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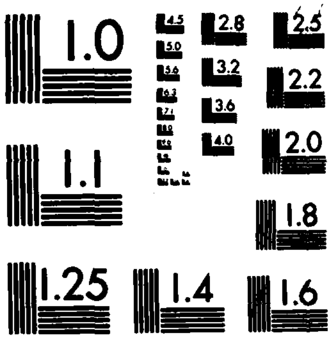

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The effects of soil moisture and vegetation on surface temperature

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April 1983

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U.S. ARMY CORPS OF ENGINEERS
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This report from the Duke University test site augments data collected at the test site of the U.S. Army Engineer Topographic Laboratories (ETL). In an instrumentation sense the two sites are analogous. The Duke University site, however, can provide variations in vegetation cover, is large enough to approximate boundary-free conditions, and has individual test plots of sufficient size to be used in support of aircraft remote sensing missions. Thus, the general purpose of this analysis is to gain a better understanding of how the variable weather conditions in the Eastern United States interact with the soil moisture content

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) and the plant canopy temperature in determining the surface energy balance components on a diurnal and longer periodic basis.

PREFACE

This document is generated under Contract DAAK70-77-C-0210 for the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia 22060 by the School of Forestry and Environmental Studies, Duke University, Durham, North Carolina 27706. The Contracting Officer's Representative is Alan E. Krusinger.

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INTRODUCTION

With the advent of satellites containing visible and infrared data channels, it has become possible to observe large areas of the earth's surface and to measure the energy emitted by the earth-atmosphere system. Agronomists, foresters, engineers, geologists, hydrologists, and meterologists, alike, have found this satellite data useful in their respective areas. For example, satellite data can be used to estimate crop yield; to determine areas of vegetation damage due to disease, drought, or insect infestation (Idso, et al., 1975a); to detect large scale geologic formations; to estimate water supply; and to track storm systems. From the 500- to 600-meter ground resolution of the scanning infrared radiometer data currently available from the Heat Capacity Mapping Mission (HCMM) polar orbiting satellite, surface temperature estimates are available at approximately 0230 and 1330 local time at mid-latitudes. The LANDSAT-D meteorological satellite launched in 1982 has a resolution of 30 meters in the visible bands and 120 meters in the thermal bands, giving an area resolution of 0.09 and 1.4 hectare (0.22 and 3.5 acres) respectively. Unfortunately, the LANDSAT-D does not give daily coverage of maximum and minimum temperatures. In any case, in order to use information from these satellites effectively, the relationship between the emitted surface radiation and the soil cover and the soil itself must be known. Much progress has been made by the scientists at the U.S. Water Conservation Laboratory in Phoenix, Arizona, as well as by other scientists in the Plains States in understanding the relation between radiometric surface temperature and the soil water content of bare soil and vegetated surfaces. These relationships were developed under relatively ideal conditions where the amplitude of the diurnal heating cycle was relatively constant from day to day because of clear skies and "stationary" air masses, and where the soil moisture content could be controlled by using irrigation. However, in the Eastern United States, where there is a larger variability in cloudiness, atmospheric humidity, and precipitation, these "ideal" conditions are not met. Thus, additional studies must be carried out on data collected in the East in order to determine the effects of these conditions on the parameters developed in the Western United States.

Data to help determine these relationships have been collected from 1979 to 1981 during this cooperative study between the U.S. Army Engineer Topographic Laboratories (ETL) at Fort Belvoir, Virginia, and the School of Forestry and Environmental Studies, Duke University, to investigate "The Effects of Soil Moisture Status and Vegetative Cover Conditions on the Apparent Surface Radiometric Temperature." The following report describes the experimental site and instrumentation used for this study, summarizes the character of the data collected during the investigation, reviews the current state of knowledge about the relation of apparent surface temperature to surface vegetation and soil moisture conditions, and proposes some analyses of this data for which funding is currently being sought.

THE RESEARCH SITE

The research site was in the Rock Field Research Area, Blackwood Division, Duke Forest, Orange County, North Carolina, (35°58.4' N, 79°6.2' W) about 16 kilometers (10 miles) west of Duke University, Durham, North Carolina. The area had been used previously for agriculture, but it had been abandoned for this purpose for some time. Thus, at the beginning of the project the site was covered with a mixed pine and hardwood forest stand. During the first two years of the project, considerable effort was expended in clearing this forest and preparing the site for establishing the agronomic crops to be used for the study.

In 1979, the first season in which data were collected, the research site was a nearly rectangular field, 182 m x 275 m (600 ft x 900 ft), with the long side oriented in a north-south direction. The field was surrounded by a 23-36 m tall (75-85 ft) loblolly pine (Pinus taeda, L.) forest with a mixed hardwood undergrowth. During the spring of 1980 the field was enlarged by clearing the surrounding forest on all sides. The final size of the field was nearly rectangular, approximately 283 m x 407 m (930 ft x 1335 ft). In addition, the pine forest surrounding the site had been harvested another 45-150 m (150-500 ft) or more beyond the field on all but the north side, with the few remaining large hardwood trees a considerable distance away from the field.

During the 1979 measurement season one 9.3 m (30.5 ft) scaffold-type micrometeorological tower was situated about 52 m (171 ft) from the western edge of the field and about two-thirds of the way up from the southern end of the field. The tower was located to give the maximum fetch from southeast and southwest, the most frequently occurring wind directions, under the constraint of limited length of the available signal cables. The field was flat north of the tower, with a slight downslope near the southeastern corner of the field. The field was prepared according to normal agricultural practices: plowed, limed, fertilized, and planted with soybeans (Glycine max L., Merrill var. Ransom). The uncultivated surface soil is loam to gravelly loam and the subsoil is a clay to clay loam (U.S. Soil Conservation Service, 1977).

For the 1980 and 1981 measurement seasons the enlarged field was divided in half along a north-south axis, with milo, a grain sorghum (Sorghum vulgare L., var, Dekalb C42-Y) and Ransom soybeans planted in the eastern and western halves of the field, respectively. Each half was prepared, fertilized, and treated with herbicide for weed management for its respective crop. Two micrometeorological towers, each 9.3 m (30.5 ft) tall were placed about half way from their respective north-south ends of the field, 57m (183 ft) from the east side of the field, and 86 m (282 ft) from the west side of the field, respectively. In each field, plant study plots were set up in which plants were randomly selected for measurements of leaf area, plant height, and stomatal resistance.

INSTRUMENTATION AND DATA COLLECTION

The data were collected during periods of active vegetative and reproductive growth (beans and milo heads maturing) in 1980 and 1981 and during and after senescence in 1979, 1980, and 1981. In 1980 and 1981 two crops, soybeans and milo, were grown to see if their different rooting depths had any effect on the availability of water for transpiration and, thus, on their effective canopy temperature (independent of their plant structure) during dry spells. The soil moisture was supplied only by natural rainfall, which was measured by a standard rain gauge and a weighing rain gauge, for measuring the timing and intensity of the precipitation.

The data collected included measurements of soil, plant, and atmospheric factors and remotely sensed canopy temperature. The soil data included surface and/or subsoil moisture content, measured with neutron probes in at least two locations in each field. Soil moisture measurements were made regularly, usually at least once a week. Soil temperatures were measured with copper-constantan thermocouples at six levels, 2, 4, 8, 16, 32, and 64 cm, in the soybean field. For the 1981 measurements, two soil heat flux disks were positioned at approximately 1 cm below the surface in each field.

Through the observation period, in selected plots in each field, plant height, stomatal resistance, leaf water potential, and leaf area were measured regularly. Stomatal resistance of the soybeans and milo was measured with a diffusion porometer. Leaf water potential was also measured, though less frequently, with the Scholander pressure chamber technique, using, in many cases, the same leaf that was used for the stomatal resistance measurement. These two measurements were made within half an hour of one another. Leaf area measurements were made once or twice a month during the growing season, using a leaf area meter.

The atmospheric variables were measured from the micrometeorological tower in each field, except for the radiation balance and rainfall measurements, which were located away from any shadow effects of the towers. The micrometeorological data necessary to calculate the sensible and latent heat fluxes, using the Bowen ratio-energy balance, were collected above each crop with a computerized data-acquisition system. These data consisted of profile measurements of wind (soybean field only), temperature, and water vapor (dew point) at six levels; wind direction atop the soybean tower; incoming and reflected solar radiation; and net radiation. During the 1979 measurement period all wave incoming radiation was measured, using a net radiometer, with the down-facing hemisphere covered by a black-body heat sink. The surface canopy temperatures were measured using 20° field of view infrared radiation thermometers aimed at the crop surfaces at an angle of 60° from the horizontal. They were mounted, facing south, at the end of booms that extended 3 meters out from each tower at 7 meters above the ground. Table 1 gives additional details about the instruments, their manufacturers, and frequency of measurements.

All the raw data collected by the computerized data-acquisition system were recorded on magnetic tape along with 5-minute and 30-minute summaries, which were also printed. The summaries listed averaged data in scientific units for checking the operation of the system and the validity of the data. The 30-minute summaries also include simple Bowen ratio-energy balance and Richardson number calculations. The raw data can be used for the detailed analysis of environmental variables and for any re-analysis of the summarized data, as might be needed if instrument problems occurred. On days when weather conditions permitted, data were normally recorded starting between 1000 and 1100 EST and ending between 1530 and 1630 EST. Data were collected on 7, 22, and 46 days in 1979, 1980, and 1981, respectively. In addition, overnight data collection runs were made on two nights in 1979 and five nights in 1981 for reference purposes. Data collected before 1100 were often degraded due to the formation of dew or fog during the early morning hours, which affected the radiation and water vapor measurements.

Table 1. Summary of measurements, sampling periods, and instrumentation

Measurement	Sampling Period	No. of Instrument Sampling Location: Soybeans	No. of Instrument Sampling Location: Milo	Technique	Manufacturer
Soil Measurements					
Bulk Density	twice in 1981	24	24	Gravimetric	--------------------
Soil Moisture	weekly but not in each plot	in each sample plot		Neutron probe	Nuclear Chicago/Troxler
Soil Heat Flux	20 Sec	2	2	Flux disks	Micromet Instruments
Soil Temperature Profile	20 sec	6 levels	-	Copper-Constantan thermocouple with heated reference	"homemade"
Plant Measurements					
Plant Height	weekly	X	X	Meter stick	--------------------
Plant Density	monthly	X	X	Stem count	--------------------
Leaf Area	monthly during growing season	X	X	Leaf area meter	Lambda Instruments Corp. Model LI-3000
Diffusion Resistance	weekly	X selected plants	X	Diffusion porometer	Lambda Instrument Corp.
Leaf Water Potential	weekly	X	X	Scholander pressure bomb	Duke Instrument Shop

Table 1. Summary of measurements, sampling periods, and instrumentation - Continued

Measurement	Sampling Period	No. of Instrument Sampling Location: Soybeans	No. of Instrument Sampling Location: Milo	Technique	Manufacturer
Atmospheric Measurements					
Solar Radiation					
incoming	2.5 sec	1	1	Pyranometer	Kipp and Zonen
reflected	2.5 sec	1	1	Pyranometer	Kipp and Zonen
Net Radiation					
1979	5 sec	1	-	Net radiometer	Swissteco Pty. Ltd.
1980, 1981	5 sec	1	1		Type S-1
All Wave Incoming Radiation-1979	2.5 sec	1	-	Net radiometer with heat sink	Swissteco Pty. Ltd. Type S-1
Crop Surface Temp.					
1979	2.5 sec	1	-	Radiation	PRT-5, Barnes Engr.
1980, 1981	2.5 sec	1	1	Thermometer	Optitherm, Barnes Engr.
Air Temperature Profile	5 sec	6 levels	6 levels	Aspirated/Shielded 10 junction copper-Constantan thermo-couple with ice reference	"homemade"
Water Vapor Profile	5 min avg	6 levels	6 levels	Dew point	EG&G hygrometer
Wind Speed Profile	5 min avg	6 levels	----	Sensitive cup anemoneters	C.W. Thornthwaite Assoc.
Wind Direction vane	2.5 sec	1	----	Wind direction	
Atmospheric Pressure	5 min		1	Bourdon tube	Texas Instruments
Precipitation	daily		1	Standard 8" rain gauge	
	weekly		1	Weighing rain gauge	

The establishment of the research site and the collection and preliminary processing of the data utilized all of the funds available for this project. Detailed analysis of the data and its publication in summarized form will have to await the availability of additional funding, which the investigators are currently seeking. In planning for the future data analysis, we have prepared the following review of the current state of knowledge about factors affecting apparent surface temperature.

CURRENT STATE OF KNOWLEDGE

In order to interpret remotely sensed, surface infrared radiation data, knowledge of two phenomena is required. The first is the effect of the attenuation of the energy as it passes through the atmosphere from the surface to the sensor, and the second, the effect of the surface environment that determines the surface temperature and, in turn, the amount of the infrared energy emitted from the surface. Because all of the measurements were made near the surface, we will concentrate on those variables that determine the surface energy balance and the surface temperature.

Basically, two approaches have been used for modeling the relationship between remotely sensed surface temperature and soil moisture. The first is an empirically derived model, based on a form of the heat conduction equation, in which the amplitude of the diurnal surface temperature variation is determined by the solar heat load at the soil surface and by the soil properties. These soil characteristics determine the thermal inertia of the soil, while any variations in the thermal inertia are largely determined by variations in the soil moisture. The second approach is to model the full water balance or energy balance of the soil-plant-atmosphere boundary layer system. These models are complex and require detailed information about the intrinsic nature of the materials and the initial and boundary conditions of the soil, plants, and atmosphere. Although the models are very useful for detailed studies of the physical processes and sensitivity analyses, they don't easily lend themselves to remote sensing methods. Thus, the first approach has been emphasized.

The simplest natural surface to study is smooth, bare, uniform soil. Areas of this nature have been studied by geologists and hydrologists using the thermal inertia approach, in which the heat conduction equation is solved either analytically or numerically, depending on the complexity of the thermal forcing functions used at the soil surface. The forcing functions represent the changing energy inputs at the soil surface. If the forcing function is a simple sine wave or can be expressed as a Fourier series representing diurnal solar heating at the surface, the heat conduction equation can be solved analytically (Churchill, 1941; Kreith, 1958; Price, 1977). When more realistic boundary conditions that include the latent and sensible heat or longwave radiation balance are included in the model, the equations must be solved numerically. Kahle (1977) has used this technique for geologic mapping.

Rosema (1975) developed a soil model to predict the daily course of surface temperature and soil surface heat flux over bare soils, emphasizing the physical theory of moisture and heat transfer in the various soil layers, in the surface soil water levels, and in wind speed conditions. Because these complex models require many initial and boundary conditions, empirical submodels have been developed that are used to simplify some of the functional relationships. On the other hand, scientists at the U.S. Water Conservation Laboratory in Phoenix, Arizona, have developed empirical models for estimating moisture in the soil using easily obtainable data from either remotely sensed surface temperature data or nearby climatic stations. Idso et al. (1975b) initially found that the albedo (ratio of solar energy reflected from the ground surface to the incoming solar radiation) could be related to the soil moisture content in the first 2-mm depth of the soil when the soil moisture content, by volume, ranged between 4 percent and 22 percent. The results appeared independent of season. However, for soil moisture content averaged over a depth of 2 cm, a linear albedo versus soil moisture content relationship held only when the soil moisture content was between 15 percent and 25 percent by volume. Over larger depths, seasonal differences did appear (Idso et al., 1975b). Several other problems also occur when albedo is used: it varies with solar angle, slope of the land, and roughness of the soil surface, besides essentially being strictly a surface phenomena. On the other hand, Reginato et al. (1976) demonstrated that infrared imagery in the 8-14 micrometer wavelength range gave better discrimination between wet and dry soils, with the relationship improving over a greater soil depth when the amplitude of day-night surface temperature of the bare soil was plotted against volumetric soil water content (Idso et al., 1975c). The physical basis for using the amplitude of the diurnal temperature difference as a parameter in the empirical relationship is that diurnal temperature variation is inversely proportional to the thermal inertia of the soil and directly proportional to the soil heat flux in a semi-infinite soil (Van Wijk; Idso et al., 1976) If the soil surface heat flux is constant from day to day, then any variation in the surface temperature difference must be due to a change in the soil moisture content. Of course, another soil type (with different soil density and thermal conductivities) would also have a different diurnal thermal response. Fortunately, Idso et al. (1975c) have found that when the amplitude of the diurnal surface temperature wave is plotted against soil moisture in terms of soil water pressure potential rather than in terms of percent by volume, the effects of different soil types become negligible. Similarly, if the diurnal temperature wave is correlated to percent field capacity, again the effect of soil type disappears (Schmugge et al., 1978; Cihlar et al., 1979). Conversely, when the surface soil heat flux is changing, its effect on the surface temperature must be taken into account.

If the heat supplied to the soil surface does change from day to day, then an adjustment must be made in the empirical relationship to account for the change in the magnitude of the diurnal temperature, which is due to the changing heat supply and is not related to the more slowly changing soil moisture content. The day to day changes in surface heat supply could be due to changes in incoming radiation, resulting from changes in cloudiness, fog, smoke, or haze, or due to changes in air temperature or specific humidity, resulting from a change in air mass. The change in specific humidity would also affect the evapotranspiration and Bowen ratio. In order to remove these effects, Idso et al. (1976) suggested a new parameter normalizing the maximum-minimum air temperature difference to a fixed valve of 18° C and showed how this adjustment reduced the scatter in their observed data. However, in a study of soil water content over fallow fields, Chiar et al. (1979) found no improvement in the soil moisture estimation using Idso's et al. (1976) 18° C normalization factor. A second normalization method was used by Zhang Ren-hua (1980) in which the mean daily temperature was used as an index rather than using the 18° C difference normalization method. He found that the mean daily temperature correction factor linearized his data (reducing his scatter) much more than the 18° C difference normalization method did. Although remotely measured soil moisture is easiest to estimate over bare soil, the extensive areas covered by vegetation make the estimation of soil moisture in field and forests very important to farmers, foresters, and hydrologists alike.

The introduction of a plant canopy between the soil and the atmosphere greatly modifies the relationship between soil moisture content, soil surface temperature, and the remotely sensed canopy-surface temperature. The most obvious difference is that remotely sensed surface temperature will indicate the integrated value of the temperature of the vegetative canopy surface over its depth, and possibly of the soil surface, depending upon the canopy structure and density. Thus, the difference between maximum and minimum canopy temperature is no longer directly related to the thermal inertia of the soil, but instead to both soil factors and plant physiological factors that combine to control the plant canopy temperature. Fortunately, a major way in which the plants respond to changes in soil moisture content is by opening and closing their stomates. When the stomates are open, evapotranspiration occurs and the leaf temperatures are usually reduced to near or below air temperature. Conversely, when the stomates close during the day because of leaf water stress, the canopy temperature can rise several degrees or more above air temperature, but the rise would not be as high as over dry bare soil. As an example, Wiegand and Namken (1966) observed a 3.6° C increase in the leaf temperature due to plant water stress, as indicated by a decrease in the relative turgidity from 83 percent to 59 percent. Ehrler and van Bavel (1967) noted that the leaf temperature of grain sorghum rose as much as 5° C above air temperature in the midafternoon, for a leaf diffusion resistance around 8 sec/cm. While under low stress conditions, the leaf temperature was greater than air temperature only during mid-morning and less than air temperature the rest of the day. The relation between plant water potential and temperature was evaluated in a more extensive test at twelve sites in six wheatfields in Arizona. The results support the validity of the air-canopy temperature difference method for sensing plant response to plant water stress (Ehrler _et al._, 1978). Other factors that influence the plant water stress include the ability of the plants to extract water from the soil, which in turn depends upon the plant species, plant age, soil type, soil water content, and atmospheric factors. The atmospheric factors include wind speed, specific humidity of the air, radiation intensity, and heat load. The soil type, porosity, and density determine the soil moisture retention and the water replacement rate of the water removed from the soil by the plant's roots. Plant species determine the rooting depth and physiological characteristics, which in turn determine the resistance to the water flow through the roots, stem, leaves, and stomata of the plant. Byrne _et al._ (1979) have reviewed many of the physiological effects that regulate canopy temperature.

Thus, two methods have been used to characterize the plant-water/soil-moisture condition. The first parameter is the difference between maximum (midday) and minimum (nighttime) canopy temperatures. The second parameter is the difference in temperature at a given time between the canopy and the air at 1 meter above the canopy. For remote sensing of the canopy from satellites or aircraft, the first parameter method has been used. On the other hand, for surface-based remote measurements, the second has been used, especially for monitoring the water stress of crops in agricultural regions. These temperature difference parameters have also been used to define a plant water-stress parameter, the Stress Degree Day (SDD) (Idso et al., 1977). Gardner et al. (1981) suggested that the "timing of the crop temperature measurements may also be used to distinguish the degree to which plants are stressed for water," and in turn may be used to estimate soil moisture content. Ehrler (1978) also reported a difference in the time rate of change of the canopy-air temperature difference between wet and dry plots.

In particular, Idso and Ehrler (1976) directly related midday leaf-air temperature difference measurements to soil moisture content. They found that when the soil moisture content was below field capacity, the temperature differences were linearly related to the soil moisture content in the root zone. If the day-to-day sequence of the temperature difference is followed, the linear relationship can be extended to water contents greater than field capacity. After a rain or after the crop was irrigated, they found that the air-canopy temperature difference initially went to zero and then slowly went negative as the evaporation from the soil surface decreased. When the temperature difference started to increase again (became less negative), the relationship appeared to be valid. However, when data were plotted without the time relationship, the data points appeared random.

Idso et al. (1976) attempted to extend the relationship between soil moisture content and their normalization parameter for bare soil to the plant canopy by using canopy temperature of alfalfa instead of soil surface temperature. The normalization process reduced the scatter for data points by one-third, where the soil moisture was above the field capacity, but it didn't improve the results. There did appear to be an effect of atmospheric water vapor content When the data were plotted, using the midday canopy-air temperature difference, after Idso and Ehrler (1976), the data (almost all representing moisture contents greater than field capacity) varied randomly. Since the day-to-day sequence was not indicated, no comment can be made about when the data might become valid by using the method Idso and Ehrler (1976) described above.

In two recent papers, Idso et al. (1981b) presented evidence that the foliage-air temperature differential was linearly related to the atmospheric vapor pressure deficit (or vise versa) over well-watered alfalfa, soybeans, and squash. Each crop had its own unique equation irrespective of other environmental parameters except cloud cover. This finding is significant, since the data were collected on several research farms in North Dakota, Kansas, and Arizona.

Although the diurnal time rate of change of the canopy temperature has been mentioned as a means of determining the plant water stress and, in turn, the soil moisture content, no quantitative relationships have been noted in the literature. If this technique could be developed, data from high resolution geostationary satellites could be used to estimate the desired quantities. To test these relationships, time series measurements in the order of tens of seconds are needed, especially during partly cloudy conditions. In addition, it would be even better if the physical processes of energy exchange at the canopy surface could be modeled and an error and sensitivity analysis of the different estimates could be made.

Most of these relationships between temperature difference and soil moisture content and plant water stress have been developed in the Southwestern United States where the conditions are ideal for these kinds of micrometeorological measurements, namely clear skies and little precipitation. Under these conditions, day-to-day changes in temperature due to cloudiness are minimized and occur only when a front passes and the entire air mass changes. Soil moisture and, in turn, plant water stress can be maintained at different levels, in different fields by differential irrigation. Under these conditions, the diurnal course of air and soil temperature is relatively uniform, and longer time constant processes dominate, on the average. In the Eastern United States, however, these ideal conditions do not normally exist. Cloudiness and normal precipitation are common and quite variable. In the case of cloudiness, the diurnal temperature cycles can be very irregular and the maximum and minimum temperature differences cannot be used directly as parameters to estimate the plant water stress or soil moisture content. Unless some method can be developed to estimate the effect of cloudiness on the heating of the plant canopy and soil and, in turn, on the resulting interaction between stomatal resistance, plant water-stress, and soil water-content on the canopy temperature, then remote sensing of canopy and air temperature will remain ill defined. Stone et al. (1975), who measured the influence of cloudiness on sorghum canopy temperature, reported time constants for cooling and heating of the canopy, as clouds passed over the field, of 1-2 minutes and 2-3 minutes duration, respectively. Any small passing cloud will not have much effect on the maximum temperature unless it passes over just before the time of measurement. However, if the sky is partly cloudy over a significant period of the day before the maximum temperature occurs, the accumulative effects of the cloud shadows over a crop would certainly have a definite effect on the maximum canopy temperature.

Although rainfall in the Eastern United States is much greater than in the Southwest, and although, on the average, there is definite seasonality to the rainfall patterns, the timing of the rainfall is quite variable. As a result, the soil moisture content may never get below field capacity if it rains frequently, or it may follow a drying cycle for several weeks. If it is dry for several weeks, a well-defined change in soil moisture occurs and should be detectable by remote sensing. The times when the fields are near field capacity or when there are only short drying periods are the times that need to be more thoroughly evaluated.

If one is to estimate soil moisture using remote sensing over cropland throughout the year, seasonally varying vegetative conditions must be considered, namely, the condition of the field during a dormant season and the growing season with the crops in different developmental stages: vegetative growth with partial plant cover, flowering-pollenation, grain filling, maturation, senescence, harvest stubble, and cover crop. Cihlar (et al., 1979), as mentioned earlier, analyzed soil moisture data from fallow fields. Heilman and Moore (1980) looked at the more complex solution of estimating soil moisture content over a new barley crop that only partially covered the ground. Heilman and Moore's analysis took a three-step approach to estimating soil moisture content over a partial barley cover, using remote sensing methods.

Assuming that the relationship between diurnal maximum-minimum soil surface (measured at 1-cm depth) temperature difference and soil moisture content still held, even when the vegetation partially covered the soil, they developed a set of three regression equations. The first equation predicted maximum daytime soil surface temperature, at 1-cm depth, from infrared canopy temperatures, measured vertically, and from percent of canopy cover. The second equation related the 0230 local solar time (LST) nighttime soil surface temperature, at 1-cm depth, to the minimum National Weather Service temperature and the 0230 LST infrared radiation canopy temperature. The third regression equation related the measured diurnal surface soil temperature difference, at 1-cm depth, to the soil water content. The equations were developed from measurements made over barley grown under natural rainfall conditions in South Dakota. They were then tested over a pasture with 50-80 percent plant cover and over corn, soybeans, and millet with 90-95 percent plant cover. The soil moisture content, expressed in terms of field capacity, for these several cover conditions was calculated using the equations developed over barley. The calculated soil moisture content differed from the observed soil moisture content by -24.5 percent to +15.3 percent, with an average difference of 1.6 percent. Considering that the comparisons were made over different crops than those for which the equations were developed, it is surprising that the differences between the predicted and measured soil moisture were not greater.

Although much work has been done in understanding the relationships between radiometric surface temperature and soil moisture, the complications generated by weather variability in the Eastern United States and by variability of the energy sources and sinks in surface boundary layer and plant canopy environments still leave much work to be done.

FUTURE DATA ANALYSIS

The data set collected during the course of this study will permit a detailed evaluation of the surface energy balance, including remotely sensed radiometric canopy temperature. It will provide the basis for evaluating the relationship of the apparent surface temperature to the physiological conditions of soybean and milo crops and to the soil moisture content under the variable meteorological conditions typically found in the humid Eastern United States. The five major tasks of this analysis, using surface energy balance methods, will be

1. Evaluate the effect of cloudiness on the diurnal heating cycle of the plant canopy and soil and, in turn, on the maximum radiometric canopy temperature. Evaluate how the reduced heat load affects the estimation of soil moisture content and plant water stress, respectively.

2. Determine whether the rate of change of air or canopy temperature can be used to estimate soil moisture and/or plant water stress.

3. Evaluate the effect of changes in crop structure on the air and canopy temperature and on soil moisture content at different stages of growth during and after the growing season.

4. Summarize the microclimate over the soybean and milo fields during the different stages of growth under different conditions of cloudiness, plant water stress, atmospheric humidity, and soil moisture content, on a diurnal basis as well as on a longer term basis.

5. Test and compare several old, and develop new, microclimatic parameters and/or "models" for estimating actual evapotranspiration, canopy temperature, plant water stress, and soil moisture content.

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