THERMAL INFRARED RESEARCH

WHERE ARE WE NOW?

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The Past

In recent years much attention has been given to utilization of thermal infrared measurement for application to agriculture and hydrology. A portion of this interest has arisen because thermal infrared measurements are relatively easy to make with sensitive, portable infrared thermometers. The use of IR temperatures in agriculture and hydrology is based on the energy balance equation,

$$R_n = \frac{\rho Cp\ (T_s - T_a)}{r_a} + \frac{\rho Cp}{\gamma} \frac{[e_s\ (T_s) - e_a]}{r_a + r_s}$$

where Rn is the net radiation, ρ the density of air, C_p the specific heat capacity of air, T_s the surface temperature, T_a the air temperature at some height z above the surface, r_a the aerodynamic resistance calculated at the height z, γ the psychrometric constant, $e_s\ (T_s)$ the saturation vapor pressure at T_s, e_a the actual vapor pressure of the air, and r_s the surface resistance to water vapor flow. This and other forms of the energy balance have been utilized to estimate evapotranspiration or crop stress.

The thermally driven energy balance equation has been used to estimate ET and stress over small areas within a field as well as large areas. Bartholic et al (1970) first showed how evapotranspiration using temperature measurements could be predicted, he later expanded this concept to use aircraft date (Bartholic et al, 1972). This approach has been modified by Brown and Rosenberg (1973) and most recently by Soer (1980). Unfortunately, there has not been an evaluation of these approaches over a complete growing season of any one crop or over any large region. Stone and Horton (1974), Blad and Rosenberg (1976) and Heilman and Kanemasu (1976) have provided limited evaluations and showed how and where potential problems may lie in the application of these methods. These methods may provide a real-time application of soil moisture through soil moisture balance models utilizing evapotranspiration.

Jackson (1982) presented a thorough review of the use of thermal infrared to detect crop stress. The research history of thermal IR techniques is fairly recent. Tanner (1963) was one of the first to suggest that infrared thermometry could be used to detect moisture stress. Since that beginning three different approaches to detect stress have been reported. Fuchs and Tanner (1966) proposed that water stress could be assessed from a comparision of canopy temperatures from the field in question to that of a well-watered area of the same crop. Wiegand and Namken (1966) proposed that canopy-air temperature (T_s-T_a) differences would be indicative of water stress. Aston and van Bavel (1972) later proposed that the variability of surface temperature would be indicative of moisture stress and would increase as the crop extracted water.

Recently, Clawson and Blad (1982) found that when the temperature of a field in question was 1.0°C above a well-watered plot and irrigation was applied the yields were reduced. However, there was also less water applied to these plots, thereby producing a water savings in comparison to the yield reduction.

Clawson and Blad (1982) also proposed that a variability greater than 0.7°C would indicate the need for irrigation in corn and found that this value would only be valid when the canopy cover was nearly complete. Hatfield (unpublished data) in a study of spatial variability in grain sorghum showed the variability along a 100 m transect within three different irrigation treatments. A clear relationship between the variability along the transect and the amount of water extracted from the soil profile was not evident. It was encouraging that the points along the transect were random, indicating that one could sample randomly within a field regardless of the soil moisture level. It is still necessary to define the optimum pixel size for satellite sensors.

Most research has been directed toward the utilization of measurements of T_s and T_a and expressed as $T_s - T_a$. Idso et al (1977) and Jackson et al (1977) showed that the midday measurement of T_s and T_a and the resultant difference could be summed and related to crop yield and soil water extraction. These models exhibited a linear relationship between crop yield and the stress-degree-days (SDD). Hatfield (1982a) found it was necessary to incorporate spectral measurements as a measure of potential harvestable yield in order to account for the yearly variation in growth and yield-stress relationships. Recent research has shown that other environmental variables are necessary to include in that use $T_s - T_a$ measurements to better detect crop stress. Idso et al (1981a) found that $T_s - T_a$ in a well-watered crop was linearly related to vapor pressure deficit. As the vapor pressure deficit increased the $T_s - T_a$ value decreased. They also proposed that the upper limit of canopy temperature above air temperature would be independent of vapor pressure deficit. A plant water stress index calculated from these lines was related to leaf water potential

(Idso et al, 1981) and to soil moisture extraction (Hatfield, 1982b). Before this method could become operational, the validity of the upper and lower baseline would have to be evaluated for a variety of species and cultivars. Hatfield (1982) found there was an exponential relationship between the plant water stress index and available water extracted from the soil profile. Jackson (1981), however, cautioned that changing rooting volume and ground cover would have to be accounted for in these relationships. This aspect needs continued research before any method can be applied over a growing season.

Jackson et al (1981) suggested another approach utilizing midday measurements of T_s and T_a along with net radiation and vapor pressure deficit. From these data, a crop water stress index was calculated and is related to the ratio of actual to potential evapotranspiration. They showed this index to follow the water extraction patterns in wheat very closely. Slack et al (1981) used these same variables in a regression model to relate $(T_s - T_a)$ to water extraction in corn for Minnesota but since this model is based on regression analysis it may not be applicable to large areas or remote sensing platforms. This approach however, does include the environmental parameters of energy balance with local adjustment factors. These types of relationships need to be compared with the theoretically based evapotranspiration crop water stress index models to determine if a locally adjusted stress indices may be more useful than the more theoretically based models. This would be particularly true in the estimation of soil water status within individual fields for the purpose of irrigation scheduling.

All of the approaches discussed up to now have been based on daily readings. The lack of a satellite platform with a resolution applicable to agriculture will have to posses a temporal resolution of a few days. In an attempt to evaluate the temporal resolution of remote acquired data, Vieira and Hatfield (1982) have analyzed the temporal behavior of air temperature and surface temperature over bare soil. Bare soil was chosen for this study in order to eliminate the effect of the changing ground cover present in a growing crop. Standard geostatistical analyzes were preformed on data sets from 1977, 1978 and 1979 and involved the analysis of the temperal features of each parameter. In all years, the data were collected daily from January through June. It was found that both air and surface temperature became independent regionialized variates after a lag of 5 days. These analyses were made on the residuals from a 10-day smoothed average because of the lack of second-order stationarity in the original data. The importance of this finding reveals that if estimates are to be made of surface temperature from an ancillary meteorological parameter such as air temperature a resolution of 5 days or less is needed. When cross-variograms were calculated for air and surface temperature the data for the three years fit the same models. This suggests that, for bare soil, surface temperature could be estimated from air temperature for a period up to 5 days. This type of relationship needs to be evaluated for a growing season with changing ground cover to determine if similar models could be developed and they would be applicable over a range of conditions and locations. It is possible that the temporal resolution may even require more detailed sampling than the 5-day values found for the bare soil cases.

There have been several attempts to compare ground-based thermal infrared measurements with those from aircraft sensors. One study applicable to this discussion was reported by Hatfield et al (1982) in which comparisons of air and ground measurements were made over a large agricultural area in California. It was found that the comparisons were within 1°C when the field was recently irrigated and bare or was completely covered with vegetation. Bare, dry soil surfaces exhibited the largest differences between the aircraft and the ground-based measurements due to sampling problems. In a subsequent study over bare soil, it was found that surface temperature was random along both north-south and east-west transects within a field as was surface soil moisture. This suggests that random sampling could successfully be used to compare ground-based measurements to aircraft provided that samples could be taken that would be comparable to the minimum resolution on the aircraft. Bare soil studies on surface temperature along a transect following an irrigation showed that the surface warmed as it dried but did not exhibit spatial structure. This effect was noted with both an 8 and 20° fov hand-held infrared thermometers positioned in a nadir direction 1 m above the surface (Vauclin et al, 1981). Soil moisture was also random along this transect. It is difficult to extrapolate these data to satellite platforms but it does suggest that additional work is needed on the variability of thermal infrared data within agricultural fields in order to fully evaluate the aspect of pixel size relative to agricultural management.

Future Directions

Thermal infrared data provide a surface measurement which is directly related to the energy balance and hence the energy exchange of the surface. In order to fully utilize this measurement it will have to be combined with other spectral data, the visible, near-infrared and and microwave portions. These data must be collected in a time resolution sufficient to detect changes in the agricultural or hydrological systems and at a spatial resolution with enough detail to sample within individual fields. The most stringent requirement is that the data be readily available to the user by the most rapid means of communication possible. Jackson (1983) proposed that a high altitude powered platform (HAPP) would be necessary to provide these data for agricultural management. Before we can begin to design this type of system we need to further our body of knowledge in several areas.

1) Evaluation of the spatial resolution necessary for thermal infrared measurements to be incorporated into evapotranspiration models to accurately estimate field and regional evapotranspiration or measure crop stress.

2) Evaluation of methods to estimate crop stress and hence yield over large areas and different cultivars within a species to determine if a generalized model could exist.

3) Investigate the temporal resolution adequate for detect of stress or inclusion into evapotranspiration models.

4) Evaluation of ancillary parameters which could be used to estimate thermal infrared measurements to fill in between acquisition times. These techniques would have to be evaluated over large regions to determine if the same or even similar models exist.

5) Evaluate the errors which would be introduced into estimates of soil moisture status from the use of remotely sensed data compared to standard meteorological measurements.

These experiments are only a few which are necessary to further our knowledge of the use of remotely sensed data for agricultural management. We need to increase both our basic understanding of remotely sensed parameters as well as the application of these data in management decisions. To accomplish this we must continue both our ground-based, aircraft, and satellite programs.

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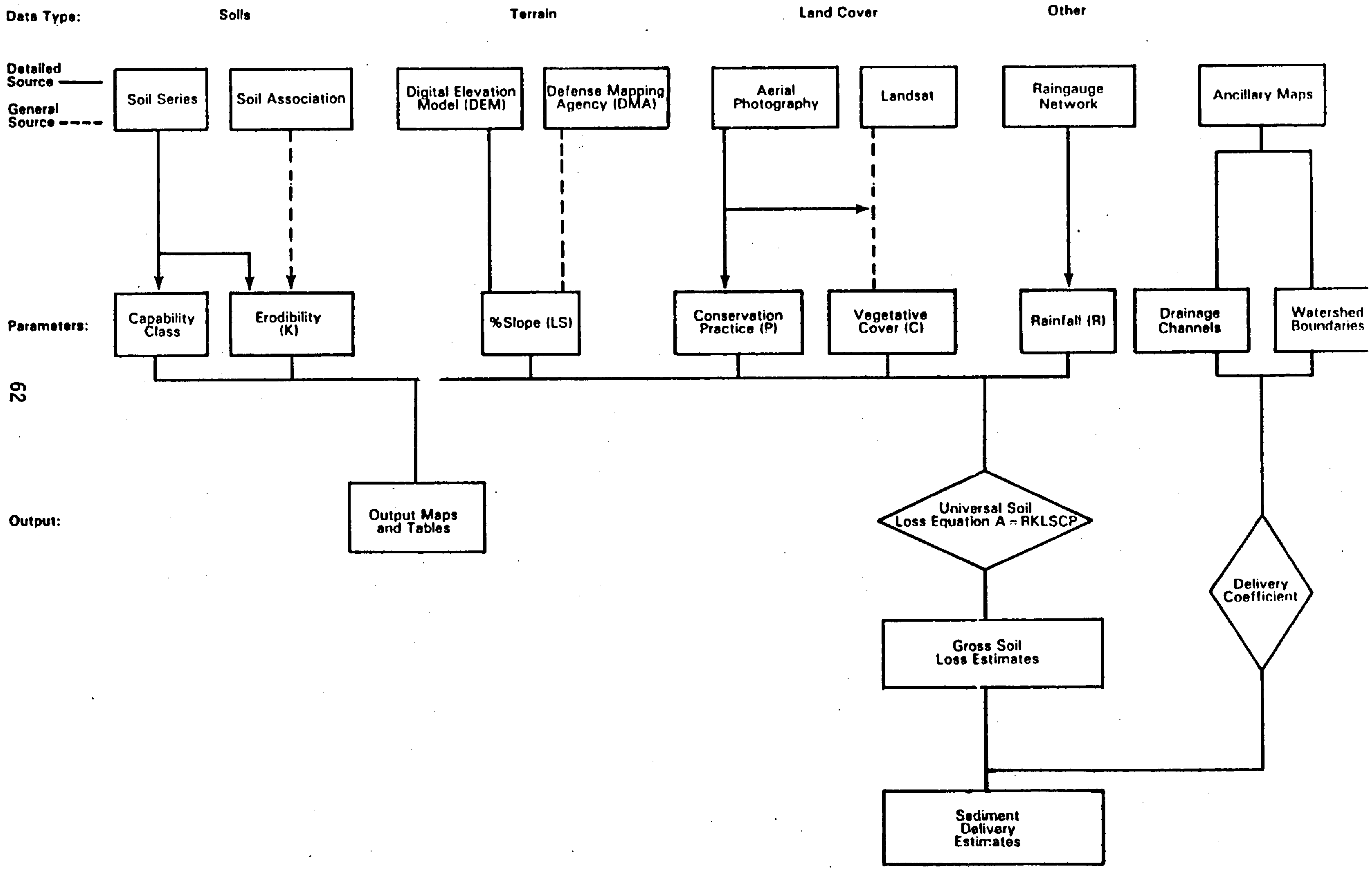
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Parameters:
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%Slope (LS)
Conservation Practice (P)
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Rainfall (R)
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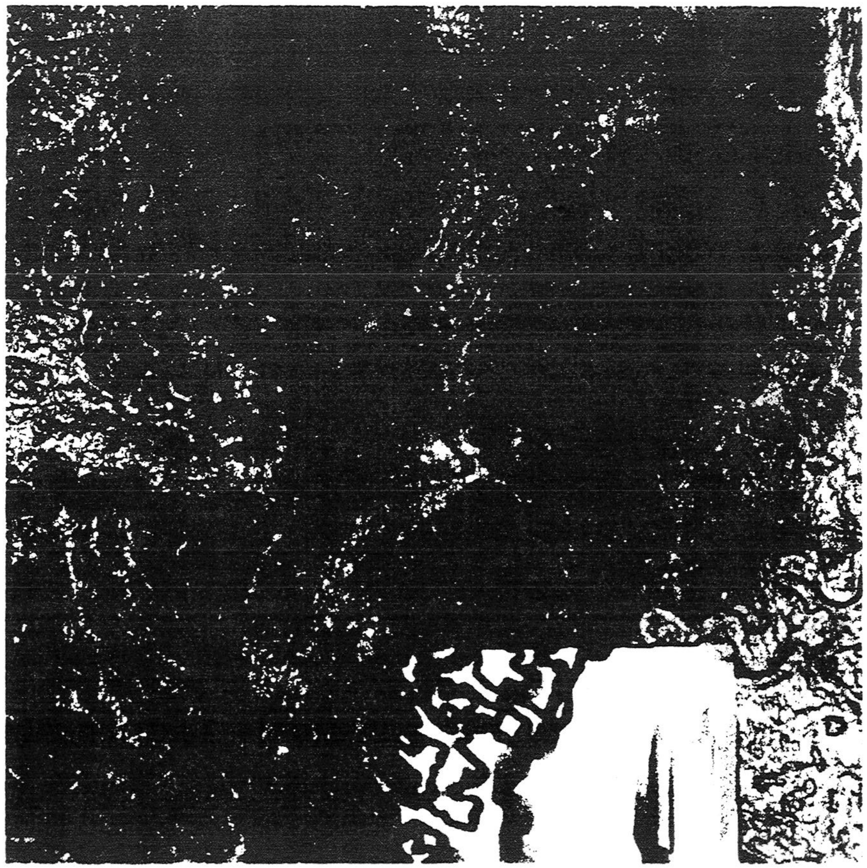

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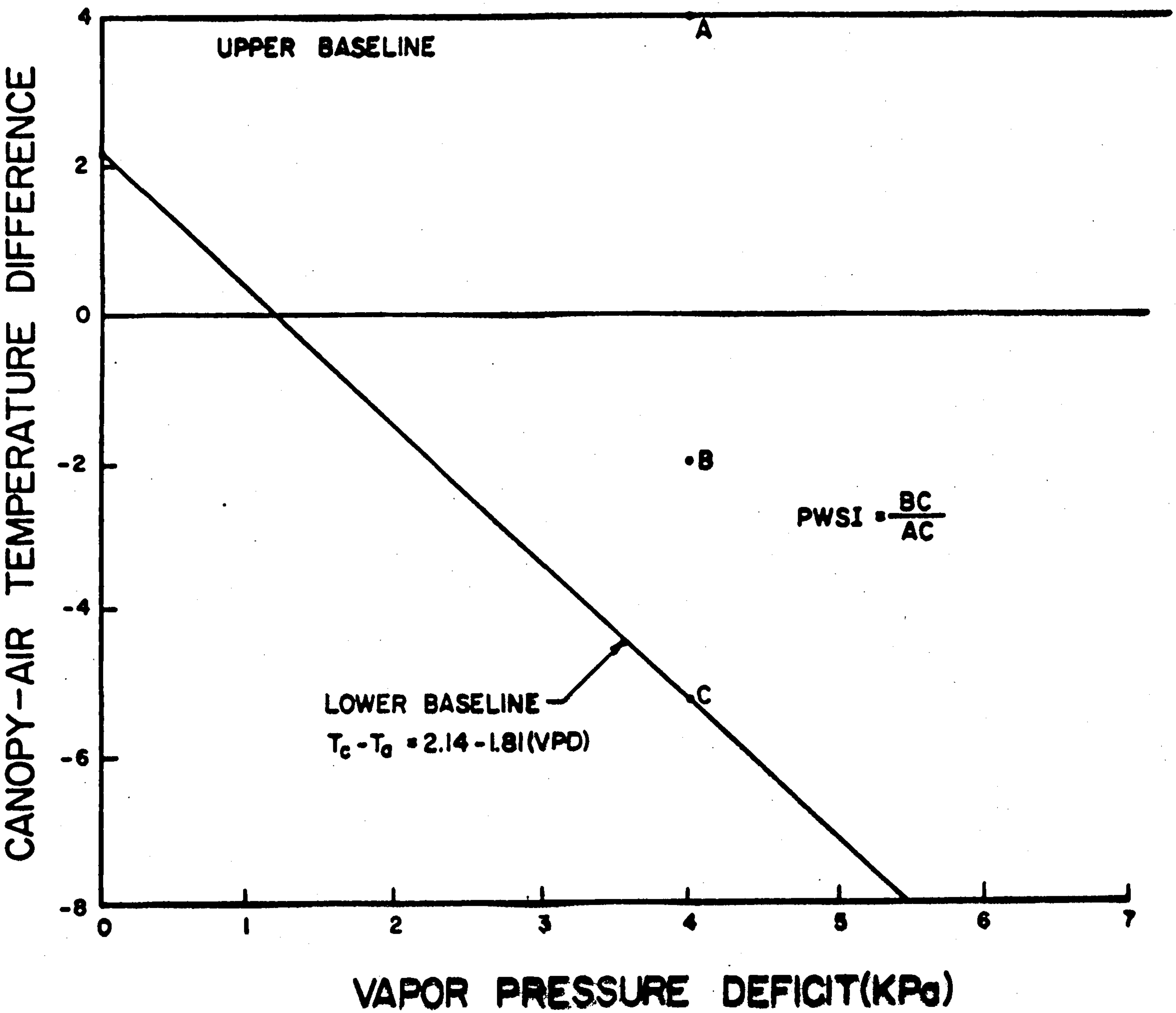
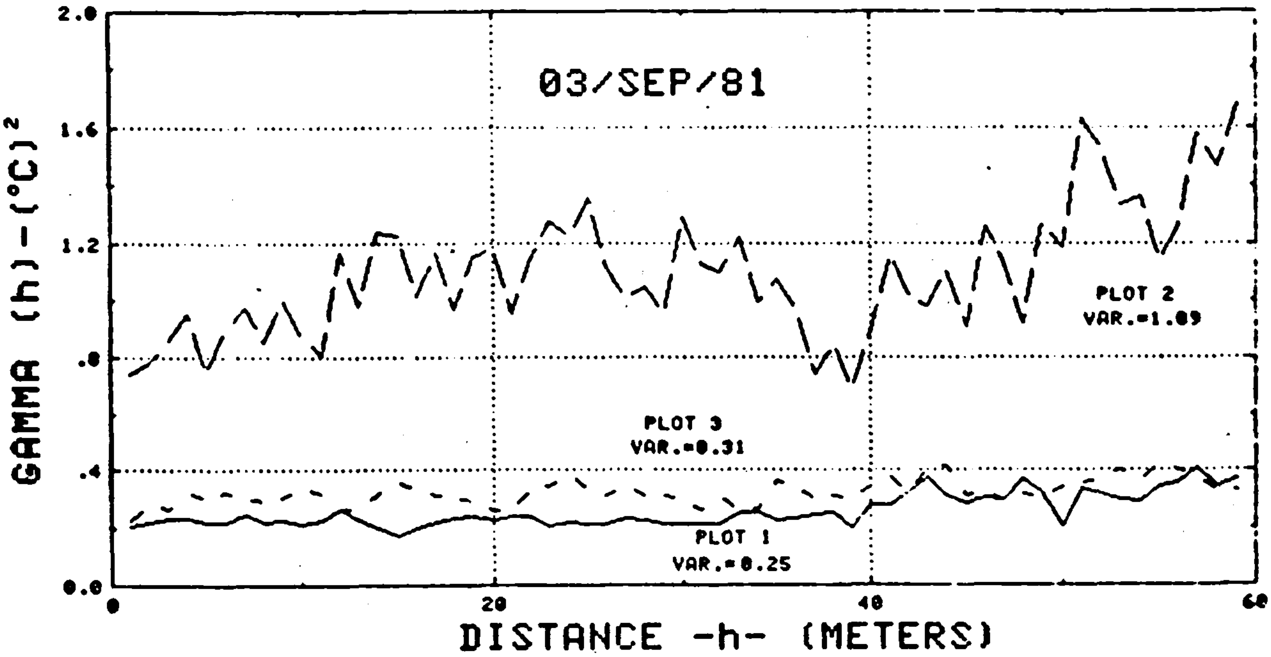
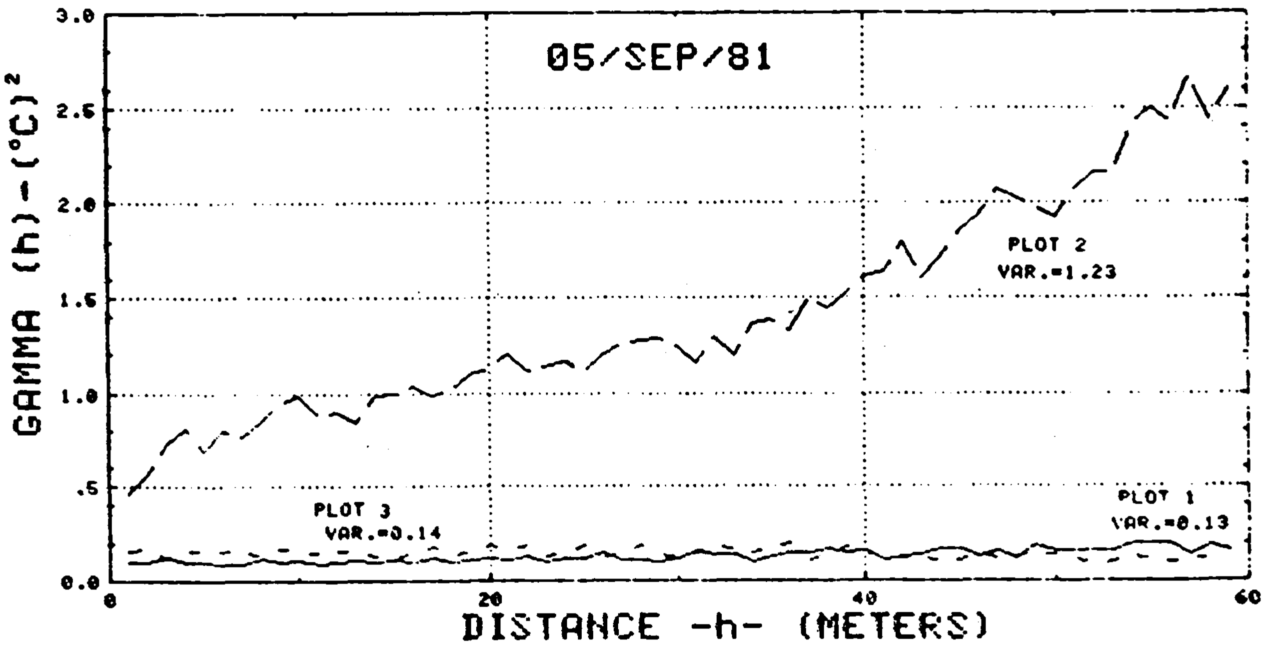

UPPER BASELINE
A
B
C
PWSI = BC/AC
LOWER BASELINE
$T_c - T_a = 2.14 - 1.81(VPD)$
CANOPY-AIR TEMPERATURE DIFFERENCE
VAPOR PRESSURE DEFICIT(KPa)
4
2
0
-2
-4
-6
-8
0
1
2
3
4
5
6
7


03/SEP/81
GAMMA (h)-(°C)²
2.0
1.6
1.2
.8
.4
0.0
PLOT 2
VAR.=1.09
PLOT 3
VAR.=0.31
PLOT 1
VAR.=0.25
0
20
40
60
DISTANCE -h- (METERS)


05/SEP/81
GAMMA (h)-(°C)²
3.0
2.5
2.0
1.5
1.0
.5
0.0
PLOT 2
VAR.=1.23
PLOT 3
VAR.=0.14
PLOT 1
VAR.=0.13
0
20
40
60
DISTANCE -h- (METERS)

CROP STRESS VIA THERMAL IR APPROACHES

1. CANOPY-AIR TEMP.

2. CANOPY (ACTUAL-WELL-WATERED)

3. WITHIN FIELD VARIABILITY

BARTHOLIC ET AL.

$$LE = \frac{-(R_N + G)}{1 + T\,\frac{(T_A - T_C)}{(E_A - E_O)}}$$

BROWN - ROSENBERG

$$LE = -(R_N + G) + C_P\,\frac{(T_C - T_A)}{R_A}$$

SOER

$$LE = -\theta C_P \left(\frac{T_A - T_C}{R_A}\right) - (L - \phi S)\,R_S - c(L_P - T_C^4) - G$$

EVAPOTRANSPIRATION METHODS

BARTHOLIC	-	MODIFIED BOWEN RATIO
BROWN & ROSENBERG	-	RESISTANCE
SOER	-	ENERGY BALANCE
CANOPY TEMPERATURES	-	ACTUAL EVAPOTRANSPIRATION