J. VLCEK
D. KING
Faculty of Forestry
University of Toronto
Toronto, Ontario M5S 1A1, Canada

Detection of Subsurface Soil Moisture by Thermal Sensing: Results of Laboratory, Close-Range, and Aerial Studies

The relationship between diurnal surface soil temperature variations and subsurface soil moisture was investigated.

ABSTRACT: *Close-range and airborne thermal studies as applying to the thermal inertia concept for moisture detection are presented. The relationship between the diurnal surface soil and/or canopy temperature variations and soil water content in near-surface layers was investigated. For the surface layer, the relationship was found to be curvilinear as theoretically predicted. With increasing depth it tends to be linear but it deteriorates gradually with depth until it breaks down at about 9 cm. Studies over fields covered by small tree seedlings in a forest tree nursery gave similar results. Related to the study, artificial and natural drainage patterns were analyzed using thermal images, and it is suggested that such images could be useful in studying subsurface water migration and more efficient design of drainage structures.*

INTRODUCTION

SOIL MOISTURE affects the physical properties of soil related to both engineering applications and plant life. Several remote sensing methods have been applied to survey soil moisture over large areas: aerial photography, thermal imaging, and microwave imaging. Each has certain advantages and limitations. This paper is a contribution to the application of thermal imaging, both close-range and aerial, to detect variations in surface and subsurface soil moisture.

Initial studies of the relationship between soil moisture and bare soil surface temperature variations were carried out using ground-based measurements (Idso *et al.*, 1975). The data were later extended to incorporate airborne data using surface temperatures derived from thermal scanner measurements (Reginato *et al.*, 1976; Schmugge, 1978). These studies presented results showing a linear or near-linear relationship between the diurnal surface soil temperature variations and soil moisture in the surface, 0 to 2 cm, and 0 to 4 cm layers for a wide variety of textural classes. Cihlar *et al.* (1979) investigated the airborne sensing methods in a similar fashion over fallow fields. The relationship was again studied by Heilman and Moore (1980) for barley covered fields and was found to be more curvilinear than had previously been reported. The theoretical background of this relationship will be briefly discussed in the first section. The second and third sections will describe procedures and present results from two close-range studies and one airborne study conducted for both surface and sub-surface soil layers for bare soil and two vegetative covers of varying density.

REVIEW OF THEORY

Soil surface temperature is a function of both meteorological conditions and soil heat transfer prop-

0099-1112/83/4911-1593$02.25/0

erties, primarily thermal inertia, which is a measure of the thermal conductivity and volume heat capacity of the combined physical components of the soil. Of these components, the soil air content, which can be varied by either compaction or addition of water, has the greatest bearing on soil thermal properties.

Thermal conductivity and volume heat capacity of various soil textural classes differ on three accounts: (a) different total porosities (percent total volume), e.g., sand has lower total porosity than clay (Hardy, 1980); (b) different soil water distributions in the pores, e.g., thermal conductivity increases much more rapidly by addition of water in sand than clay (de Vries, 1963); and (c) different soil mineral compositions (de Vries, 1963). Consequently, thermal inertia will vary with differing water content, porosity, textural class, and mineral composition.

The application of thermal sensing for soil moisture detection exploits the relationship between soil thermal inertia and the diurnal surface temperature variation. Theoretically, this relationship is nonlinear (e.g., Watson, 1975). Also, thermal inertia is a nonlinear function of near-surface soil water content ($w\%$) (de Vries, 1963). Therefore, the diurnal soil surface temperature difference (ΔT_s) varies nonlinearly with the near-surface soil moisture content. This is borne out by the data of Idso *et al.* (1975), Schmugge (1978), and Heilman and Moore (1980). The non-linearity, however, tends to disappear with increasing depth due to (1) the damping of the temperature gradient and (2) the more constant soil moisture level causing a gradual breakdown of the ΔT_s versus $w\%$ relationship at low depth.

EXPERIMENTAL PROCEDURES

At the University of Toronto we have studied the soil surface temperature—water content relationship using both close-range and airborne thermal scanners in association with contact probes. Moisture sampling was conducted at various depths in separate experiments.

The close-range experiments were carried out using a 2-m by 3-m experimental plot consisting of thermally insulated compartments filled with prepared soil mixtures (Figure 1) of varying characteristics. Surface temperatures were measured using an AGA Thermovision T-750 (Vlcek, 1981) from a 4-m elevated platform with a near-vertical angle of view. Additional soil temperature and meteorological data were obtained using standard equipment and probes. Two soils of four levels of water content each were observed over clear sky diurnal periods.

In 1980, soil moisture content was determined gravimetrically at the 5 to 7 cm depth. No attempt was made in this study to eliminate albedo differences between compartments due to moisture presence at the surface. The ΔT_s versus $w\%$ relationship was found by standard regression techniques.

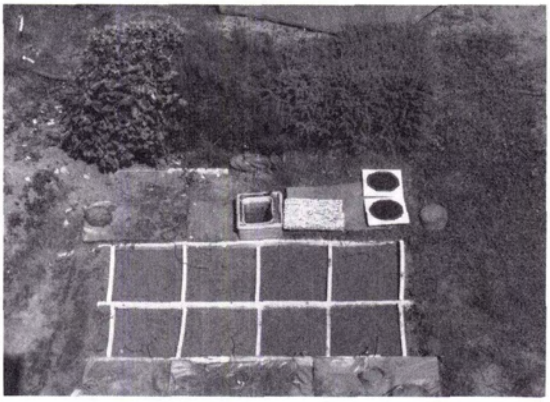

FIG. 1. Thermally insulated 2 m by 3 m experimental plot for close-range studies containing two uniform soil types (sand and sandy loam) which have four moisture contents each.

In the 1981 series, soil moisture sampling was conducted at the 0 to 2, 2 to 4, 4 to 6, and 8 to 10 cm depths using removable water permeable wire-mesh soil cylinders buried in the soil. A uniform 1-cm layer of corresponding dry soil was placed on top of each soil surface at the beginning of the experiment in order to eliminate the albedo differences due to surface moisture. The ΔT_s versus $w\%$ relationship was found for each layer.

Because we still observed minor albedo differences between different soil types, even in a dry state, we designed a controlled laboratory experiment in which we sprayed three types of soils with a uniform coat of black matte paint. The soils were kept in insulated containers and slowly rotated under an illumination source so that they obtained equal amounts of radiation. Their surface temperatures were measured at the end of irradiation and after cooling off.

Three aerial thermal sensing missions including black-and-white and color infrared photography were conducted over a forest tree nursery at Orono, Ontario, during the spring and summer of 1981. Thermal images were obtained at a scale of 1:5,200 while the scale of the 70-mm photography was 1:7,500. The tree nursery was chosen as a site for this study because (a) it consisted of flat rectangular compartments between 1 to 2 ha in size, (b) it presented a wide variety of uniform surface conditions—fallow fields, plowed and tilled fields, and fields covered with planted spruce, pine, and cedar trees ranging in height from 5 cm to 40 cm with a correspondingly varied ground cover—, and (c) it provided an opportunity to study the effects of irrigation.

The soils were light, ranging from sand to sandy loam with some peat admixtures. Soil moisture sampling was carried out at specific locations in the 5 to 7-cm subsurface layer using both gravimetric and neutron probe methods (Schmugge *et al.*, 1980).

Thermally differential targets made of 4 by 4 foot styrofoam sheets covered by crinkled aluminum foil were placed in strategic areas to locate some of the sample points exactly and to provide an opportunity to measure sky radiance. An earlier version of these targets, which featured open squares of aluminum foil appears, in Figure 5 at "c."

Apparent surface temperatures were derived from grey scale analysis of the 8.5 to 12.5 μm midday (ca. 1300 hrs) and predawn (ca. 0600 hrs) thermal images. The diurnal soil temperature difference, ΔT_s, expresses absolute temperature difference on the assumption that the atmospheric transmission properties have not changed (Drummond, 1982). The ΔT_s versus *w*% relationship was determined for July and August and two main cover heights: 5 to 25 cm trees (15 to 40 percent cover) and 10 to 40 cm trees (50 to 90 percent cover). The bare soil compartments had to be omitted from this study because the midday temperatures fell outside the range determined by the blackbody settings.

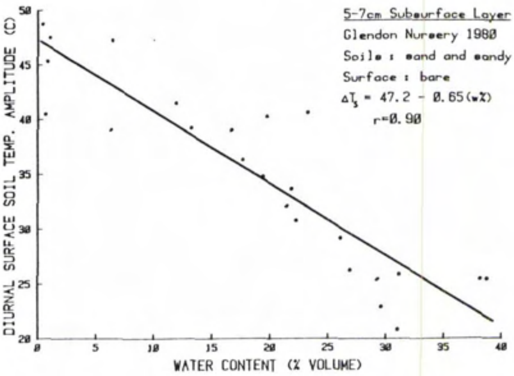

FIG. 2. Diurnal surface soil temperature amplitude versus soil water content between 5 to 7 cm depths.

RESULTS

The results from the close-range studies are given in Figures 2 and 3. Figure 2 shows the ΔT_s versus *w*% (5 to 7 cm) relationship for two soils (sand and sandy loam) based on three repeated experiments using four moisture levels (one per compartment in Figure 1) in each soil. By the diurnal soil surface temperature amplitude is meant the difference between the daytime maximum and the predawn min-

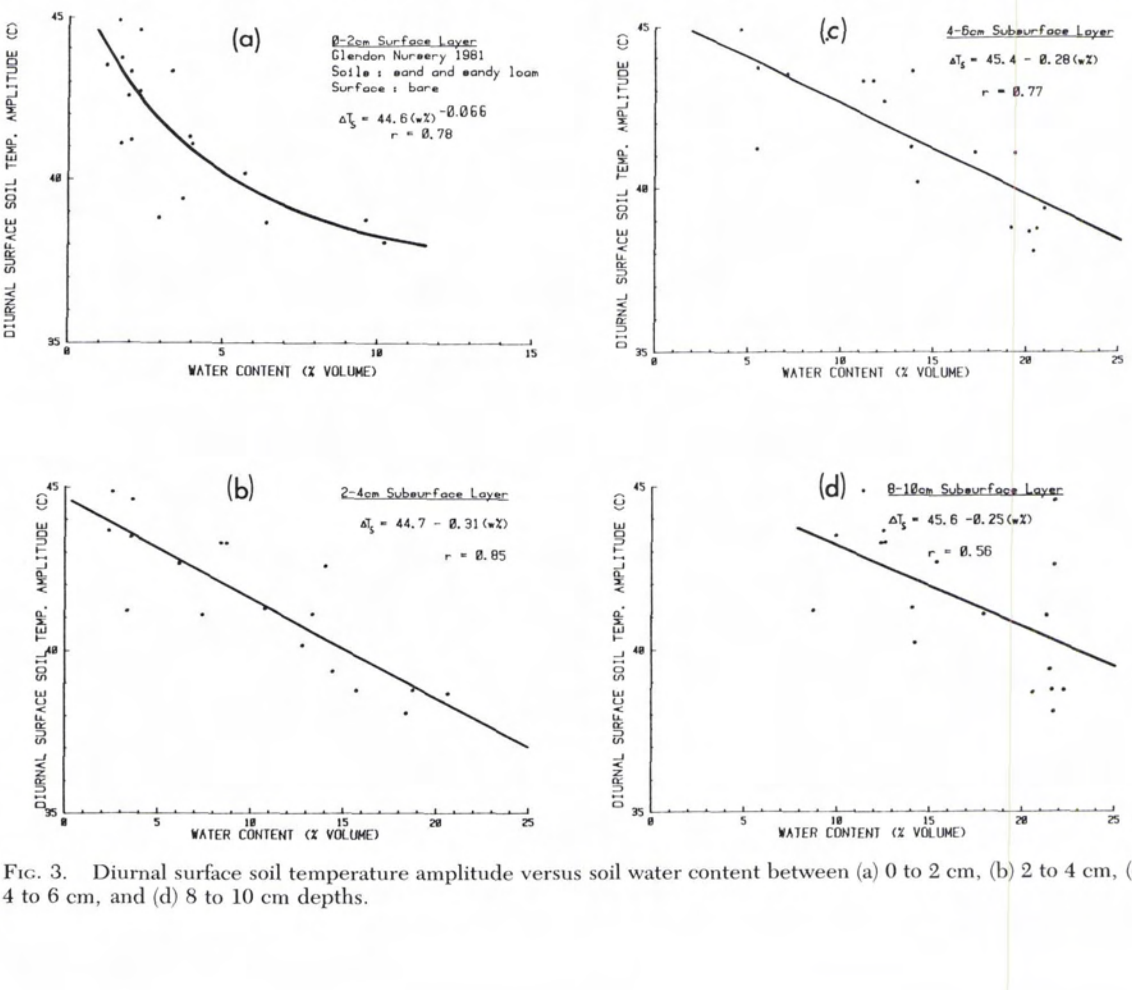

FIG. 3. Diurnal surface soil temperature amplitude versus soil water content between (a) 0 to 2 cm, (b) 2 to 4 cm, (c) 4 to 6 cm, and (d) 8 to 10 cm depths.

imum soil surface temperature (ΔT_s). An attempt to incorporate the effect of textural class differences by expressing volume water content as matric suction (Idso *et al.*, 1975) or as percent field capacity (Schmugge, 1978; Cihlar *et al.*, 1979) showed no improvement in the closeness of fit. However, the results of our controlled laboratory experiment discussed above showed definite inertia differences among the three soil types used at the same moisture levels. Further studies are needed to investigate the effect of soil textural differences. Figures 2a to 2d give the ΔT_s versus $w\%$ relationship for water content at 0 to 2, 2 to 4, 4 to 6, and 8 to 10 cm depths, respectively. The correlation coefficients are not as high as in the previous figure, probably resulting from less accurate depth moisture sampling using the wire-mesh cylinders and from the masking effect of the dry soil layers on the surface of each compartment. Further, Figure 3a shows that, in the surface layer, the correlation is better for a power curve fit than a linear fit as previously discussed. These figures also demonstrate that the relationship deteriorates with depth as moisture distribution becomes relatively uniform and has little direct effect on surface temperatures.

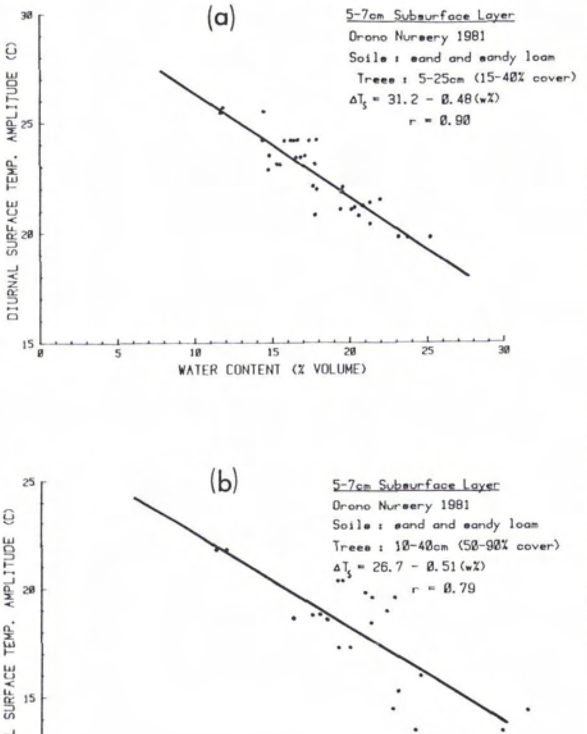

FIG. 4. Diurnal surface soil-canopy temperature amplitude versus soil water content between 5 to 7 cm depths for (a) 5 to 25 cm trees with 15 to 40 percent ground cover and (b) 10 to 40 cm trees with 50 to 90 percent ground cover.

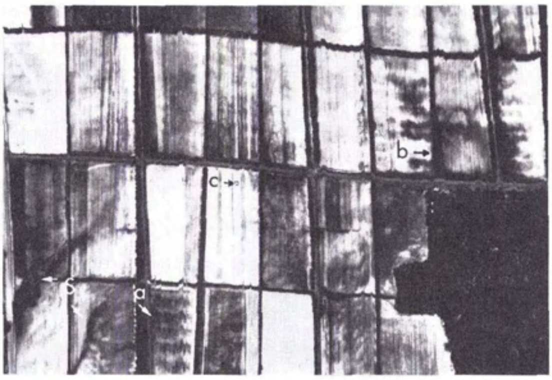

FIG. 5. 2 May, 1981 day-time thermal image of Orono, Ontario, forest tree nursery showing temperature and moisture patterns. Typical field size is 200 m by 90 m.

Results of the airborne missions are given in Figure 4. Graph (a) shows the ΔT_s versus $w\%$ (5 to 7 cm) relationship where the soils were covered by a vegetative layer of 5 to 25 cm height (15 to 40 percent ground cover). Graph (b) presents similar results for 10 to 40 cm tree seedlings with 50 to 90 percent ground cover. The correlations shown are based on sample sizes of between 20 and 40. The results show that increasing canopy density lowers the diurnal soil temperature difference, causing a shift of the curve along the vertical axis and a drop in accuracy of the relationship.

Other results that were not planned for but were obtained in this study are worth brief mention. Figure 5 represents the day-time 2 May thermal image. The quality of this image was affected by a malfunctioning vertical gyro control, resulting in tear between scan lines. It shows one section of the tree nursery pointed to by an arrow at "a" where the effect of an old tile drainage system at an average depth of 60 cm can be seen. Installed to facilitate the use of heavy automated equipment for tree planting and harvesting, the tiles have caused the drainage pattern shown by the stripes at "a." The tile lines can be seen to run parallel to the main service roads. Under the conditions of high surface moisture, the striped drainage patterns can also be seen on black-and-white and color infrared photography. However, what is not visible on the photography is the natural subsurface drainage in the area. At least two different subsurface drainage systems can be identified in the thermal images: (a) one associated with the two surface channel scars at "S" that drain toward the lower left corner of the picture (freshly tilled, light toned fields partially obscure this system at certain locations) and (b) another drainage pattern near the upper right at "b" which drains down into the forested area below the main service road. The road has no culvert, thus acting somewhat as a dam in both systems and causing a build-up of moisture (dark tones) on the upper side of the main service road.

Because the striped pattern caused by the drainage tile is generally oriented at right angles to the natural drainage, it does not take advantage of the natural water pathway as shown on the imagery and is thus less efficient. If this information had been available at the time the artificial drainage was being considered, a better system could have been designed. The striped lines are a combined result of dislocation of natural soil horizons due to ditching and the corresponding change of rate of vertical drainage. This resulted in an unbalanced chemical and physical soil matrix which has led to stunted tree growth along the drainage lines.

Finally, the light permeable soils at the nursery, which are best suited for the development of planting stock and field operations, must be irrigated regularly to meet the water demands of the growing stock. Summer missions thermal images, in this regard, show thermal sensing to be an excellent tool for determining the uniformity of an irrigation system by showing the resulting moisture patterns.

CONCLUSIONS

This paper presents further evidence that diurnal thermal sensing provides a means of quantifying moisture levels in a subsurface layer of soils of the same textural class and under similar weather conditions. The above relationship has been found experimentally even when the surface is covered by a uniform plant growth such as rows of small trees. However, for denser vegetative covers, the relationship is more complex and indirect. The depth at which moisture still significantly affects the surface temperature variations reached 5 to 7 centimetres, which is the root zone for small trees. Thermal imaging can therefore provide useful information not only regarding temperature-moisture relations but also with respect to near-surface water migration patterns. It can serve as a mapping tool that may show moisture deficient areas and therefore be an aid in irrigation and management practices.

ACKNOWLEDGMENTS

The experimental work was supported partially by the National Science and Engineering Research Council of Canada and the Canadian Forestry Service. The airborne data were generated free of charge by the Ontario Centre for Remote Sensing. Appreciation for help and accommodation in this study is expressed to the staff of the Orono Nursery, Ontario Ministry of Natural Resources.

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(Received 9 July 1982; accepted 12 June 1983; revised 14 July 1983)