General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

NASA

Technical Memorandum 80331

Effects of Vegetation Canopy Structure on Remotely Sensed Canopy Temperatures

D. S. Kimes

(NASA-TM-80331) EFFECTS OF VEGETATION CANOPY STRUCTURE ON REMOTELY SENSED CANOPY TEMPERATURES (NASA) 20 p HC A02/MF A01 CSCL 08F

N79-33530

Unclas

G3/43 38916

JULY 1979

NOV 1979
RECEIVED
NASA STI FACILITY
ACCESS DEPT.

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

TM 80331

EFFECTS OF VEGETATION CANOPY STRUCTURE ON REMOTELY SENSED CANOPY TEMPERATURES

D. S. Kimes
Earth Resources Branch
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771 USA

July 1979

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

EFFECTS OF VEGETATION CANOPY

STRUCTURE ON REMOTELY SENSED CANOPY TEMPERATURES

D. S. Kimes

ABSTRACT

Remote sensing of vegetation temperatures is a promising technique for inferring plant water stress and yield on a large spacial scale. The effects of vegetation canopy structure on thermal infrared sensor response need to be understood before vegetation surface temperatures of canopies with low percent ground cover can be accurately inferred. The response of a sensor is a function of vegetation geometric structure, the vertical surface temperature distribution of the canopy components, and sensor view angle. Large deviations between the nadir sensor effective radiant temperature (ERT) and vegetation ERT for a soybean canopy were observed throughout the growing season. The nadir sensor ERT of a soybean canopy with 35% ground cover deviated from the vegetation ERT by as much as 11°C during the mid-day. These deviations were quantitatively explained as a function of canopy structure and soil temperature. Remote sensing techniques which uniquely determine the vegetation canopy temperature(s) from the sensor response need to be studied.

CONTENTS

	Page
INTRODUCTION	1
BACKGROUND	2
STUDY APPROACH	6
RESULTS AND DISCUSSION	6
SUMMARY AND CONCLUSIONS	8
ACKNOWLDEGEMENTS	9
REFERENCES	10

ILLUSTRATIONS

Figure		Page
1	Abstraction of a vegetation canopy into four layers. Any number of canopy layers containing canopy components (leaves, stems, reproductive structures, and soil) can be abstracted.	12
2	Measured sensor ERT (T_S) versus the measured mean canopy ERT (T_C) of a soybean cnaopy for the 10 measurement periods (1330 hours) throughout the growing season. The number for each data point is the corresponding percent cover.	13
3	Measured mean ground ERT (T_G) versus the measured mean canopy ERT (T_C) of a soybean canopy for the 10 measurement periods (1330 hours) throughout the growing season. The number for each data point is the corresponding percent cover.	14
4	Measured sensor ERT (T_S) versus the theoretical sensor ERT ($\hat{T}_S$) for a soybean canopy for the 10 measurement periods (1330 hours) throughout the growing season. The number for each data point is the corresponding percent cover.	15

PRECEDING PAGE BLANK NOT FILMED

EFFECTS OF VEGETATION CANOPY STRUCTURE ON REMOTELY SENSED CANOPY TEMPERATURES

INTRODUCTION

Advances in thermal scanner technology in the last few years have created great interest in utilizing the thermal infrared region to gain additional information concerning the status of earth resources. Two NASA satellites have been launched which contain thermal scanners: Landsat-C and the Heat Capacity Mapping Mission (HCMM). Future missions with thermal IR scanners are being considered. Currently there is great interest in utilizing the thermal infrared region to make inferences about vegetation canopy characteristics.

There have been a number of studies concerning the use of vegetation surface temperatures along with other variables to infer the water status of the vegetation canopies (Blad and Rosenburg, 1976; Heilman et al., 1976; Jackson et al., 1977; and Ehrler et al., 1978). Jackson et al., 1977 cited other related studies. In addition there has been some work using soil surface temperature to predict the water status of bare soil as reviewed by Idso et al. (1975). Both temperature and moisture of the canopy components (leaves and soil) are of primary importance in determining crop yields. As a specific example Idso et al. (1977) used wheat canopy temperatures and auxiliary air temperature measurements as an index to plant water stress for the period from head emergence to the cessation of head growth. This index was successfully used to estimate crop yield. The study demonstrated a promising empirical relationship to schedule irrigations and predict yield by remote sensing techniques.

There is a need for monitoring the temperature of vegetation foliage and soil temperatures during the early stages of growth before the vegetation completely covers the ground. Such information is useful in predicting the maximum potential yield of a crop. For example, Idso et al. (1977) hypothesized that information on wheat canopy temperatures and soil surface temperatures during early crop stages would be useful in predicting the maximum green leaf area index which may determine the final potential grain yield. Canopy temperatures early in the growing season would also be useful in scheduling the first few irrigations in arid lands.

The effects of the canopy's geometric structure on the sensor response need to be understood and corrected for before empirical relationships dependent on vegetation temperatures such as presented above can be accurately applied to vegetation canopies with relatively low percent ground cover. In this study the theoretical aspects of these effects were explored and the magnitude of the variability of some of these effects were documented for a soybean canopy.

BACKGROUND

The geometric structure of a vegetation canopy can be mathemetically described by such physical characteristics as the distribution and density of plants on the ground, foliage-area-index, and foliage angle frequency distribution as discussed by deWit (1965). From these parameters the probability of gap (PGAP) through horizontally infinite canopy layers as a function of view angle can be estimated (Nilson, 1971).

The PGAP function of a vegetation canopy is an important parameter in determining thermal infrared, radiant transfers. In the thermal infrared region the emissivity and absorptance values of natural objects approach 1.0 (Idso et al., 1969). Thus for first order approximations, radiant transfers within a vegetation canopy (including the ground) are simplified in that reflections are minimal (Ross, 1976). As a consequence, only direct line emissions from the source to the sensor (e.g. a leaf surface within the canopy having an unobstructed path to the sensor) need to be considered. The vertical surface area distribution of canopy components (leaves and soil) which has a direct line emission path to the sensor can be conveniently described by the PGAP function as presented below.

The contribution of thermal radiance from the soil and vegetation canopy components to the sensor is a function of canopy geometry, spatial distribution of canopy component surface tempertures, and sensor view angle. Kimes et al. (1979a) presented a numberical equation for estimating the thermal radiance of a vegetation canopy as a function of view angle. The canopy was abstracted into a number (n) of horizontally infinite layers (Figure 1). A generalized form of the equation is:

$$L(\theta,\phi) = \pi^{-1} \cdot \sum_{i=1}^{n} \left[\left(\prod_{k=0}^{i-1} PGAP_k\ (\theta,\phi)\right) \cdot PHIT_i(\theta,\phi) \cdot \epsilon_i \cdot \sigma \cdot T_i^4 \right] \tag{1}$$

where

$L(\theta,\phi)$ = Thermal infrared radiance of a canopy as a function of view angle (θ, ϕ) where θ and ϕ are the inclination and azimuth angles respectively $(W \cdot M^{-2} \cdot SR^{-1})$

n = Number of discrete layers in the canopy system including the ground

$PGAP_k(\theta,\phi)$ = Probability of gap in the direction θ, ϕ for layer k. By convention $PGAP_0\ (\theta,\phi) = 1.0$ for all θ and ϕ.

$PHIT_i(\theta,\phi)$ = Probability of hit in the direction θ,ϕ for layer i and $PGAP_k\ (\theta,\phi) = 1-PHIT_i(\theta,\phi)$ for i=k. By convention $PHIT_n(\theta,\phi) = 1.0$ for all θ and ϕ where n denotes the ground.

ϵ_i = Mean component emisivity in layer i

T_i = Mean component surface temperature in layer i (°K)

σ = Stefan-Boltzmann constant $(W \cdot M^{-2} \cdot {}^{\circ}K^4)$.

The underlying assumptions and justification of the above formula are presented by Kimes et al. (1979a).

The $\left(\prod_{k=o}^{i-1} PGAP_k\ (\theta,\phi)\right) \cdot PHIT_i(\theta,\phi)$ term can be thought as the proportion of projected leaf area which is in the direct line of sight to the sensor for a particular view angle described by θ, ϕ and for a specific layer i. The remaining portion of the equation is just the Stefan-Boltzman equation for emitted exitance. Thus, Equation 1 sums the contribution of thermal infrared radiance from each layer of the canopy in a particular direction (θ,ϕ). The simplest case of Equation 1 was used in the following analysis.

The observed vertical canopy temperature distributions are a result of a number of simultaneous energy transfers. These transfers include foliage transpiration, soil and foliage evaporation, soil and foliage solar absorption, thermal infrared emission and absorption for soil and foliage.

soil conduction, and soil and foliage convection. These energy transfer functions between the environment and the vegetation canopy are discussed by Rosenberg (1974), Gates (1975), and Ross (1976).

Many of these energy transfers are controlled by the vegetation canopy geometry. For example, the proportion of spectral solar irradiance which is absorbed by each canopy layer is controlled as a function of canopy geometry, optical properties of canopy components, and solar zenith angle (Kimes et al., 1979a). The variation of absorbed solar irradiance in canopy layers due to changing solar irradiance conditions is paralled by a change in layer temperature. These relationships, however, are complicated by other energy transfers (convection, transpiration, evaporation, and conduction) which occur simulataneously as discussed by Gates (1975). These transfers are a complex function of wind speed, relative humidity, air temperature, solar irradiance conditions, vegetation geometry, several water relation factors of the vegetation and soil, and the optical and thermal parameters of the vegetation and soil.

The remote sensing problem is to relate the response of a thermal infrared sensor to the plant and/or soil conditions of interest. However, as discussed above there are a large number of environmental and botanical permutations which effect the sensor response and mask the desired target characteristics of interest. Presently, there are no studies which attempt to explore the comprehensive relationships between the observed variability in sensor response to the underlying enviromental and botanical conditions.

In this study the effects of canopy geometry on the response of a nadir looking sensor were documented throughout the growing season for a soybean canopy. The observed variability in the response of a nadir sensor was quantitatively described by applying the simplest case of Equation 1.

STUDY APPROACH

Radiometric thermal measurements of a soybean canopy at the USDA Beltsville Agricultural Research Center, Beltsville, Maryland were taken during the 1978 field season. The data were collected and reported by UHL et al. (1979). The authors presented supporting microclimatic and agronomic data. Effective radiant temperatures (ERT) were taken with a Barnes PRT-5 Precision

Radiation Thermometer (field of view = 2°, accuracy = 0.5°c). All measurements were taken at approximately 1330 hours (Eastern Daylight Time) for 10 days throughout the growing season.

For each measurement period canopy ERT, ground ERT, and composite sensor ERT were obtained. Canopy ERT was measured at four random points with the field of view (FOV) of the radiometer entirely on vegetation components. A mean canopy ERT (T_C) was calculated. Ground ERT was measured at four random points with only the soil surface in the FOV of the radiometer and the mean ground ERT (T_G) was calculated. A composite sensor ERT (T_S) of the canopy was measured from a 10 m high platform. The T_S measurement was taken in the nadir direction. The T_C and T_G measurements were assumed to be the mean surface temperatures of the vegetation canopy and ground, respectively. The T_S measurement represented the composite response from the scene composed of vegetation and ground.

The percent ground cover of the vegetation was estimated ocularly by the same individual throughout the growing season. These percent cover measurements were used as an estimate of probability of hit (PHIT) in the nadir direction. PGAP and PHIT values are related as PGAP = 1 – PHIT.

The variability observed in the T_S measurement were explained quantitatively as follows. The canopy was abstracted as a simple two layered system (vegetation and soil). Only a nadir view angle of the sensor was considered. Equation 1 was reduced to this specific case and was expressed exclusively in terms of ERT rather than true surface temperatures and emissivities. The simplified equation is:

$$\hat{T}_S^4 = PGAP \cdot T_G^4 + (1-PGAP)T_C^4 \qquad (2)$$

where

$\hat{T}_S$ = theoretical effective radiant temperature of a nadir looking sensor

T_G = mean effective radiant temperature of ground

T_C = mean effective radiant temperature of the canopy foliage

PGAP = probability of gap through the canopy in the nadir direction.

The above measurements of T_G, T_C, and PGAP for the 10 measurement periods were used to calculate the respective $\hat{T}_S$ values. Comparisons of the theoretical $\hat{T}_S$ and measured T_S were made.

RESULTS AND DISCUSSION

In several research applications as noted above, one would like to infer a mean canopy temperature from the T_S measurement. Figure 2 shows the measured sensor ERT (T_S) versus the measured mean canopy ERT (T_C) as a function of percent cover. The dashed line in Figure 2 and all subsequent figures is a reference line where the dependent variable equals the independent variable. Equation 2 was used to explain the observed deviations between T_S and T_C. Equation 2 was transformed as follows.

$$\hat{T}_S^4 = PGAP \cdot (T_G^4 - T_C^4) + T_C^4. \tag{3}$$

From Equation 3 it is evident that only at relatively high PGAP values and high ($T_G^4 - T_C^4$) differentials is the T_S significantly different than T_C. As seen in Figure 2, the measured sensor ERT (T_S) significantly deviated from the canopy ERT (T_C) only for those measurements with high PGAP values (Low percent cover). The magnitude of these deviations were directly related to the ($T_G - T_C$) differential as presented in Figure 3.

The ($T_G - T_C$) differential can vary widely. Canopy ERT (T_C) closely approximates air temperature during low water stress as reported by Gates (1966), Monteith (1973), Uhl et al. (1979), and others. The ground ERT (T_G), however, can deviate greatly from air temperature. Uhl et al. (1979) reported that the surface temperature of bare soil surfaces was occasionally as much as 20°C higher than ambient air temperature. The difference in the soil temperatures (Figure 3) can be qualitatively explained by variations in solar irradiance, soil moisture, canopy geometry, and wind speed.

Solar irradiance absorbed by the ground is strongly affected by geometric and optical properties of the overlying vegetation canopy. The physical principles were discussed by Oliver and Smith (1974) and Ross (1976). From simulated results and literature studies, Kimes et al. (1979b) showed for photosynthetically active wavelengths that spectral absorption of the ground under

vegetation canopies was highly variable as a function of canopy geometry, and solar zenith angle. This variability in ground solar absorption changes the soil energy budget which effects the soil surface temperature. Uhl et al. (1979) reported that summer soil temperatures were generally reduced several degrees centigrade by the presence of vegetation. At the same time, however, the authors report a decrease in wind speed near the ground within vegetation canopies as opposed to bare ground. Thus, convectional transfers for the canopy and the ground varies as a function of the canopy geometry and environmental conditions. Uhl et al. (1979) also reported that soil moisture greatly influenced the soil surface temperature. The energy dynamics of the soil were discussed further by Geiger (1965) and Rosenberg (1974).

Figure 4 represents the measured sensor ERT (T_S) versus the theoretical sensor ERT ($\hat{T}_S$). Most of the variability in T_S was explained by Equation 2. The root mean square of the deviations between $\hat{T}_S$ and T_S was 1.4°C.

The mean canopy temperature (T_C) is the variable which is often desirable to infer from the composite sensor ERT (T_S). As demonstrated above soil temperature can have significant effects on the composite sensor signal. Remote sensing can readily obtain a nadir looking T_S. However, to uniquely determine T_C other information is required. Research is needed to explore possible approaches to remotely correct for this composite effect. One possible approach is to use additional information gained by off nadir view angles. Such a technique is suggested by Equation 1. These possibilities will be explored in a future article.

The above analysis and discussion was based on the assumption that one mean canopy temperature (T_C) is characteristic of the entire canopy. However, vertical temperature gradients do occur in vegetation canopies. Bauer et al. (1977) presented the vertical temperature profiles of two wheat canopies for various measurement periods. During the afternoon mean foliage temperature differentials (top-bottom layer) were as much as −11°C. The authors suggested that such information could be used to improve the accuracy of water relation models. There is the possibility of remotely sensing mean canopy layer temperatures using a series of off nadir view angles (Equation 1).

Not only do canopy temperature gradients occur but also air temperature gradients within the canopy. Bergen (1971) showed that air temperature differentials within lodgepole pine canopies can be as much as 4-5°C in the vertical profile for clear, sunny days. Bauer et al. (1977) found that air temperature differentials within wheat canopies can be as high as 7.5°C. These observed variations have important implications in developing and applying relationships dependent on air temperature.

SUMMARY AND CONCLUSIONS

Past studies have utilized vegetation surface temperatures to infer the water status and yield of vegetation canopies. Remote sensing of canopy temperatures is a promising technique for monitoring plant characteristics on a large spatial scale. The thermal infrared sensor response of a vegetation canopy is not a simple measurement of foliage temperature but is a function of canopy geometric structure, vertical foliage surface temperature distribution, soil temperature, and sensor view angle. The surface temperature distribution of foliage is a complex function of a number of simultaneous energy transfers. Many of these transfers are dependent on canopy geometric structure.

The soybean data and analysis documented the effects of the geometric structure of a simple two layered system (ground and vegetation) on the response of a nadir sensor (T_S) throughout the growing season. For vegetation canopies with relatively low percent cover, the ground surface temperature (T_G) can significantly influence the sensor response (T_S). For a soybean canopy with 35% ground cover T_S exceeded the canopy temperature (T_C) by 11°C. T_G can be highly variable due to variations in absorbed solar irradiance and soil moisture. Soil temperatures (T_G) as high as 20°C above air temperature have been observed for bare soil. T_G for a soybean canopy with a 35% ground cover was as high as 15°C above canopy temperature. This solar heating phenomena is controlled by the vegetation geometry, solar zenith angle, optical properties of the soil surface and vegetation, and physical properties of the soil matrix. The deviations of T_S from T_C were quantitatively explained by variations in soybean canopy geometry and soil temperature. The root mean squared deviation between the calculated theoretical T_S and the measured $\hat{T}_S$ was 1.4.

Remote sensing techniques which correct for or circumvent these geometric effects need to be developed before remote sensing of foliage temperatures can be accurately inferred throughout the growing season. First order corrections are needed which separate the composite sensor signal into mean soil and vegetation temperatures. For more developed canopies, second order corrections which separate the sensor response into a vertical profile of mean canopy layer temperatures would be desirable.

ACKNOWLEDGEMENTS

I would like to thank J. Uhl, J. Barker, J. McMurtrey III, and J. Elgin, Jr., for their permission to use the soybean data and for their assistance in accessing the data. In addition, I would like to thank J. Barker for his helpful review of the manuscript.

REFERENCES

Bauer, M. E., L. F. Silva, R. M. Hoffer, and M. F. Baumgardner, 1977. Agricultural Scene Understanding. Principle Investigator, D. A. Langrebe. Final Report to National Aeronautics and Space Administration, Johnson Space Center, T-1314/4 MA-129TA, LARS Contract Report 112677.

Bergen, J. D. 1971. Vertical Profiles of Windspeed in a Pine Stand. Forest Sci. 17:314-321.

Blad, B. L., and N. J. Rosenberg. 1976. Evaluation of Resistance and Mass Transport Evapotranspiration Models Requiring Canopy Temperature Data. Agronomy J. 68:764-769.

deWit, C. T. 1965. Photosynthesis of Leaf Canopies. Agr. Res. Rep. 663. Inst. Biol. Chem. Res. on Field Crops and Herbage, Wageningen, the Netherlands.

Ehrler,W. L., S. B. Idso, R. D. Jackson, and R. J. Reginato. 1978. Wheat Canopy Temperature: Relation to Plant Water Potential. Agronomy J. 70(2): 251-257.

Gates, D. M. 1966. Transpiration and Energy Exchange. Quart Rev. Biol. 41:356-364.

Gates, D. M. 1975. Introduction: Biophysical Ecology. In: Perspectives of Biophysical Ecology (D. M. Gates and R. B. Schmerl, eds.) Springer-Verlag, NY p. 1-28.

Geiger, R. 1965. The Climate Near the Ground. Harvard University Press, Cambridge, MA. 611 p.

Heilman, J.L., E.T. Kanemasu, N.J. Rosenberg, and B.L. Blad. 1976. Thermal Scanner Measurement of Canopy Temperature to Estimate Evapotranspiration. Remote Sensing of Environment 5:137-145.

Idso, S. B., R. D. Jackson, W. L. Ehrler, and S. T. Mitchell. 1969. A Method for Determination of Infrared Emittance of Leaves. Ecology, Vol. 50(5): 899-902.

Idso, S. B., T. J. Schmugge, R. D. Jackson, and R. J. Reginato. 1975. The Utility of Surface Temperature Measurements for the Remote Sensing of Surface Soil Water Status, J. Geophysical Res. 80(21): 3044-3049.

Idso, S. B., R. D. Jackson and R. J. Reginato. 1977. Remote-Sensing of Crop Yields. Science 196: 19-25.

Jackson, R. D., R. J. Reginato, and S. B. Idso. 1977. Wheat Canopy Temperature: A Practical Tool for Evaluating Water Requirements. Water Resources Research, 13:651-656.

Kimes, D.S., J. A. Smith, and K. J. Ranson. 1979a. Terrain feature canopy modeling. Final Report, U.S. Army Research Office. Grant Number: DAAG 29-78-G-0045/ 160 p.

Kimes, D.S., K. J. Ransom, and J. A. Smith. 1979b. A Monte Carlo Calculation of the Effects of Canopy Geometry on PhAR Absorption. Accept. Pub. Photosynthetica.

Monteith, J. L. 1973. Principles of Environmental Physics. American Elsevier Publ. Co., Inc. New York, 241 p.

Nilson, T. 1971. A Theoretical Analysis of the Frequency of Gaps in Plant Stands. Agr. Meteorol., 8:25-38.

Oliver, R. E., and J. A. Smith. 1974. A stochastic Canopy Model of Diurnal Reflectance. Final Report, U.S. Army Research Office, Durham, North Carolina, DAH CO4-74-60001. 105 p.

Rosenberg, N. J. 1974. Microclimate: The Biological Environment. John Wiley and Sons, New York. 315 p.

Ross, J. 1976. Radiative Transfer in Plant Communities. In: Vegetation and Atmosphere, Vol. 1 Principles (J. L. Monteith ed.). Academic Press, London.

Uhl, J. B., J. L. Baker, J. E. McMurtrey III, and J. H. Elgin, Jr. 1979. Multicrop, Thermodynamic, Microclimatic, Agronomic, and Spectral Measurements under Constant Climatic and Soil Conditions. USDA/NASA Co-operative Research, Beltsville Agricultural Research Center and Goddard Space Flight Center.

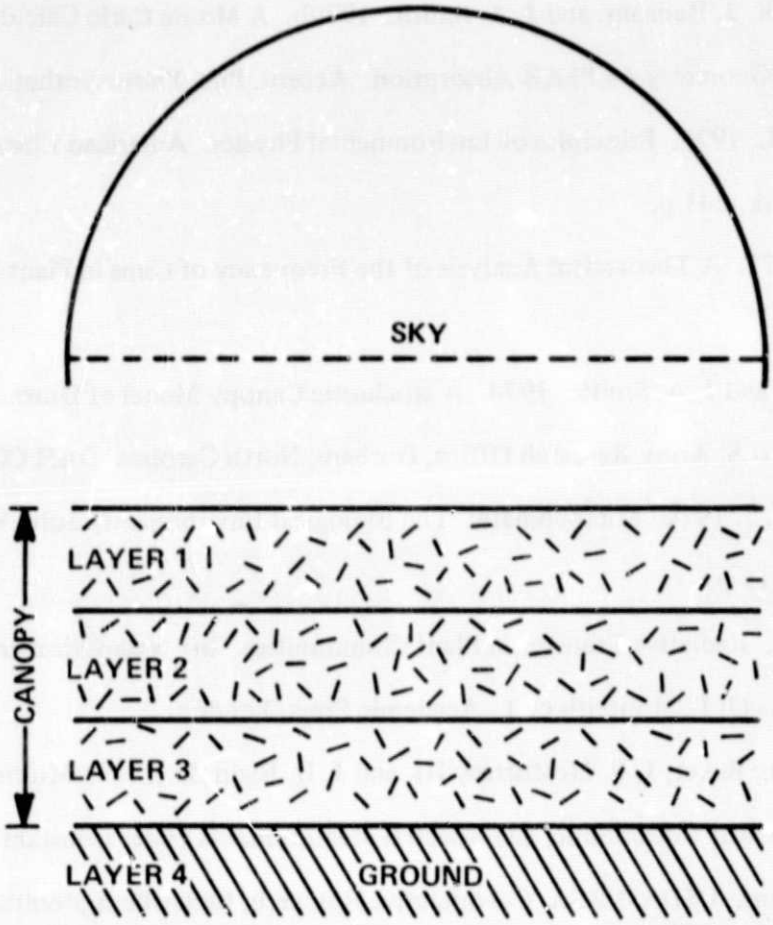

Figure 1. Abstraction of a vegetation canopy into four layers. Any number of canopy layers containing canopy components (leaves, stems, reproductive structures, and soil) can be abstracted.

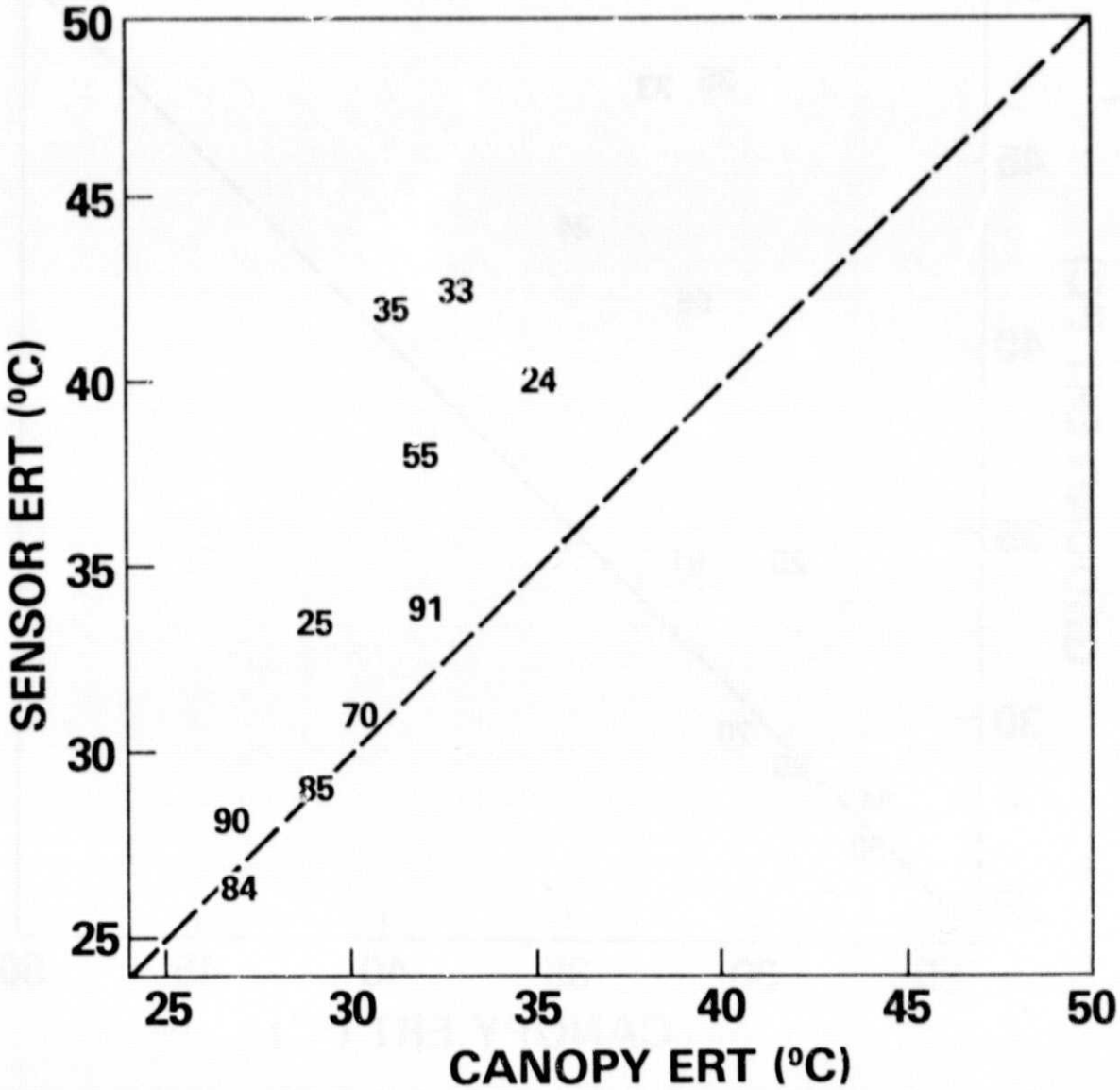

Figure 2. Measured sensor ERT (T_S) versus the measured mean canopy ERT (T_C) of a soybean canopy for the 10 measurement periods (1330 hours) throughout the growing season. The number for each data point is the corresponding percent cover.

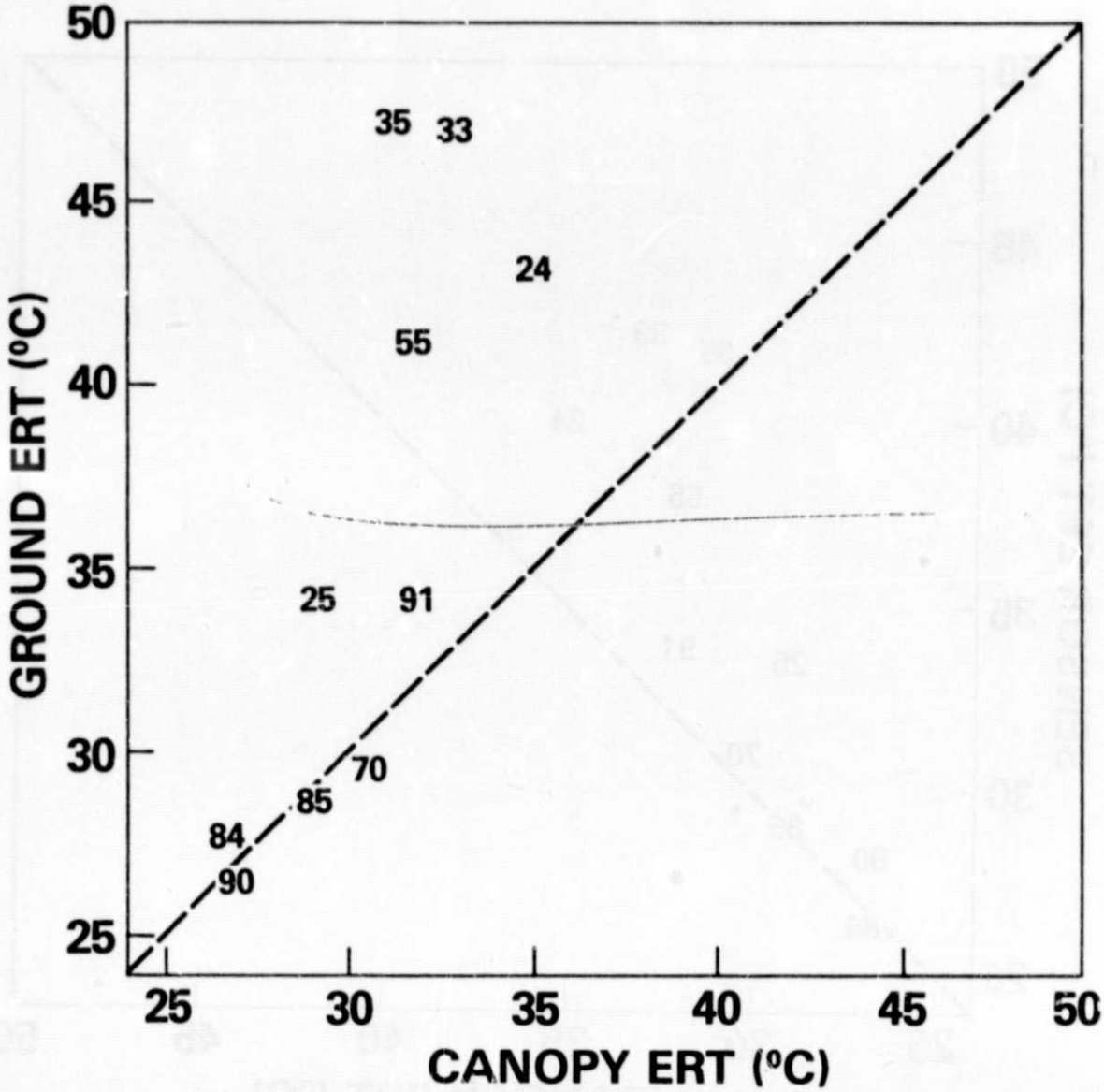

Figure 3. Measured mean ground ERT (T_G) versus the measured mean canopy ERT (T_C) of a soybean canopy for the 10 measurement periods (1330 hours) throughout the growing season. The number for each data point is the corresponding percent cover.

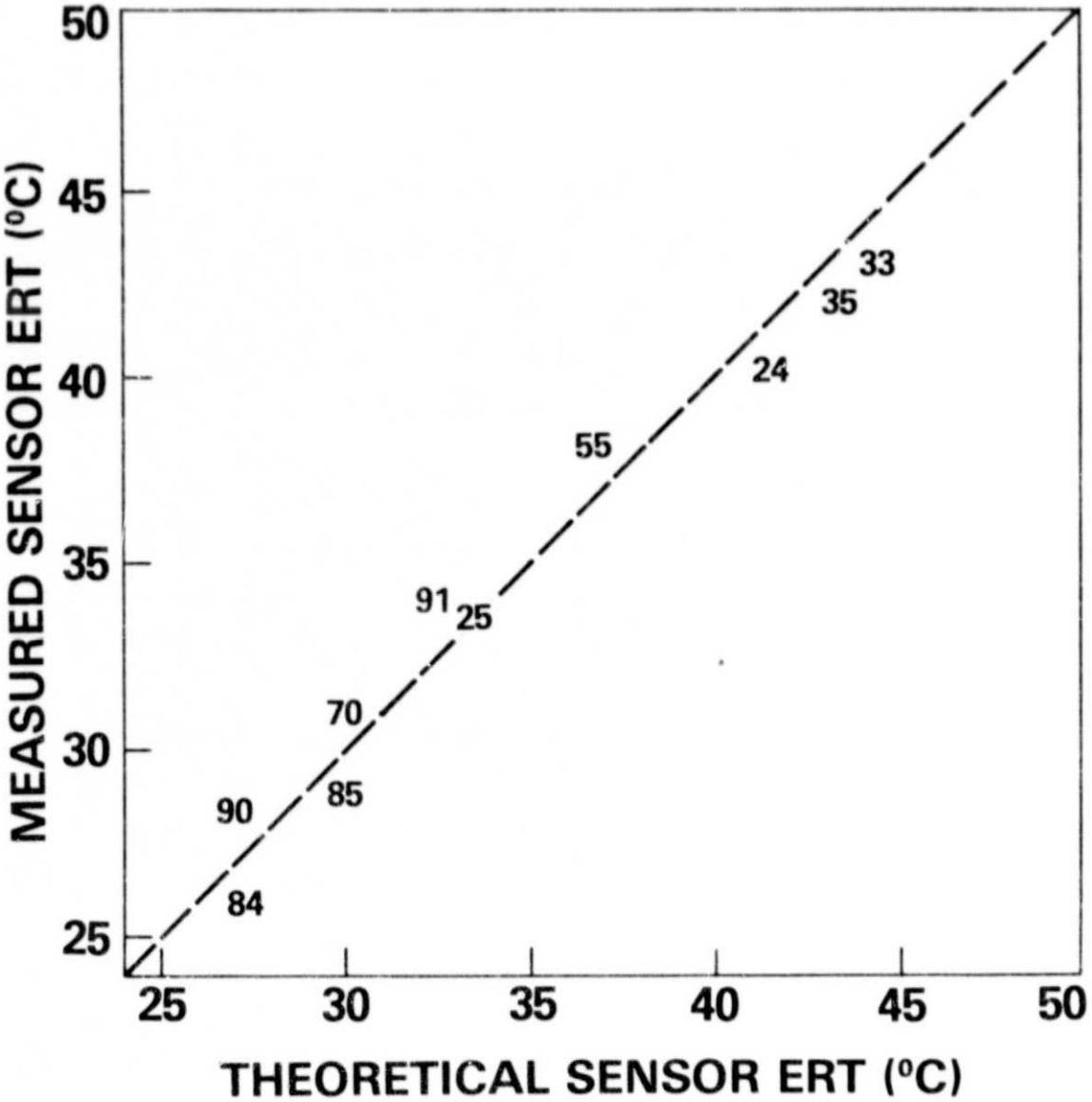

Figure 4. Measured sensor ERT (T_S) versus the theoretical sensor ERT ($\hat{T}_S$) for a soybean canopy for the 10 measurement periods (1330 hours) throughout the growing season. The number for each data point is the corresponding percent cover.