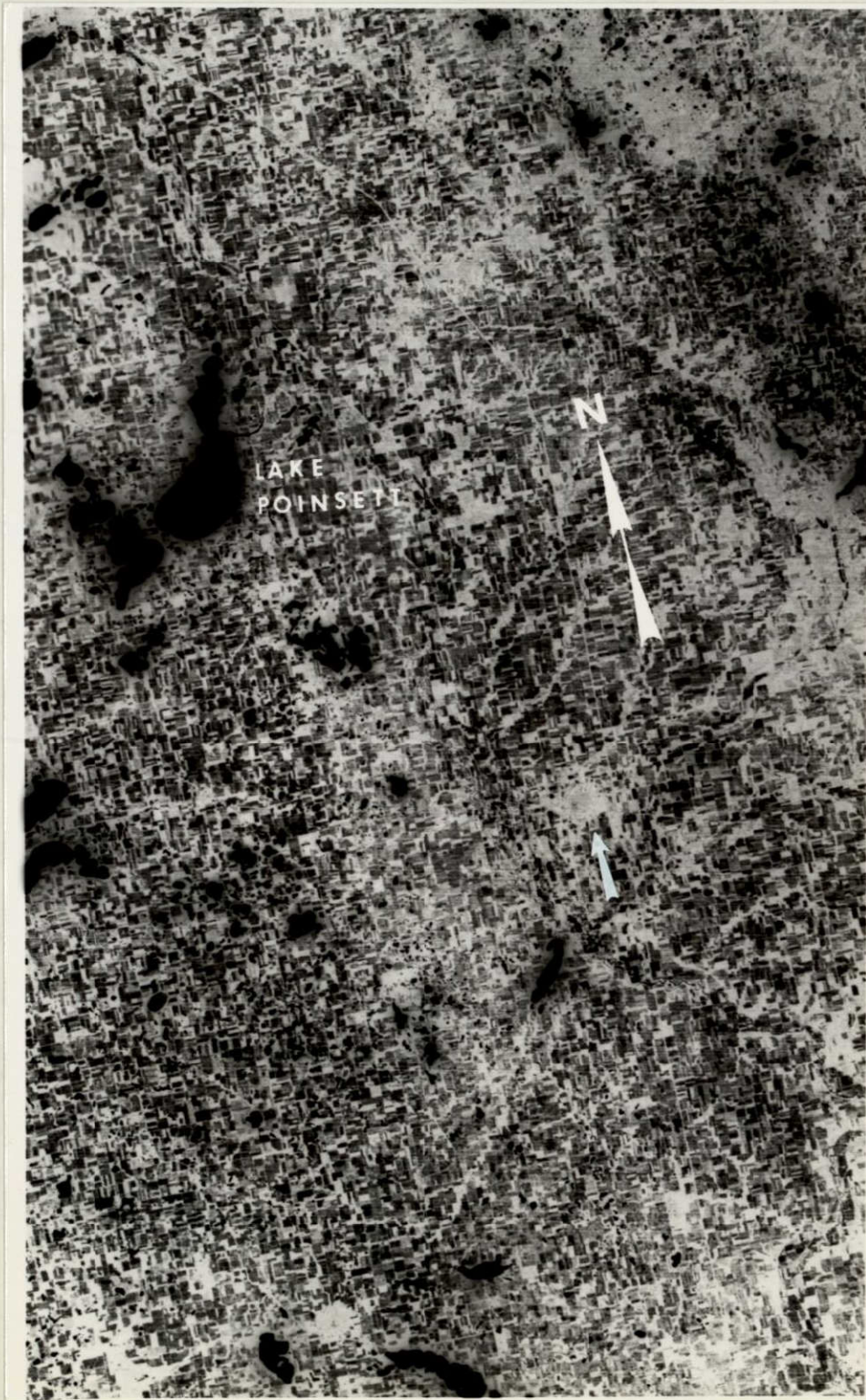
Fig. 4. Same as Fig. 3 except image is from band 7.

2. Water Table Depth

The previous quarterly HCMM progress report (September 1978) discussed the significant correlation between soil temperatures at 50-cm below the soil surface and depth to water table to about four meters. Results indicated that shallow water tables produced a heat-sink effect, thereby influencing soil profile and surface temperatures for possible detection using remote sensors.

To evaluate the effect of water table depth on surface temperatures, thermal scanner data[1] collected on September 5 and 6, 1978, at approximate HCMM overpass times at an altitude of 3650-m AGL were analyzed. Scanner data were not corrected for emissivity variations. Test sites included three land-cover categories (stubble, pasture, corn) with percent covers ranging from about 20 to 95 percent, and six soil types (Renshaw sandy loam, Fordville loam, Estelline silt loam, Kranzburg silt loam, Lamoure silty clay loam, Volga silty clay loam). Ground data collected included soil moisture (0 to 15 and 0 to 50-cm layers), 50-cm soil temperatures, and percent cover. Data corresponding to water table depths greater than four meters were not included in the analysis.

Apparent surface temperatures measured by the scanner included emittance contributions from the soil surface and the land cover (canopy, stubble, etc.). Scanner estimates of the diurnal surface

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[1] Aircraft data were collected as part of a watershed development investigation supported by NASA Grant No. NGL-42-003-007.

temperature difference were not significantly correlated with water table depth (Fig. 5).

Results of a study in a barley canopy (see Appendix A) indicated that soil surface temperatures could be estimated from remote measurements of canopy temperature if minimum air temperature and percent cover were known. The equations

$$T_s = 0.40 \ T_c + 0.60 \ T_{a \ min} + 5.10 \qquad (1)$$
$$(R^2 = 0.78)$$

and

$$T_s = 0.79 \ T_c \ e^{(-0.80 \ PC)} + 20.35 \qquad (2)$$
$$(R^2 = 0.86)$$

were developed for measurements at 0230 and 1330 local standard time, respectively, where T_s (°C) is soil surface temperatures, T_c (°C) is the remote measurement of canopy temperature, $T_{a \ min}$ (°C) is the minimum air temperature from the nearest National Weather Service Station, and PC is percent cover expressed as a fraction.

Soil surface temperatures were estimated from the scanner measurements using equations (1) and (2), and the resulting diurnal temperature differences were significantly correlated (r = 0.87**) with depth to water table (Fig. 6). The results in Fig. 6 indicated that the shallow water tables produced a damping of the amplitude of the diurnal surface temperature wave.

Depth to water table was correlated (r = 0.66**) with soil water content in the 0 to 50-cm layer of the profile (Fig. 7).

7
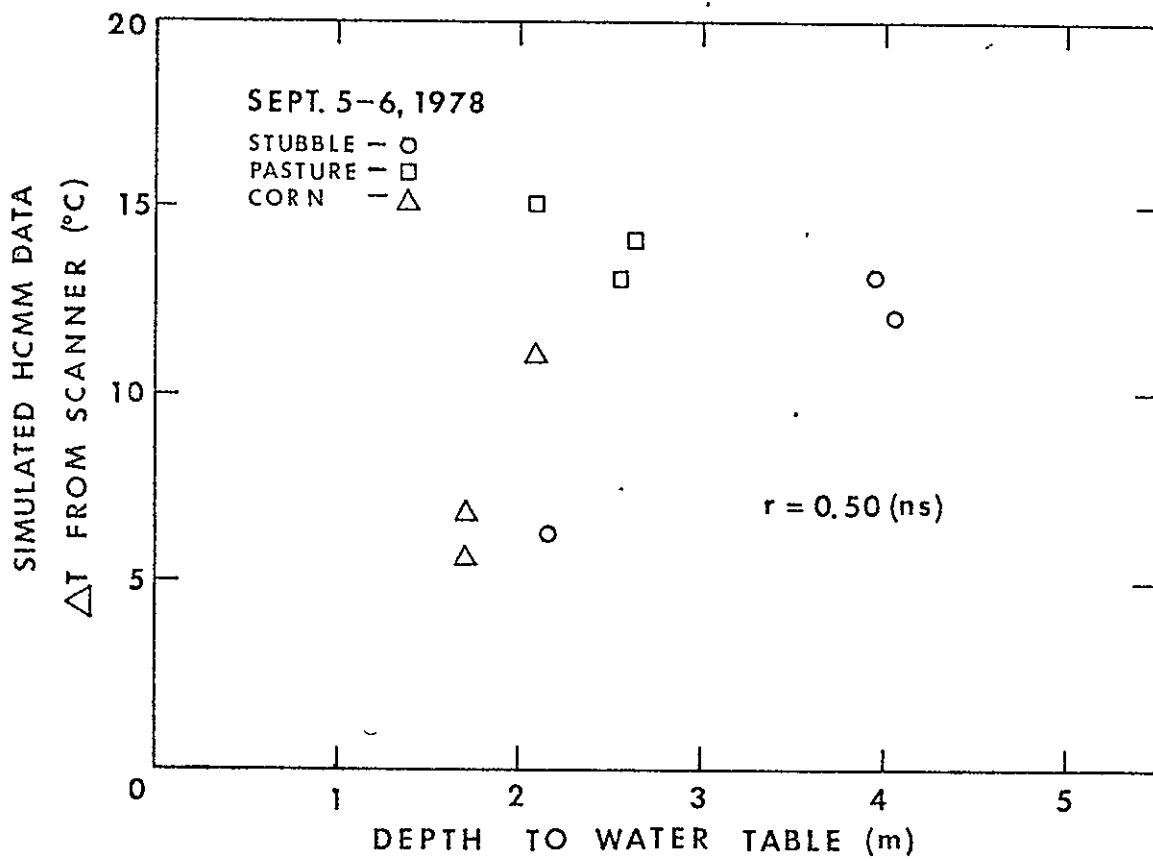
Fig. 5. Diurnal surface temperature difference (ΔT), estimated from simulated HCMM data (uncorrected for effects of land cover), as a function of depth to water table.
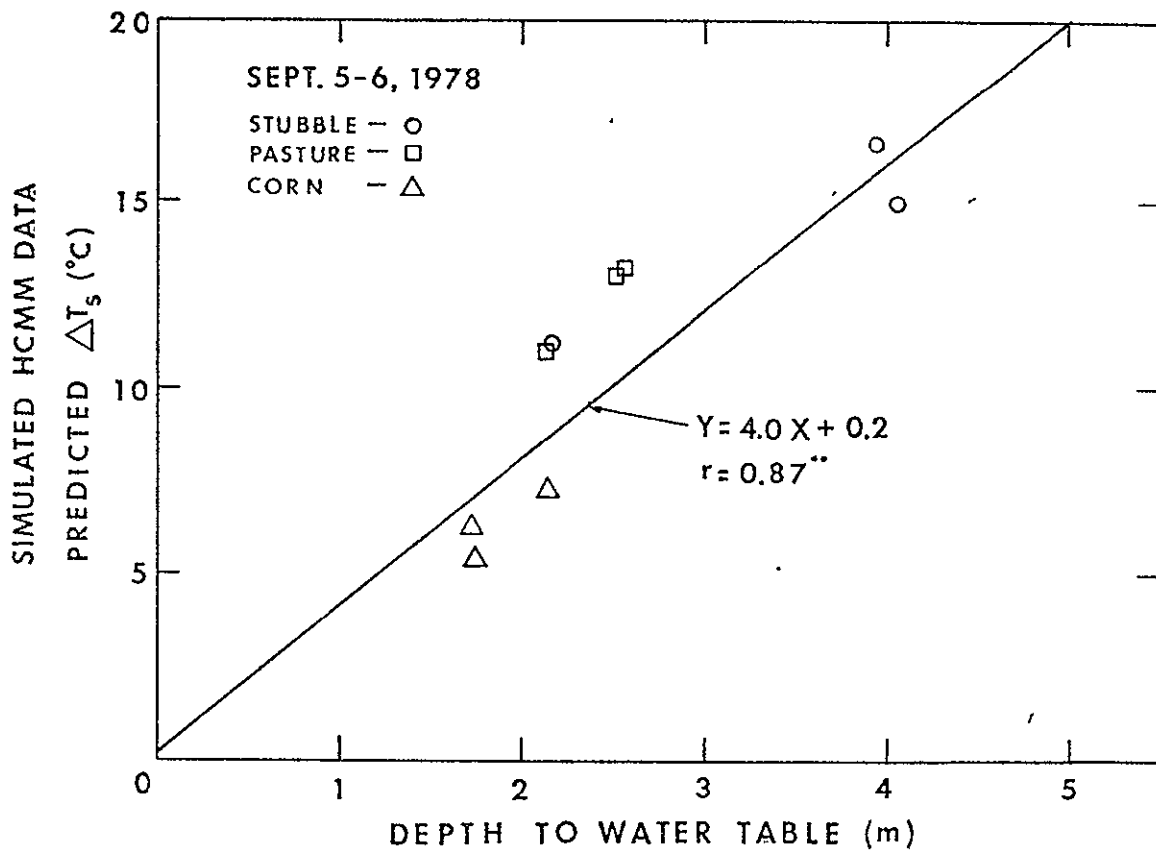
Fig. 6. Diurnal surface soil temperature difference (ΔT_s), estimated
using simulated HCMM data and a land cover correction, as
a function of depth to water table.

SOIL WATER CONTENT (% of f.c.)

80

SEPT. 5-6, 1978
STUBBLE — O
PASTURE — □
CORN — △

60

$Y = 98.2e^{(-0.43X)}$
$r = 0.66$

40

20

0

1   2   3   4   5

DEPTH TO WATER TABLE (m)

Fig. 7. Soil water content in the 0 to 50-cm layer as a function
of depth to water table.

10

Water tables that were less than 2 m below the soil surface occurred under irrigated corn. When the two data points in Fig. 8 corresponding to the irrigated corn fields were excluded from the analyses, soil water content and depth to water table were not correlated.

Previous results indicated that depth to water table was significantly correlated to 50-cm soil temperature. We found a significant correlation ($r = 0.84**$) between scanner temperature at 1330 local standard time (uncorrected for land cover) and 50-cm soil temperatures (Fig. 8). We also found that corrections for land cover improved the correlation (Fig. 9).

Results to date using simulated HCMM data appear very promising for evaluating water table depth from thermal data. Thermal data can be corrected for effects of land cover, and the resulting estimates of surface soil temperature can potentially be used to estimate depth to water table directly, or to estimate 50-cm soil temperatures which are highly correlated with depth to water table.

3. Soil Water Content

A study was conducted in a barley canopy to evaluate the potential for extending the thermal approach for estimating soil water from bare soil to developing crop canopies (see Appendix A). Equations developed as part of that study were applied to the thermal scanner data discussed in the previous section. Soil water content (0 to 15-cm layer) was estimated from the relationship

$$\Delta T_s = e^{(-0.03 \text{ SWC} + 3.58)} \tag{3}$$

11

Fig. 8. Surface temperature at 1330 local standard time, estimated
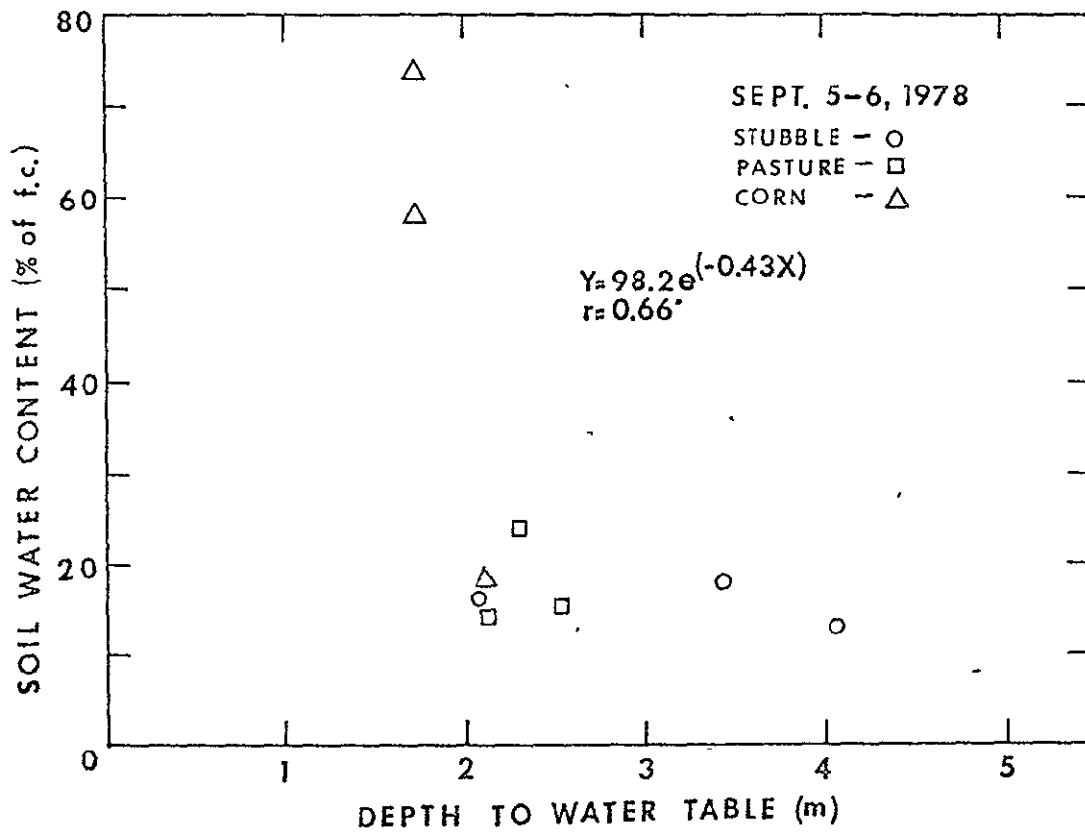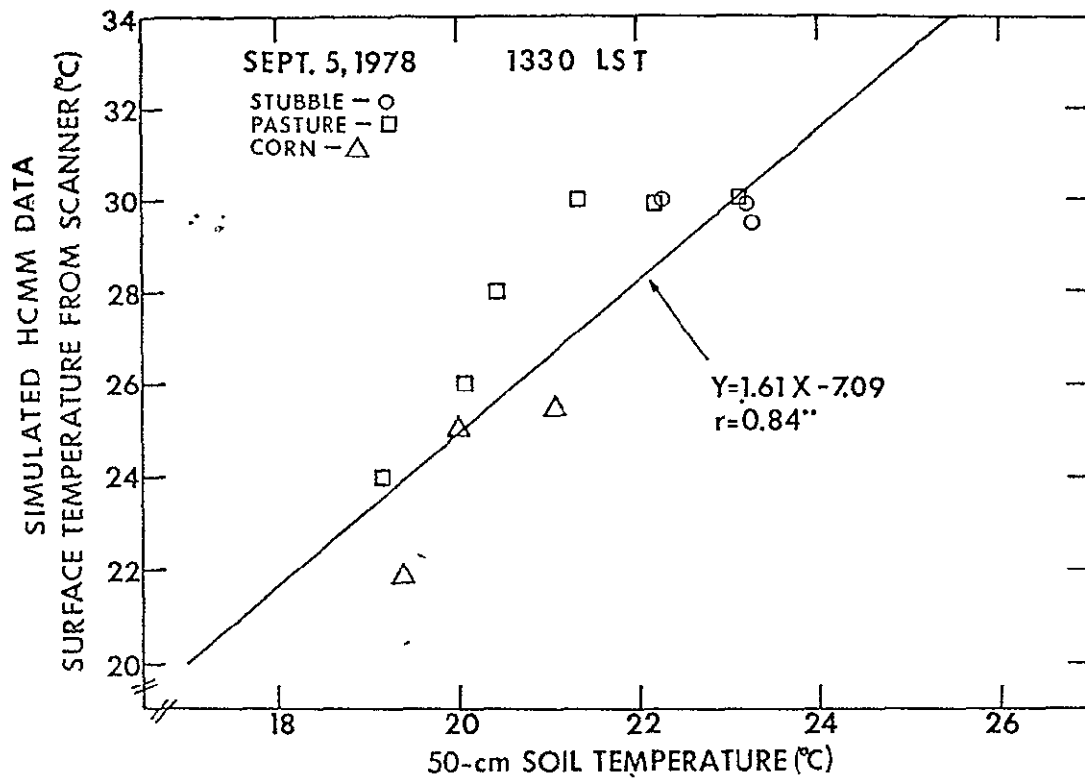from simulated HCMM data (uncorrected for effects of land
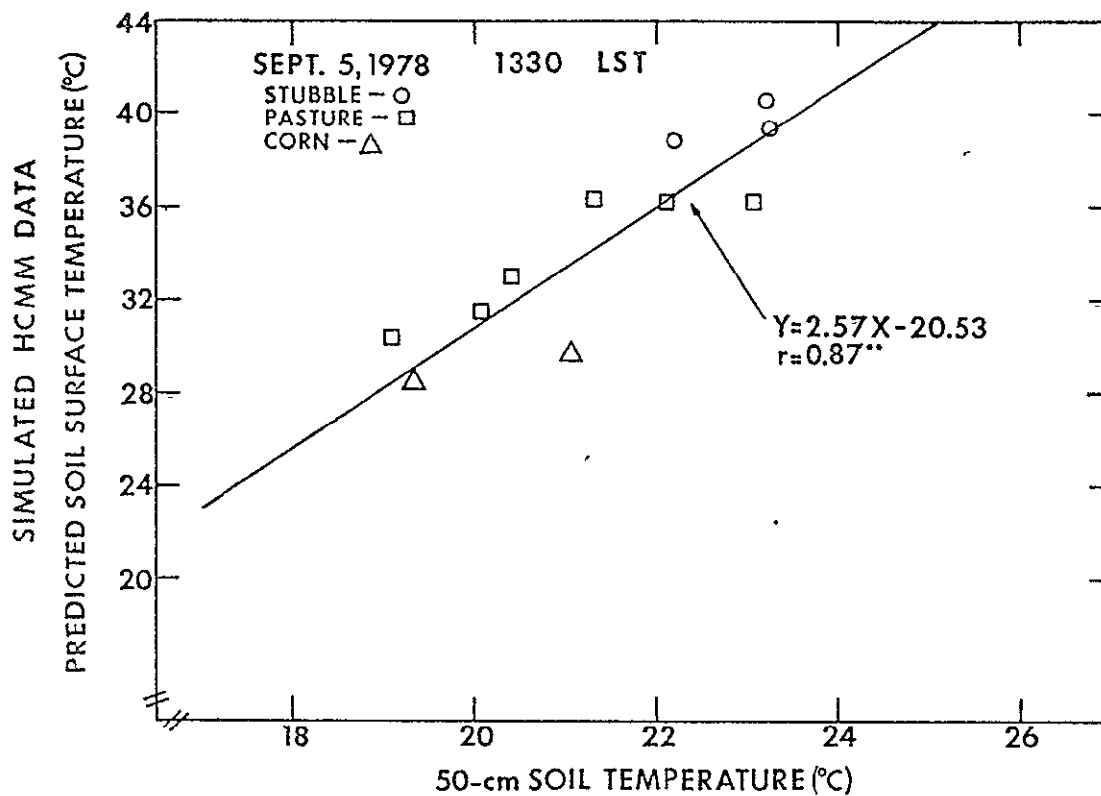cover), as a function of 50-cm soil temperature.

Fig. 9. Soil surface temperatures at 1330 local standard time, predicted from simulated HCMM data and a land cover correction, as a function of 50-cm soil temperature.

13

where ΔT_s (°C) is the diurnal surface temperature difference estimated from the scanner data and equation (1) and (2) in the previous section, and SWC (percent of field capacity) is soil water content. (Equation (3) differs from equation (1) in Appendix A only in that soil water content is expressed as percent of field capacity instead of percent by volume).

Figure 10 compares predicted and observed values of soil water content for stubble, pasture, and corn. The average difference of observed from predicted values was 1.6 percent. Differences ranged from -24 to 15 percent. Results in Fig. 10 demonstrated that extension of equations developed for barley to other land cover categories and soils was possible.

A direct comparison of soil water content with diurnal surface soil temperature differences- (ΔT_s) estimated from the scanner and the land cover correction yielded the equation

$$\Delta T_s = e^{(-0.02 \, SWC + 3.02)} \tag{5}$$

which was somewhat different than the relationship developed for barley (Fig. 11). We also found a high correlation between soil water content and diurnal temperature differences from the scanner data uncorrected for land cover (Fig. 12).

4. Model Simulation

The finite-difference heat flow model (see previous quarterly HCMM report) was used to simulate a variety of bare soil conditions that might occur for two profiles of the same soil type. The results are summarized below.

14
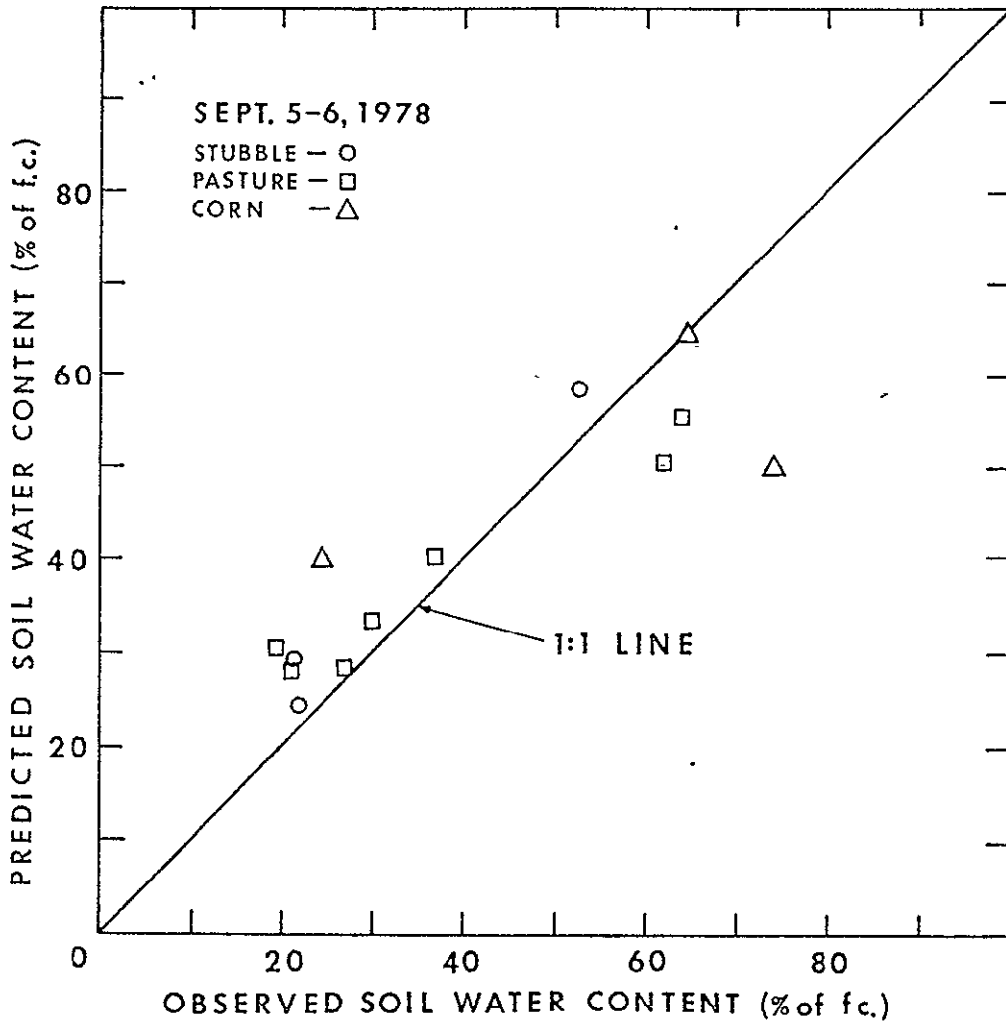
Fig. 10. Comparison of predicted versus observed 24-hr soil water
content in the 0 to 15-cm layer of the profile. Soil
water content was predicted using simulated HCMM data
and equations developed for a barley canopy (Appendix A).

15
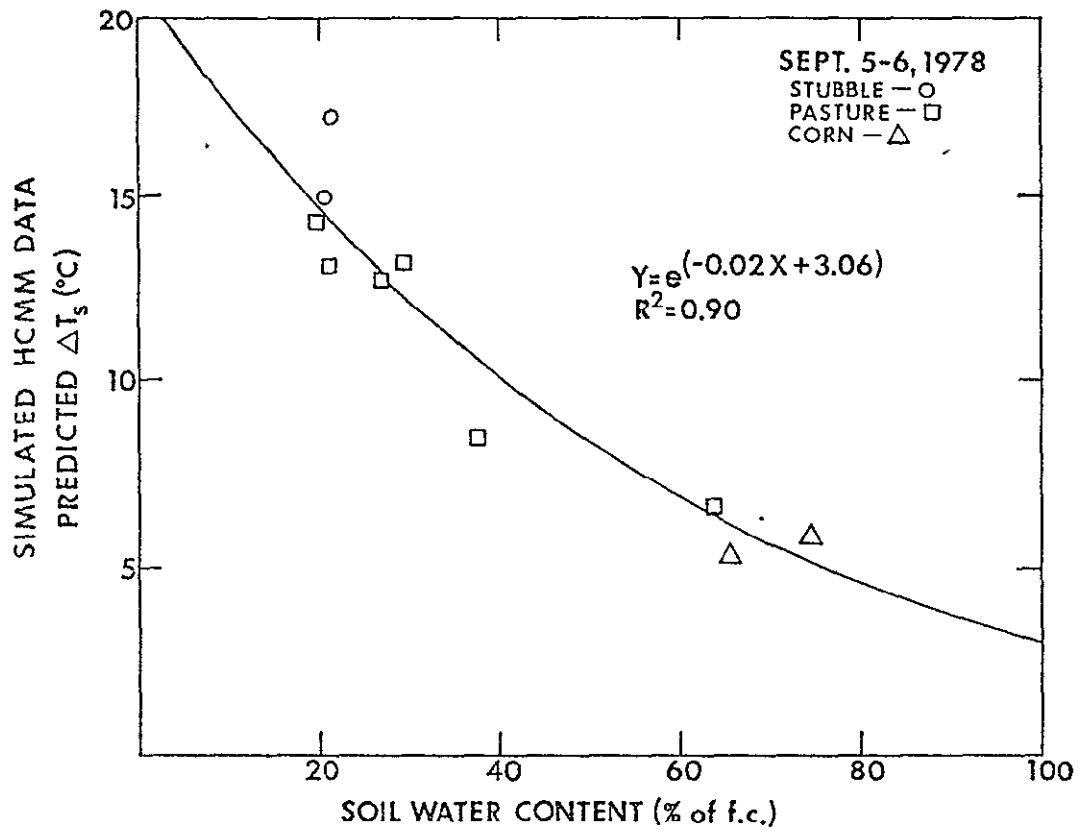
Fig. 11. Diurnal surface soil temperature difference (ΔT_s), estimated using simulated HCMM data and a land cover correction, as a function of 24-hr average soil water content in the 0 to 15-cm layer of the profile.

16
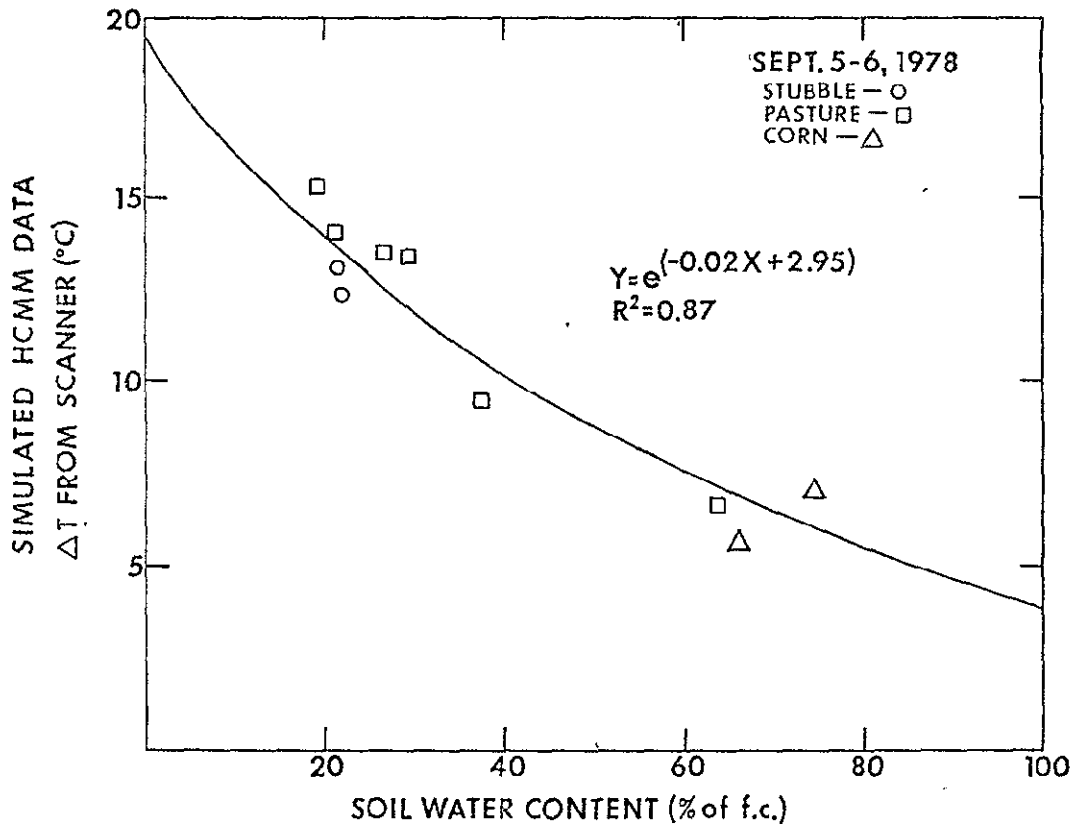
Fig. 12.   Diurnal surface temperature difference (ΔT), estimated from
           simulated HCMM data (uncorrected for effects of land cover),
           as a function of 24-hr average soil water content in the
           0 to 15-cm layer of the profile.

* Surface temperature differences associated with water
  table differences between two profiles are relatively
  constant during the diurnal cycle.
* Surface temperature differences associated with soil.
  moisture differences between two profiles are highly
  dependent on time of day.

D. Publications

"Thermography for Estimating Soil Moisture in a Developing
Crop Canopy" to be submitted to Journal of Applied Meteorology
(see Appendix A).

E. Recommendations

None at this time.

F. Funds Expended

$59,311.22

G. Data Utility

HCMM Data for the test site have not been received.

APPENDIX A

"Thermography for Estimating Soil Moisture in a Developing Crop Canopy"

(Draft copy - RSI internal review required before submission to journal)

THERMOGRAPHY FOR ESTIMATING SOIL

MOISTURE IN A DEVELOPING CROP CANOPY[1]

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ABSTRACT

Previous investigations of thermal-infrared techniques using remote sensors (thermography) for estimating soil water content have been limited primarily to bare soil. A ground-based study was conducted throughout a complete growing season to evaluate the potential for extending the thermography approach to a developing barley canopy. A significant exponential relationship resulted between the volumetric soil water content in the 0 to 4-cm soil layer and the diurnal difference between surface soil temperature measured at 0230 and 1330 local standard time (satellite overpass times of NASA's Heat Capacity Mapping Mission - HCMM). The difference between surface soil temperature at 1330 LST and maximum air temperature was also exponentially related to soil water content. Surface soil temperatures could be estimated from remote measurements of canopy temperature provided that minimum air temperature and percent cover of the canopy were known. The significant results of a data set with varying percentages of land cover over the period of a growing season indicate that aerial thermography such as HCMM together with other remote sensing or climate data may provide synoptic and repetitive estimates of soil moisture for a variety of land cover conditions.

1. Introduction

Numerous investigations have been conducted to evaluate remotely sensed surface temperatures for estimating soil water content (Idso et al., 1975; Idso and Ehler, 1976; Schmugge, 1978; Schmugge et al., 1978). The basic approaches have related soil water content to the differences between the daily maximum and minimum soil or crop temperatures, or the differences between maximum soil or crop temperatures and air temperature. The investigations have generally been limited to bare soils or fully developed crop canopies because of difficulties in interpreting thermal data at less than full cover when significant emittance contributions from both soil and vegetation occur.

Environmental factors interacting with physical and biological processes which affect soil-water-plant relations are important at all stages of plant growth and development. Thus, the ability to derive useful information from remote temperature measurements for conditions other than bare soil or fully developed canopies would greatly expand the usefulness of the remote sensing techniques.

Investigators have shown that, even at full cover, thermal emittance from the soil surface can affect remote temperature measurements of crop canopies (Blad and Rosenberg, 1976; Steinmetz, 1977). Thus, surface and soil temperatures can potentially be estimated from remote measurements of land surface emittance where a crop canopy is the primary source of radiation.

We conducted an investigation using ground based radiometry to evaluate the potential for estimating soil surface temperature and soil moisture from measurements of total area emittance (such as an aircraft or satellite would measure) at various stages in the development of a

1   crop canopy. The investigation was conducted to examine data collected

2   during times of the diurnal temperature cycle corresponding to data

3   collection by NASA's Heat Capacity Mapping Mission (HCMM), launched in

4   April 1978. The satellite, which carries a two-channel radiometer

5   (0.5 to 1.1 and 10 to 12 μm) in a sun-synchronous orbit, collects data

6   at mid-latitudes at approximately 0230 and 1330 local standard time

7   (LST) during the diurnal cycle with repeat coverage of five or 16 days

8   depending on latitude.

9   2.   Materials and Methods

10   Experiments were conducted on a 25 x 300-m field of Volga loam

11   (fine, loamy over sandy, mixed (calcareous), frigid, Cumulic

12   Haplaquoll) at the South Dakota State University Agricultural Engineer-

13   ing Research Farm located 8-km south of Brookings, South Dakota.

14   Barley (Hordeum vulgare L.) Larker was planted in the field at 15 cm

15   row spacings (north-south rows) and a population of 2.5-million

16   plants/ha. The barley was rainfed in a rainfall zone averaging 558 mm/

17   year. Surface roughness of the soil was minimal.

18   Surface soil temperatures (about 1 mm below the soil surface) were

19   measured with copper-constantan thermocouples for two replications

20   within the field. For each replication, three thermocouples were

21   wired in parallel to obtain an average surface temperature measurement.

22   Apparent canopy temperatures consisting of emittance contributions from

23   the soil surface and the barley were measured with a portable infrared

24   radiometer (Model PRT-5, Barnes Engineering Co.) at a vertical position

25   (zero degree look angle measured from nadir). The temperature

26   resolution of the 20 degree field of view PRT-5 was ±0.5° C in the 8 to

27   14-μm wavelength interval. Apparent crop temperatures were measured

with the PRT-5 at a look angle of about 60 degrees to minimize emittance contributions from the soil. Temperatures were measured at times corresponding to HCMM overpass (0230 and 1330 LST).

The temperatures measured with the PRT-5 were not corrected for emissivity. Emissivities, determined using a procedure similar to that described by Fuchs and Tanner (1966), ranged from 0.96 for bare, dry soil to 0.98 for the fully developed barley canopy.

Soil water contents (0 to 4-cm layer) for each replication were gravimetrically sampled at the time of the temperature measurements. The average of soil water contents measured at 0230 and 1330 LST was used to represent the 24-hour average. Jackson et al. (1976) reported that the average of the daily maximum and minimum water content closely approximated the 24-hour average.

Temperature and soil water content measurements were initiated when the percent cover of the canopy reached 30 percent. Data were collected for 22 dates during the 45-day investigation.

Plant samples for determining leaf area index (LAI) were taken every five to seven days. Leaf areas (green leaves only) were measured with an optical planimeter (Lamda Instrument Corp.). Percent cover was determined using 35-mm color infrared slides of the canopy (photographed from a vertical position approximately 1 m above the canopy) projected on a random dot grid. Daily values of LAI and per- cent cover were estimated from graphs of observed LAI and percent cover versus date (Fig. 1).

Maximum and minimum air temperatures were obtained from the Brookings National Weather Service Station (approximately 12 km from the research site). All data were subjected to regression analyses.

3.   Results and Discussion

    In the discussion that follows, canopy temperature refers to the apparent temperature measured by the PRT-5 at a zero degree look angle that viewed both exposed soil and the crop. Crop temperature refers to apparent temperature of the barley measured by the PRT-5 at a 60 degree look angle to minimize emittance contributions from the soi.

Soil Water Content Versus Temperature Relationships

    The amplitude of the diurnal soil surface temperature wave is a function of thermal inertia and meteorological factors (solar insolation, air temperature, humidity, etc.). Thermal inertia, an indication of a soil's resistance to temperature change, is defined as $\rho c \lambda^{\frac{1}{2}}$ where ρ is density, c is specific heat, and λ is thermal conductivity. Since ρ, c and λ of a soil increase as soil water content increases, the resulting amplitude of the diurnal temperature wave decreases.

    When the soil surface is wet, soil evaporation is a major factor controlling surface heat loss. After the surface layer dries and the soil water supply cannot meet the evaporative demand, surface heat loss is by conductive transfer and is largely influenced by thermal inertia. Nocturnal cooling is highly related to thermal inertia. Thus, the diurnal surface temperature range can be an indication of soil water content. Idso et al. (1975) found a linear relationship between the diurnal range of surface soil temperatures and soil water content in the 0 to 4-cm layer of soil, and reported that the temperature versus water content relationship was also a function of soil type. However, they also found that if soil water content was expressed in units of pressure potential, this dependence was minimal.

1 Vegetative cover alters the solar insolation at the soil surface

2 and thus affects soil evaporation and soil temperatures. Thus, dynamic

3 growth and development of vegetation would be expected to complicate the

4 temperature versus water content relationship.

5 Initially, we evaluated the relationship of day minus night surface

6 soil temperatures (ΔT_s), measured at HCMM overpass times, versus soil

7 water content at various stages of canopy development. Leaf area index

8 and percent cover of the barley canopy ranged from 0.3 to 3.2 and 30 to

9 90 percent, respectively. Seasonal trends in observed leaf area index

10 and percent cover are shown in Fig. 1. The exponential equation

11
$$\Delta T_s = e^{(-0.06\ SWC\ +\ 3.59)} \tag{1}$$

12 with an R^2 of 0.81 and a standard deviation from regression of 2.54 was

13 found to best represent the relationship between ΔT_s and the average 24-

14 hr volumetric soil water content (SWC) in the 0 to 4-cm layer of the

15 soil profile (Fig. 2).

16 Idso et al. (1976) proposed a procedure for compensating for

17 environmental variability in the thermal inertia approach by normalizing

18 ΔT_s measurements with respect to an arbitrary standard diurnal air

19 temperature variation. We found no significant improvement in the ΔT_s

20 versus SWC relationship using the same normalization procedure.

21 Since daily and seasonal air temperature differences influence

22 surface soil temperature, we also evaluated the relationship between

23 soil water content at 1330 LST (SWC_{1330}) and the differential between

24 surface soil temperature at 1330 LST $(T_{s,\ 1330})$ and maximum air

25 temperature $(T_{a\ max})$ measured at the nearby Brookings National Weather

26 Service (NWS) Station. The exponential equation

27

$$T_{s,\,1330} - T_{a\,max} = e^{(-0.08\,SWC_{1330} + 3.26)} \qquad (2)$$

with an R^2 of 0.70 and a standard deviation from regression of 3.70 was obtained (Fig. 3).

The temperature versus water content relationships (Eqs. 1 and 2) apply only to Volga loam. However, Idso et al. (1975) have shown that if soil water content is converted to a pressure potential, a more universal relationship results that appears to be independent of soil type. The relationships between temperature and soil water content have limited usefulness unless soil temperatures can be estimated from remote measurements under varying conditions of crop cover.

Estimating Soil Temperature from Measurements of Canopy Temperature

During the growing season, surface-soil temperatures at 0230 LST were 1.1 to 5.4° C higher than apparent crop (barley) temperatures, while PRT measurements of apparent canopy temperature (including crop and soil background) at 0230 LST were 1.1 to 2.2° C higher than apparent crop temperatures (Fig. 4a). The difference between canopy and crop temperatures suggested that, even at full cover, significant amounts of thermal radiation from the soil surface were detected by the infrared radiometer at 0230 LST. Those results agreed with results presented by Blad and Rosenberg (1976) and Steinmetz (1977).

At 1330 LST, radiometric measurements of apparent canopy temperature were 0.5 to 17° C higher, and surface-soil temperatures 1.5 to 20° C higher, than apparent crop temperatures (Fig. 4b). At full cover, greatest differences between canopy and crop temperatures occurred on days with high temperatures and high evaporative demand. On those days, some wilting of leaves occurred which exposed more of the soil background.

Because emittance contributions from the soil surface were detected by the infrared radiometer, equations were developed from regression analyses to estimate soil temperatures at HCMM overpass times from remote measurements of canopy temperature. For the 0230 LST measurements, the equation

$$T_s = 0.40 \text{ PRT} + 0.60 \text{ } T_{a \text{ min}} + 5.10 \tag{3}$$

with an R^2 of 0.78 and a standard deviation from regression of 1.31 was obtained where T_s (°C) is surface soil temperature, PRT (°C) is PRT measurement of canopy temperature, and $T_{a \text{ min}}$ is the minimum NWS air temperature. For the 1330 LST measurement, the surface soil temperatures were related to the PRT measurements of canopy temperature and an exponential function of percent cover (PC). The equation

$$T_s = 0.79 \text{ PRT} \times e^{(-0.80 \text{ PC})} + 20.35 \tag{4}$$

with an R^2 of 0.86 and a standard deviation from regression of 2.63 was obtained where PC is expressed as a fraction (Fig. 5). Correlations for (3) and (4) were significant at the 0.01 level with 19 and 25 df, respectively. We found no improvement in estimating soil temperature by including leaf area index, solar insolation, or maximum air temperature in the analyses. Figure 6 compares predicted soil temperature with observed values.

Measurements of canopy temperature used to derive (3) and (4) ranged from 13 to 22° C for (3), and from 24 to 52° C for (4). Percent cover ranged from 0.3 to 0.9.

Evaluation of Results

Figure 7 compares observed soil water contents with values predicted using Eqs. (1) through (4), and the same data sets from which (3) and (4) were derived. The PRT measurements are similar to those

1 derived from aircraft or satellite platforms excluding the effects of

2 atmospheric transmission. Differences of observed from predicted values

3 of 24-hr average soil water content ranged from -3.6 to 6.2 percent

4 (Fig. 7a). The average difference was 0.01 percent. The average

5 difference of observed from predicted soil water content at 1330 LST was

6 2.7 percent. Differences ranged from -4.9 to 9.5 percent (Fig. 7b).

7 The estimates of the diurnal soil temperature differences provided

8 a better estimate of soil water content than did the soil - air

9 temperature differential. However, both techniques demonstrated a

10 potential for evaluating surface soil moisture conditions in the

11 developing barley canopies.

12 4. Concluding Remarks

13 Results of this investigation indicate that thermography for

14 estimating soil water content can potentially be extended to

15 developing crop canopies. The diurnal difference between surface

16 soil temperatures measured at HCMM overpass times is an indication of

17 surface soil water content, as is the surface soil - maximum air

18 temperature differential. Surface soil temperatures can be estimated

19 from remote measurements of canopy temperature if minimum air

20 temperature and percent cover of the canopy are known. Remote sensing

21 techniques have been developed for evaluating crop cover (Heilman

22 et al., 1977; Kanemasu et al., 1977; Tucker et al., 1978) for certain

23 species.

24 Relationships presented in this paper are not expected to

25 universally apply for all soils, crops, and climatic conditions.

26 However, they do support continued research to more fully evaluate the

27 usefulness of the thermal-infrared techniques for estimating surface

soil temperatures and soil water contents.

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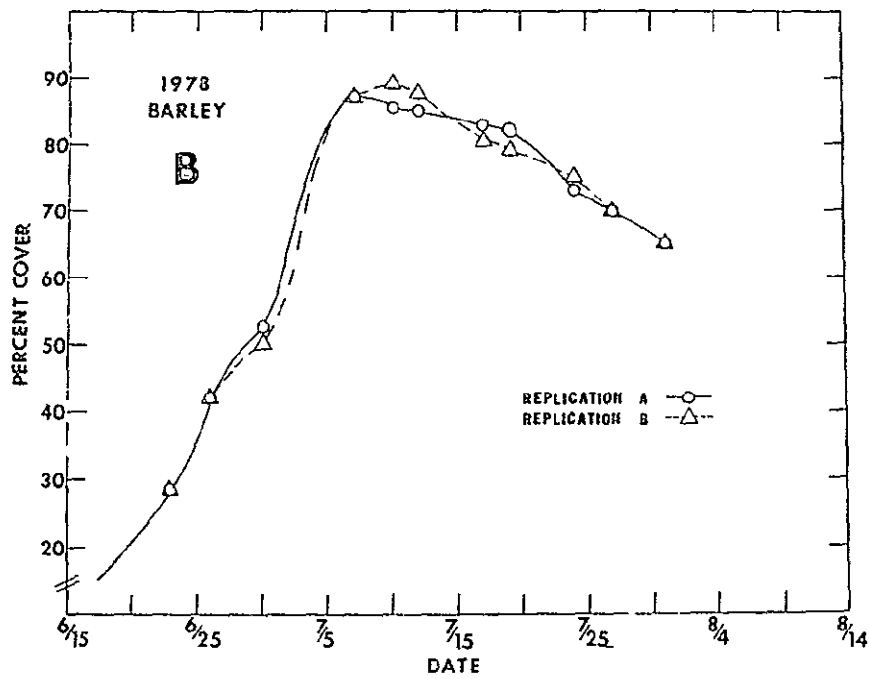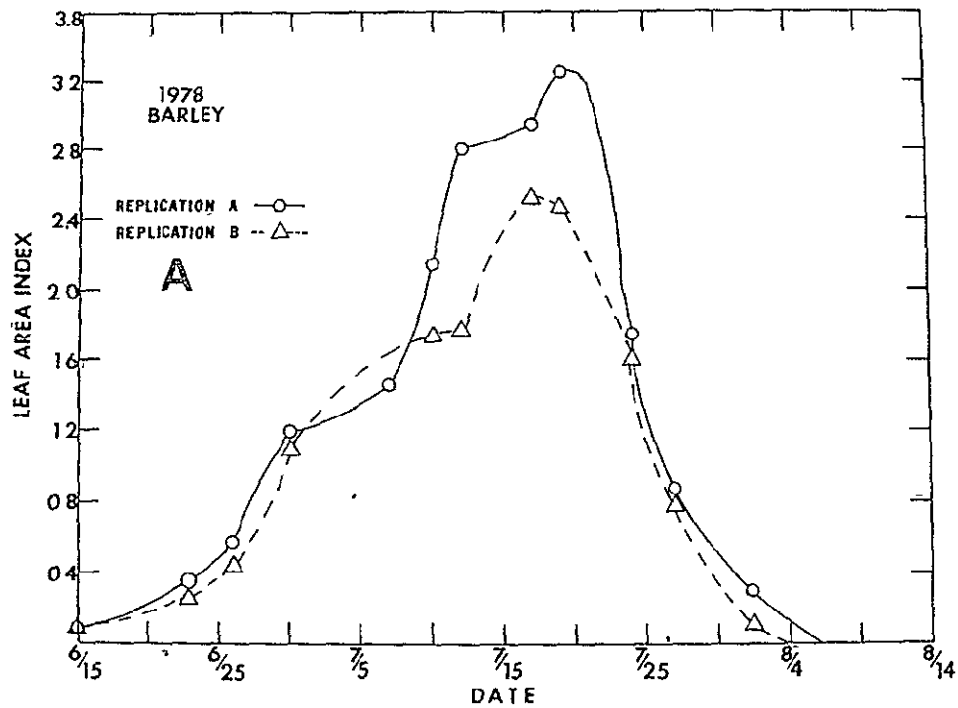
Fig. 1. Seasonal variations in leaf area index (A) and percent
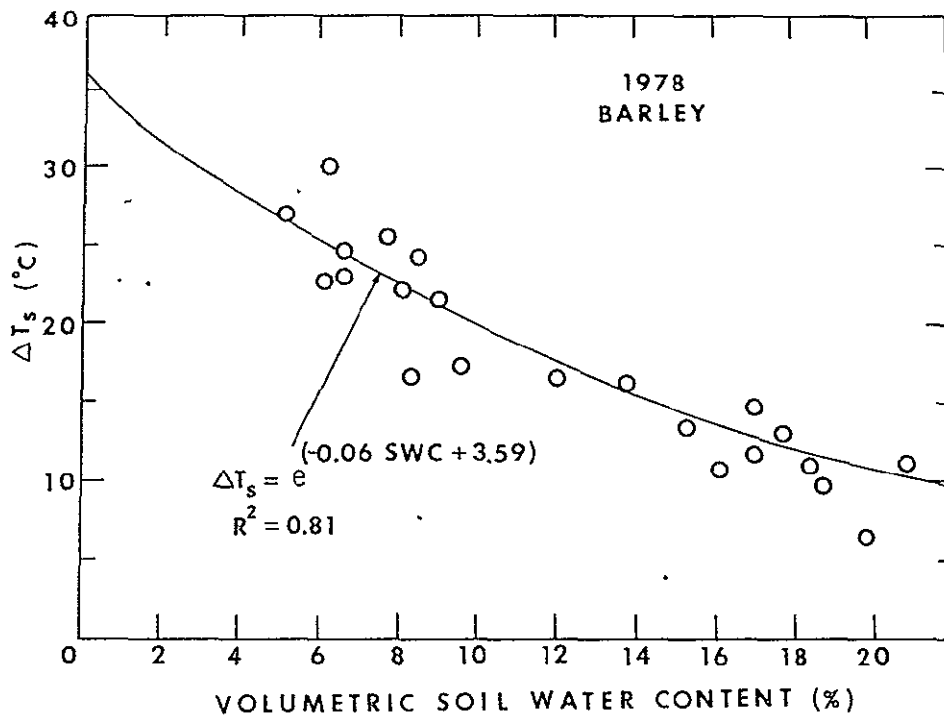   cover (B) of the barley canopy.

Fig. 2. Relationship of the difference (ΔT_s) between soil surface
temperatures measured at 1330 and 0230 local standard time
and the average 24-hr volumetric soil water content (SWC)
in the 0 to 4-cm layer of the profile. Correlation was
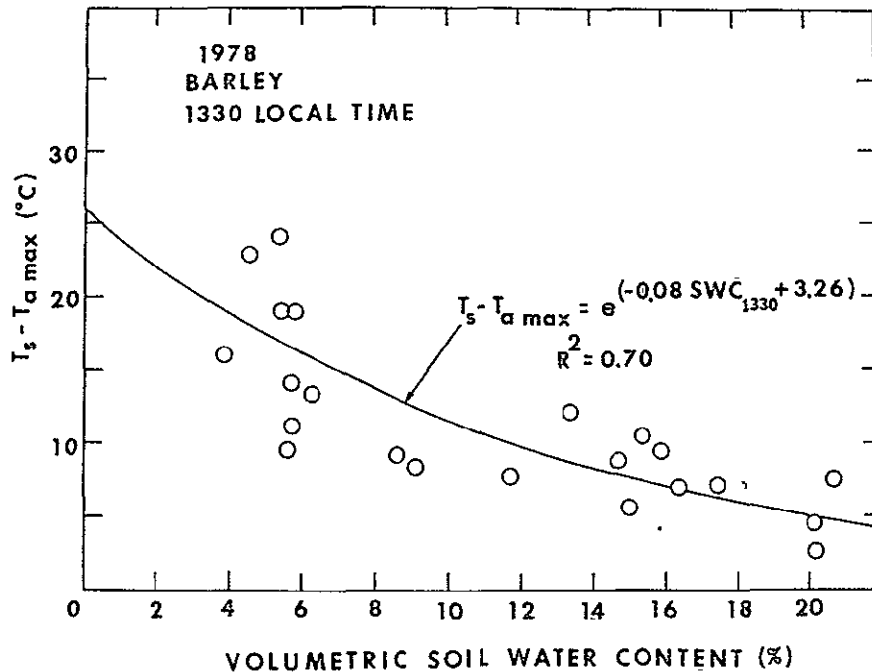significant at the 0.01 level with 20 df.

Fig. 3. Relationship of the difference between surface soil temperatures (T_S) measured at 1330 local standard time and maximum daily air temperature ($T_{a\ max}$) to the volumetric soil water content at 1330 local time (SWC_{1330}) in the 0 to 4-cm soil profile layer. Correlation was significant at the 0.01 level with 20 df.
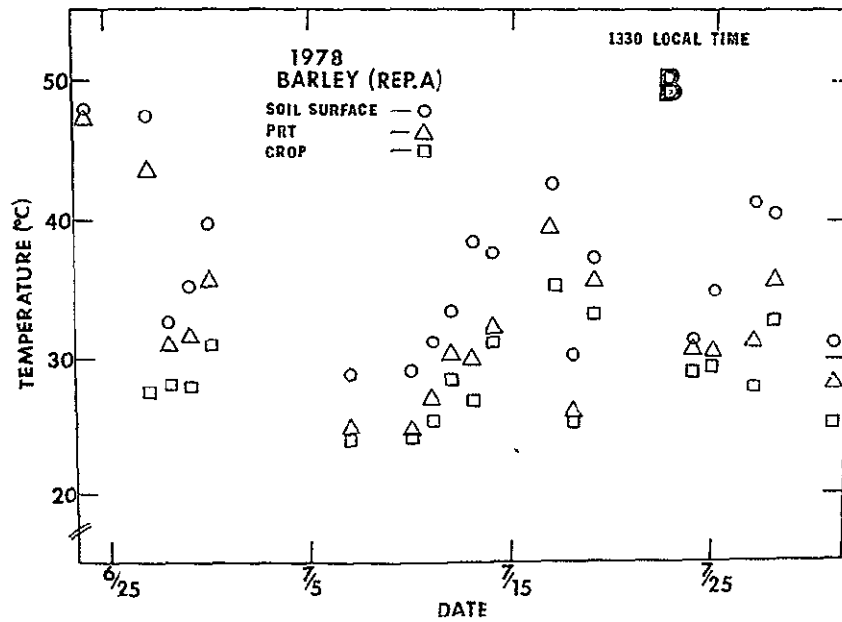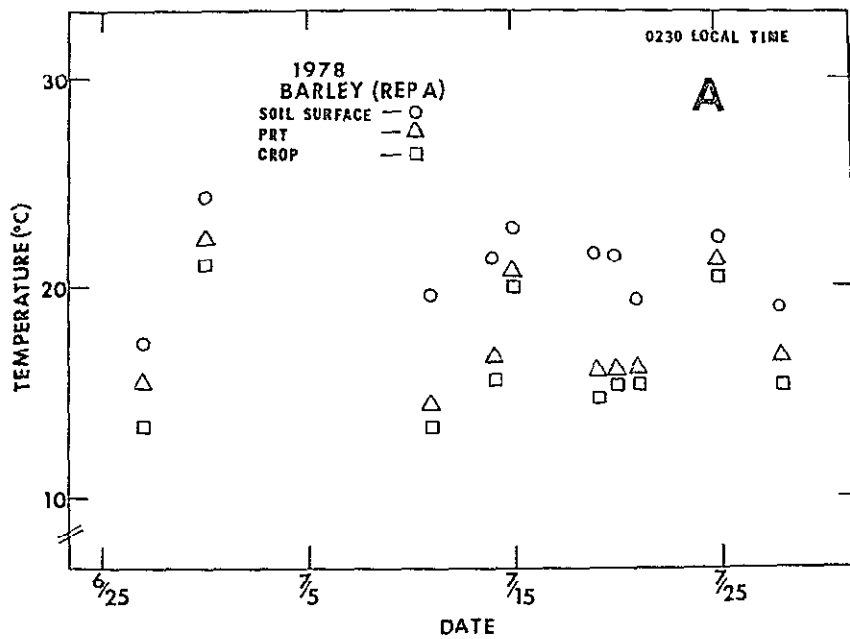
Fig. 4.   Comparison of soil-surface (1-mm below surface), apparent
          canopy (PRT), and apparent crop temperatures measured at
          0230 (A) and 1330 local standard time (B). Canopy
          temperatures included emittance contributions from the
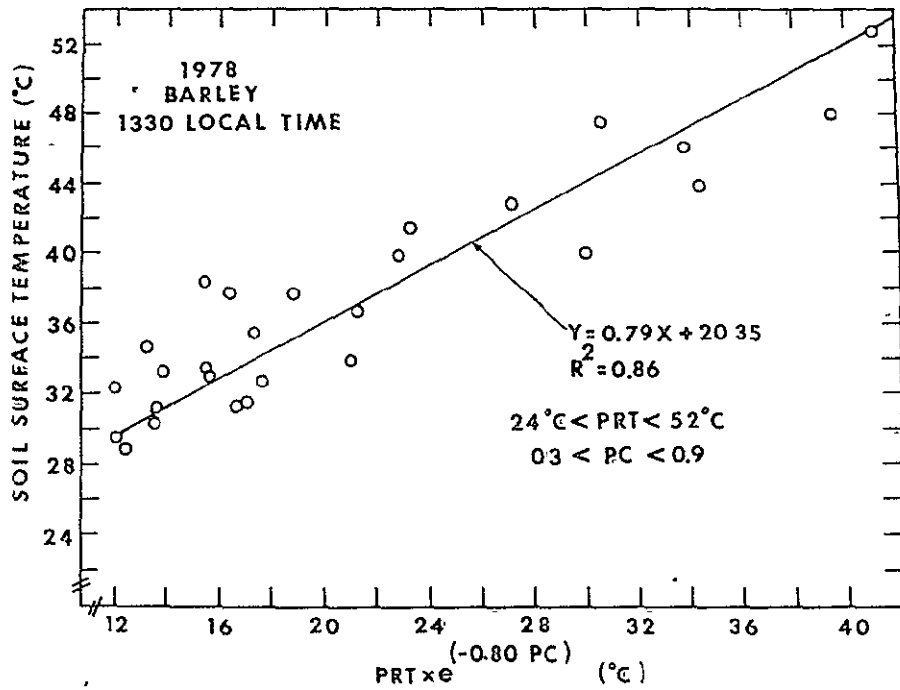   crop and soil background.

Fig. 5. Relationship between surface soil temperature at 1330 local standard time and a multiplicative function of apparent canopy temperature (PRT) and percent cover (PC). Correlation was significant at the 0.01 level with 25 df.
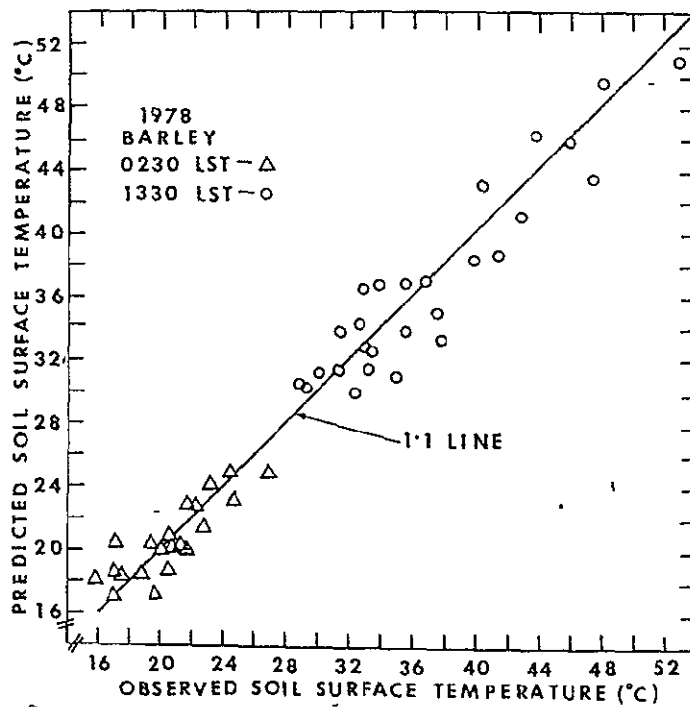
Fig. 6.   Comparison of predicted and observed values of surface soil
temperature at 0230 and 1330 local standard time (LST).
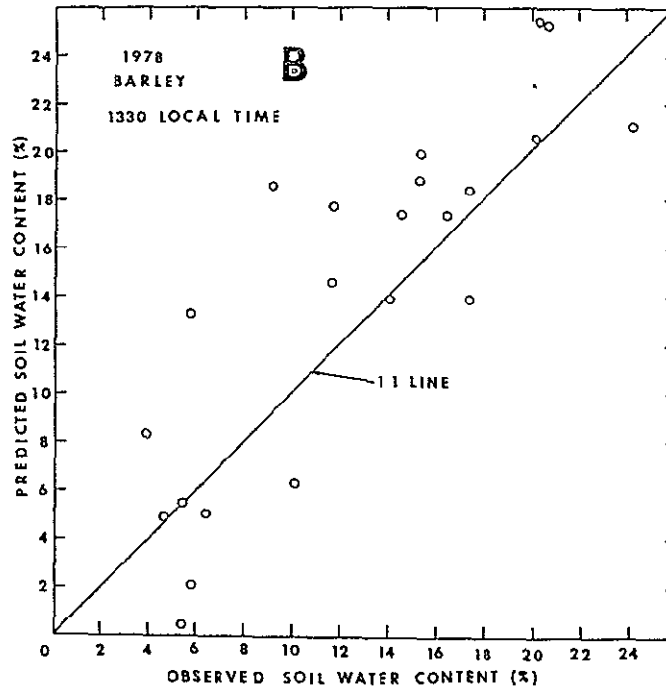Temperatures were predicted using equations (3) and (4).
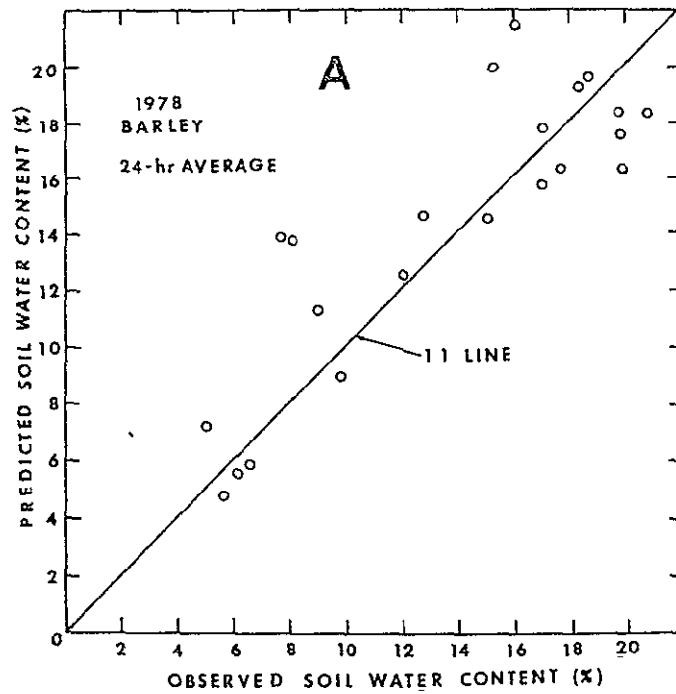
Fig. 7. Comparison of predicted and observed values of 24-hr average
         volumetric soil water content in the 0 to 4-cm layer of the
         profile (A), and the volumetric soil water content in the
         0 to 4-cm layer at 1330 local standard time. Predictions were made
         using equations (1), (3), and (4) for A, and equations (2)
         and (4) for B.