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Thermal Infrared for Soil Temperature Studies

Soil thermal relations are involved in questions of irrigation and drainage, evaporation from soil and water surfaces, heat accumulation in forests, etc.

(Abstract on next page)

INTRODUCTION

THE MAIN SOURCE OF energy for heating soils is solar radiation, much of which is absorbed by the soil and is converted into thermal energy. Physical, chemical and biological processes in the soil are affected by temperature (Smith, et al. 1964). The seed germination of most cultivated plants depends on the soil's temperature and water content. Temperature affects the growth cycle and productivity of plants. Different soils have peculiarities of soil temperature caused by various layers of the soil strata (Shul'gin, 1965). Soil thermal relations are involved in questions of irrigation and drainage, evaporation from soil and water surfaces, heat accumulation in forests, and in many other problem areas (Chudnovskii, 1962; Reifsnyder, 1965).

Soil is incredibly complex in formation, stratification, organic and mineral content, and fertility. Remote sensing measures surface phenomena, primarily, but seems promising for measuring some subsurface soil properties and transient soil conditions. In this respect, surface soil conditions† are frequently indicative of subsurface conditions. The investigation described here is intended as initial evidence that soil characteristics influence the thermal regime of soils in a manner which can be helpful to the soil surveyor.

FACTORS AFFECTING SOIL TEMPERATURE CHANGES

Many factors influence the amount of radiation that reaches the earth and is retained. Radiation from the sun passes through the space between the sun and earth's atmosphere practically undiminished and unaltered. However, in passing through the atmosphere, certain wavelengths of the spectrum are absorbed and others are attenuated, weakening the solar flux that reaches the earth. Then, according to Baver (1956), certain factors affect the amount of radiation that impinges on (or is retained) per unit area, such as slope, direction of exposure, nature of the soil and vegetation, elevation, latitude, and others.

The effect of latitude on the angle at which

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† "Surface soil conditions" as used here means surface granular soil and/or aggregate, and voids, the combination of which influence the reflectance or absorptance of solar energy.

the sun's rays strike the earth is well illustrated by differences in soil temperature between arctic and tropic regions. Even though days and nights may be of equal lengths in both regions at certain periods of the year, latitude has an enormous effect upon the soil temperature. Dynamic thermal changes within soil profiles—diurnal, seasonal, and annual—greatly strengthen the opportunity for thermal infrared sensing, provided that the soil properties causing the changes can be identified.

ABSTRACT: *Seasonal remote sensing flights by NASA and the University of Michigan were made over an area of alluvial soils. Detailed soil surveys were related to thermal infrared imagery in a manner which shows that surface soil temperatures can be indicative of subsurface soil conditions. The warming and cooling of soil depends on many factors. The specific soil characteristics that most influence heat transfer and storage are water content, size of soil particles and pore space. The time of diurnal and the season can be important factors in conducting remote sensing missions. Thermal infrared sensing gives a qualitative indication of soil water in approximately the top 50 cm. of bare soil. The magnitude of diurnal temperature oscillations can also be an indicator of soil moisture content. Thus thermal imagery can be valuable for management of farm resources. The investigation described is intended as initial evidence that soil characteristics influence the thermal regime of soils in a manner that can be helpful to the soil surveyor.*

Soil water is the most important factor influencing thermal characteristics of the soil. When soil water content is low, a water content increase results in a substantial conductivity increase, but the increase lessens as water content rises due to the dependence of thermal conductivity on heat capacity which also changes with changes in water content. The variations in thermal characteristics due to variations in water content may reach 1,000 percent for certain soils.

The size of soil particles considerably influences heat transfer. Chudnovskii (1962) demonstrated a variation of 400 percent in thermal conductivity of three kinds of soil; sand, chernozem loam, and podzolic loam. The more the soil is dispersed, the lower is its calorimetric conductivity (Chudnovskii uses the term dispersion as being synonymous with particle size). The greater the content of clay particles relative to sand, the smaller the thermal conductivity will be for the solid phase.

As porosity increases, air content increases, and soil conductivity decreases. But the heat conduction coefficient for the solid soil phase is 100 times higher than that for soil air. Thus porous soils show much lower heat conduction than nonporous soils. Molga (1962) demonstrated that the rates of heat conduction for soils drop most intensively when soil porosity increases from 30 to 40 percent. The porosity of fallow soil is 30 to 40 percent, and that of freshly tilled soil is over 60 percent. Chudnovskii (1962) conducted experiments which show the dependence of thermal conductivity on porosity, and which indicate the same hyperbolic curve for quartz sand, chernozem and podzolic loam.

Many other factors influence soil temperature; however, their effects are generally less than those already discussed. Relief has a considerable effect on soil temperature, largely as a result of slope exposure. Topographic shape is also important, because daylight warming and night cooling are strongest on concave features of relief (valleys) and least on convex features (ridges), because of intensity of air mixing. During the period of heat intake a ridgy surface warms up more than a level surface, but at night ridgy surfaces lose heat faster. Soil color also affects soil temperature to some extent.

The transfer of thermal energy by radiation to or from a soil depends on the absolute temperature and the thermal radiation properties of the material. Because no theory exists for the precise calculation of these properties, it is necessary to measure the properties under controlled conditions.

PROCEDURE

An alluvial floodplain soil site, located adjacent to the Rio Grande was selected for the thermal infrared soil study. The site is shown in Fig. 1, which is a panchromatic aerial photograph. Soils of this area vary con-

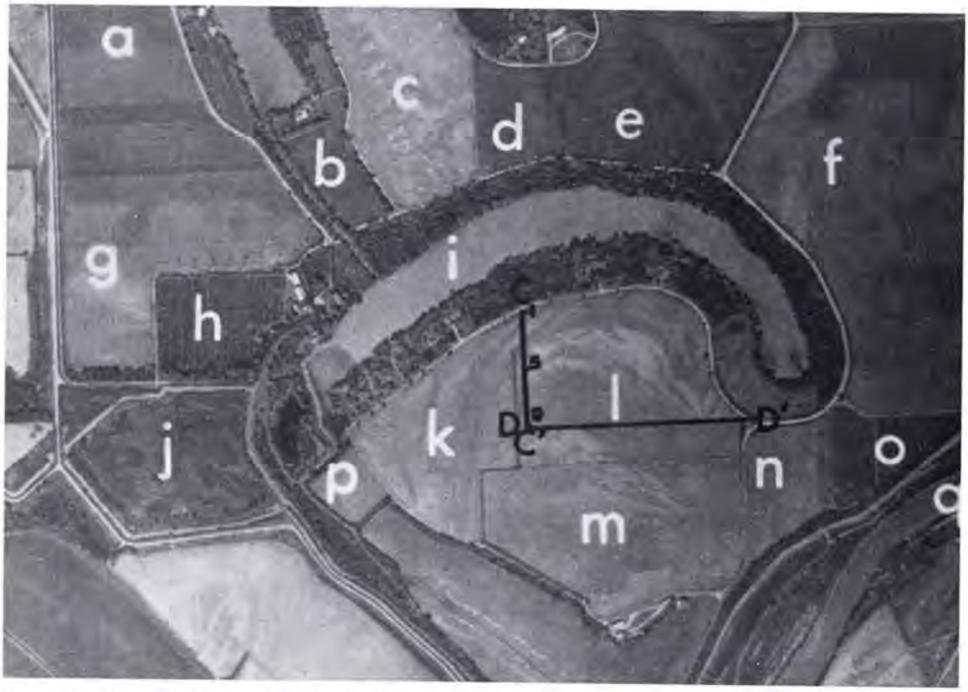

FIG. 1. Panchromatic photograph of Moon Lake agricultural area with letter identification of fields and other features. Section *C-C'* and *D-D'* are soil sampling transects. Lower Rio Grande Valley of Texas.

siderably in texture and in profile conditions. The fields of Figure 1 are identified as follows:

AREA	LAND USE
a	young vegetables
b	young vegetables
c	bare soil
d	cotton
e	cotton
f	young sorghum
g	young citrus
h	mature citrus
i	water
j	swamp
k	bare soil
l	bare soil
m	bare soil
n	bare soil
o	cotton
p	young sorghum
q	river

Seasonal remote sensing flight missions were flown on May 14, the week of May 29, and July 8. Diurnal missions were flown on June 1, 1966. The missions on May 4 and July 8 were flown by the National Aeronautics and Space Administration. The diurnal mission of June 1 was flown by the University of Michigan.

The University of Michigan C-47 aircraft was equipped with multispectral scanners which record analog signals on magnetic tape. The tape-recorded data were later played back to produce film strip imagery. The 8–14 micron (μ) wavelength imagery was used in these studies. Missions were flown at an elevation of 2000 ft.

A transect of 16 soil sampling sites (section *C-C'* of Figure 1) extended across a bare soil area varying in surface and subsurface soil characteristics. The soils vary in texture from fine sand to silty clay. Stratification is extensive, with abrupt changes occurring in short distances. Soil moisture contrasts in fields resulted from timing of irrigations. The purpose of studying the soils in the transect was to relate the soil characteristics, where possible, to the diurnally flown thermal imagery. Figure 2 shows soil profiles from nine of these sites spaced at 50-ft (15.25-m) intervals across 400 ft (122.3 m) of the transect.*

Six soil sites were selected in another field not shown on the accompanying imagery; those sites had considerable variation in soil texture. Soil particle size distribution was measured for the 0- to 1-ft (0- to 30.5-cm)

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* Credit is given to Charles Thompson, formerly Area Soil Survey Supervisor, U. S. Soil Conservation Service, for the soil survey and interpretation.

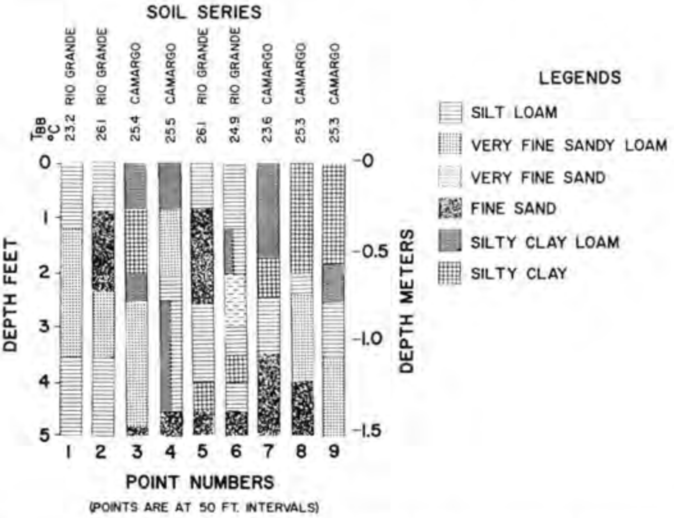

FIG. 2. Soil profile descriptions of 9 sites located 50 ft. (30.5 m) apart along transect *C-C′* of Figure 1.

and 1- to 2-ft (30.5- to 61.0-cm) depths for each of the six sites.

Thermal infrared imagery was gathered for a number of fields having various amounts of crop cover to study the relation between indicated temperatures of cropped areas having various amounts of exposed soils. Most fields were in cotton; however, three were in sorghum and one was in mustard greens.

Diurnally flown thermal imagery transparencies were scanned with an isodensitracer (IDT) to determine values of optical density *D*. Microdensitometer traces of selected isodensitracing scan lines were made.

The relation between ground-truth temperature and film-optical density was established at a well-instrumented site several miles away which was flown only a few minutes earlier, in each instance, with the same scanner electronic-gain setting.† Data from the calibration site were used to plot a graph of ground-truth temperature versus film density. The relation was linear in every case and enabled the conversion of the optical film densities to equivalent blackbody temperature T_{BB} for the June 1 and July 8, 1966 missions.

RESULTS AND DISCUSSION

Prints of diurnally flown thermal imagery of the area shown in Figure 1 are shown in Figure 3. Each of the corresponding transparencies was scanned with an isodensitracer to determine film densities. An isodensitracing of the 1900-hr thermogram is shown in Figure 4. Temperatures at 30 selected sites in the agricultural area are shown on Figure 4. The values of T_{BB} were obtained from the plotted graph showing the relation between T_{BB} and film optical densities. The diurnal imagery was produced by a line-scan imager which generates the image line by line. The distortion in the images is due to irregular aircraft motion. Lightest areas on the imagery represent the areas of highest temperature. A resaca (isolated water body) appears in the center of the thermal imagery. Because the water temperature is relatively stable, the thermal imagery shows it to be warmer than bare soil in the early morning (0615 hr) and evening (1900 hr), but cooler than bare soil at 1400 hr.

The isodensitracer automatically scans the film transparency and plots the measured density values in a quantitative two-dimensional isodensity tracing of the scanned area. The optical system of the IDT automatically probes the entire specimen area by making a series of closely spaced parallel scans. For each scan of the specimen a corresponding coded parallel line is recorded forming a contour map of the scanned area. The code in the recorded lines indicates precisely the amount of film density *D* change and shows whether *D* is increasing or decreasing. If film density continues to increase or decrease, the

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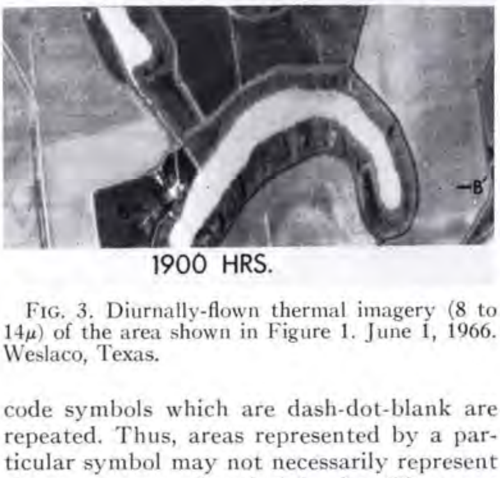
† These unpublished data furnished by Craig L. Wiegand. See also C. L. Wiegand, M. D. Heilman, and A. H. Gerbermann. Detailed plant and soil thermal regime in agronomy. Proc. 5th Symp. Remote Sensing of Environment, Univ. of Michigan, Ann Arbor, April 16–18, 1968. pp. 325–342.

0615 HRS.

1400 HRS.



1900 HRS.

FIG. 3. Diurnally-flown thermal imagery (8 to 14μ) of the area shown in Figure 1. June 1, 1966. Weslaco, Texas.

code symbols which are dash-dot-blank are repeated. Thus, areas represented by a particular symbol may not necessarily represent the same ranges of optical density. They may be 3, 6, or more density steps away. The coded areas can be interpreted easily from microdensitometer traces of isodensitracer scan lines (Figure 5). A microdensitometer trace is an *X-Y*-coordinate trace of film density along that scan line.

The soil profiles show interesting correlations with surface soil temperatures shown in the thermogram of Figure 3. Figure 6 shows a microdensitometer trace along section *C-C'* (Figure 1) from the imagery flown at 1900 hr. Imagery flown at 0615 hr shows little variation of temperature across the field, which is to be expected. Limited temperature contrast appears along transect *C-C'* in the imagery flown at 1400 hr; however, contrasts for this flight time appear greater in other fields where surface textures also have greater contrast. In the morning and early afternoon hours when only a portion of available heat has entered the soil profile, and when positive or downward heat exchange is occurring, only the shallower soil characteristics have influenced surface soil temperature.

During the evening and night, however, negative heat exchange occurs and is influenced by soil properties in about the 0- to 50-cm depth. The equivalent blackbody temperatures along transect *C-C'*, shown by the microdensitometer trace of Figure 6, and above the soil profiles of Figure 2, were related to soil texture and layering. In general, the sites with coarser-textured profiles (containing zones of fine sand) had the highest temperatures at 1900 hr. A microdensitometer trace along transect *D-D'* (Figure 6) showed a decrease in temperature from *D'* to *D*. Eleven soil profiles taken along this transect (not included in the paper) showed that the soils of coarser texture were along the east end of transect *D-D'*. As in the case of soils along transect *C-C'*, surface soil temperatures at 1900 hr were highest for profiles of coarsest texture.

Further evidence of the influence of soil texture on surface soil temperature is apparent in the data of Table 1 where soil particle size distribution for the 0- to 1-ft (0- to 30.5-cm) and 1- to 2-ft (30.5- to 61.0-cm) depths at six soil sampling sites are shown. Each soil sample analyzed was a composite of three separate samples. The sites were selected in a field (not shown on the accompanying imagery) which had considerable variation in soil texture. Surface soil temperatures for the sites also are shown. Imagery used to obtain blackbody soil temperatures was from the June 1 and July 8, 1966 missions.

The data of Table 1 show that sites *A* and *F*, which are highest in sand content, were warmer than predominantly clay sites at the 1400 flight time on June 1. Site *A* was warmer than the predominantly clay sites at the 1900 flight time. The temperature contrasts between the sites having sandier profiles and those having more silt and clay were considerably greater during the 1400 hr flight than during the flight at the 1900 hr.

SOIL MOISTURE DETECTION IN BARE SOIL

A qualitative indication of soil moisture condition in approximately the top 50 cm of bare soil can be valuable for management of

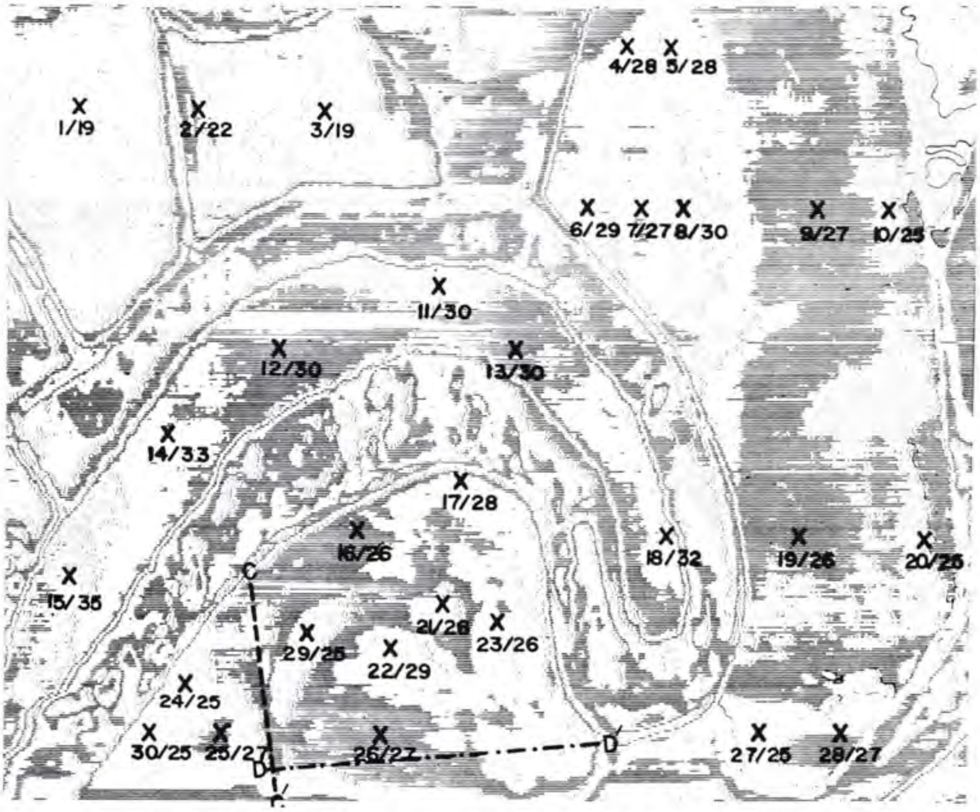


FIG. 4. Isodensitracing, Moon Lake area, June 1, 1966 (8 to 14μ) 1900 hr, 2000 ft. (Legend: 31/39 = Site number/Degree centigrade).

farm resources. Fields *k* and *l* shown in Figure 1 are good examples of bare fields with soil moisture differences that can be detected with thermal IR sensing. The 0615 hr imagery of Figure 3 showed a temperature contrast averaging about 3°C between the fields, field *l* being the warmer. None of the imagery from wavelengths other than thermal IR revealed any contrast between these fields. Also, thermal IR for the 1400 and 1900 hr missions showed no contrasts.

Field *k* had less moisture within the top 50 cm than field *l*. As moisture in a soil serves as a heat sink due to the high specific heat of water compared to air, temperature of soil with higher moisture content would fluctuate less over a given period of time. Thus, in early morning, moist soil would have a higher surface temperature than a drier soil.

Soil moisture data were not available for fields *k* and *l* for the date on which the thermal imagery was generated; however, information was available to indicate the general moisture condition of the fields.

Extensive root systems of plants such as mesquite trees often extend into fields for a considerable distance. This results in excessive withdrawal of moisture and plant nutrients, frequently resulting in poorer crops. Sites 16 and 24 in fields *k* and *l* (Figure 4) are examples of this condition. Around midday the temperatures for these sites were about 4°C higher than sites not close to natural heavily vegetated areas. The higher temperature indicated drier soils.

DIURNAL TEMPERATURE OSCILLATIONS

Diurnal oscillation of temperature can be a good indicator of gross soil moisture conditions. Sites 24 and 25, which are in a relatively dry field, had maximum diurnal temperature oscillations of 51 and 45°C, respectively, determined by taking the difference between the 1400 hr and 0615 hr temperatures. Sites 21, 22, and 23, which are in a field with more moisture, had maximum diurnal temperature oscillations of 42, 41, and 40°C, respectively.

TABLE 1. PARTICLE SIZE DISTRIBUTIONS AND RELATED SURFACE TEMPERATURES FOR SOIL FROM SITES ON MOON LAKE THERMAL SOIL STUDY*

Site	*Depth*	*Particle size distribution*†			*Flight time*	*Surface soil temp.*
		Sand	*Silt*	*Clay*		
	cm		– – *per cent* – –		*hr*	*C*
A	0–30.5	49.6	27.0	23.4	1400	62
	30.5–61.0	44.6	37.0	18.4	1900	24
B	0–30.5	16.2	53.4	30.4	1400	52
	30.5–61.0	11.8	44.8	43.4	1900	21
C	0–30.5	6.8	61.8	31.4	1400	55
	30.5–61.0	8.8	58.8	32.4	1900	21
D	0–30.5	47.4	14.2	38.4	1400	—
	30.5–61.0	7.8	44.8	47.4	1990	23
E	0–30.5	11.8	32.4	55.8	1410	49
	30.5–61.0	7.0	28.8	64.2		
F	0–30.5	46.2	26.4	27.4	1410	60
	30.5–61.0	66.2	18.4	15.4		

* Site E and F were obtained from NASA imagery flown on July 8, 1966 All other sites were flown on June 1, 1966.

† Particle size distribution determined using the Bouyoucos method (Day, 1965).

THERMAL INFRARED DETECTION OF PERCENT CROP COVER

Figures 7 and 8 show results obtained from thermal IR remote sensing imagery of a number of fields with varying amounts of crop cover. Most fields were cotton; however, three were grain sorghum and one was mustard greens. Crop cover ranged from 15 percent to 100 percent. The imagery was gathered during the 1400 and 1900 hr flights of the three-flight diurnal mission flown on June 1, 1966.

Imagery obtained during the early morning flight at 0615 hr did not show a relation between film density and percent cover; therefore, the results are not shown. In Figures 7 and 8, a negative correlation significant at the 1 percent level is shown between plant cover and T_{BB} for cotton and sorghum fields for two flight times at 1400 and 1900 hr. An average of about 50 percent of the variation was accounted for by this relationship.

It is not always possible to distinguish crops from soils on panchromatic photography or on imagery from other wavelengths. But, with the possible exception of fields with

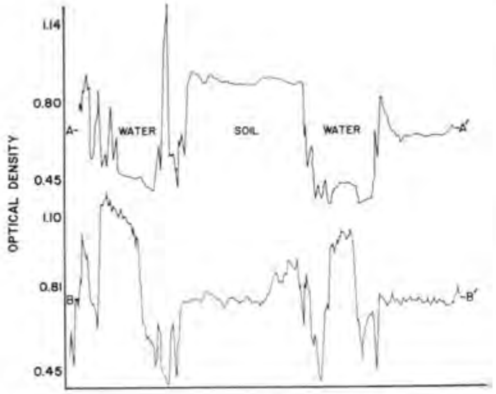


FIG. 5. Microdensitometer traces for transects *A-A'* and *B-B'* of Figure 3.

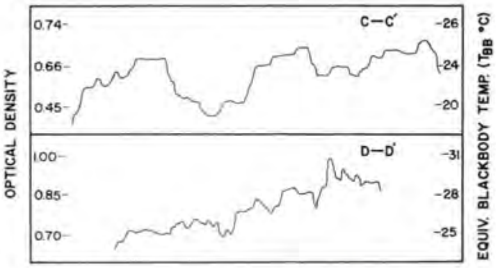


FIG. 6. Microdensitometer trace of transects *C-C'* and *D-D'* shown in Figure 1.

very sparse or very young vegetation or soils recently irrigated, soils can be distinguished from crops on thermal imagery flown at 1400 and 1900 hr. At 1400 hr bare soils had a temperature range of 55 to 66°C whereas crops ranged from 35 to 40°C. At 1900 hr bare soils had cooled to 25 to 30°C; however, crops had decreased to a range of 19 to 22°C.

FACTORS INFLUENCING TIME OF SENSING

During daylight the variations of heat exchange follow those of solar radiation. The time when heat exchange becomes negligible coincides more or less with sunrise and sunset. Thermal sensing of soils is most revealing at night when differential thermal conductivity and heat storage characteristics of soils cause surface temperature contrasts. Thermal sensing of soils at night shows contrasts indicative of profile conditions. After sundown heat flow is upward and varies with soils, depending on their respective heat storage capacities and thermal conductivities. Although early evening imagery at 1900 hr was involved in this study, more recent studies show that imagery generated several hours later usually shows surface contrasts even more indicative of subsurface conditions.

Diurnal oscillations of temperature in a moist soil are less than in dry soil. These studies lead one to conclude that thermal imagery of well-drained topsoils versus poorly-drained topsoils may show temperature differentials.

Studies by Shul'gin (1965) and others have shown that soil depths of constant daily and annual temperatures are in the ratio of the square roots of oscillation periods. Because these are one day and one year, the depth of damping of annual oscillation exceeds the depth of damping of diurnal oscillation by a factor of 19. Studies such as those described in this paper can probably be strengthened by seasonal sensing which may detect soil thermal contrasts indicative of conditions at depths substantially deeper than those indicated by diurnal sensing. The annual course of heat exchange shows another peculiarity. The greatest positive heat exchange occurs in spring and in early summer; the greatest negative heat exchange in early winter. Therefore, seasonal thermal soil sensing in the spring and in late fall or early winter can be very productive. More uniform soil moisture conditions, conducive to proper image interpretation, will probably occur at one time or the other, depending on the location.

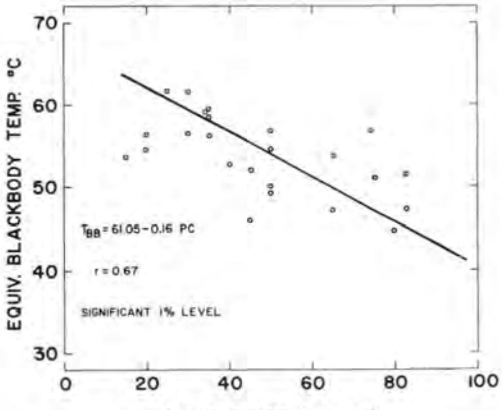


FIG. 7. Relation between equivalent blackbody temperature of selected sites and per cent plant cover. Flight mission, 1400 hr, June 1, 1966.

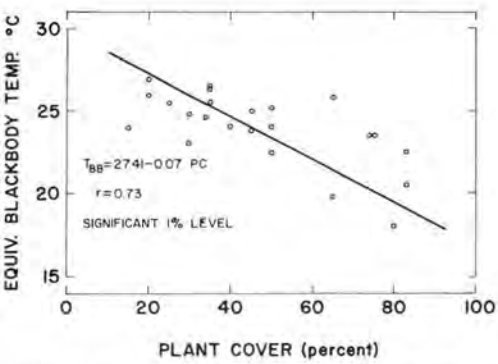


FIG. 8. Relation between equivalent blackbody temperature of selected sites and per cent plant cover. Flight mission, 1900 hr. June 1, 1966.

CONCLUSION

Association of surface temperatures with as many soil characteristics as possible enhances the opportunity for using remote sensing to help identify the responsible soil factors. Diurnal, seasonal, and annual thermal changes within soil profiles strengthen the opportunity for thermal infrared sensing, provided that soil properties causing the changes can be identified.

To take full advantage of remote sensing techniques in identifying soil characteristics, one must be able to recognize tonal patterns, texture, cultural condition, and subsurface conditions where possible. There are limitations to the amount of discrimination that is possible on conventional black-and-white photographs. A multispectral approach, using thermal infrared sensing as a supplement to color and black-and-white photography, has advantages over the use of any one approach in solving such discrimination problems.

Much progress has been made in studying thermal characteristics of soils and soil-water-plant systems. However, remote thermal detection of soils and their characteristics is in its infancy. A great deal of dependable work must be done on well-defined systems. Laboratory models with variables consisting of various soil textures, combinations of layering, moisture levels, and others under controlled variable illumination—carefully instrumented to measure heat flow and storage—will help to establish guidelines. Also, empirical field studies such as those described in this paper are needed to define the problem involved, and point to solutions.

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