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FIELD MEASUREMENTS, SIMULATION MODELING AND DEVELOPMENT OF ANALYSIS TECHNIQUES FOR MOISTURE STRESSED CORN AND SOYBEANS

1982 STUDIES

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16 Abstract

This report describes the experimental design, data acquisition and analysis procedures for agronomic and reflectance data acquired over corn and soybeans at the Sandhills Agricultural Laboratory of the University of Nebraska in 1982. Relevant remote sensing literature and theory are summarized. Statistical analysis and design considerations for field experiments are discussed.

The following conclusions were reached:

a. Predictive leaf area estimation models can be defined which appear valid over a wide range of soils.
b. Relative grain yield estimates over moisture stressed corn were improved by combining reflectance and thermal data.
c. Corn phenology estimates using the model of Badhwar and Henderson (1981) exhibited systematic bias but were reasonably accurate.
d. Canopy reflectance can be modelled to within approximately 10% of measured values.
e. Soybean pubescence significantly affects canopy reflectance, energy balance and water use relationships.

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University of Nebraska-Lincoln

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PREFACE AND ACKNOWLEDGEMENTS

This report details research conducted primarily at the Sandhills Agricultural Laboratory of the University of Nebraska in 1982. Some additional data has been supplied by LARS at Purdue University. The majority of the information reported here has been compiled by Bronson R. Gardner as part of his doctoral dissertation. Kirk L. Clawson has contributed some results which are also part of his doctoral dissertation and T. V. Ramana Rao has helped in some of the data collecting and analysis as part of his doctoral dissertation. The principal investigators gratefully acknowledge the dedication and hard work of these three graduate students. We are also appreciative of the efforts of Roberta Sandhorst who typed the report.

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1. INTRODUCTION

One challenging problem in remote sensing is to evaluate the influence of the soil background on the spectral signatures of a crop canopy. Soil reflectance properties vary considerably even at a single location. The successful application of biomass and canopy development estimation techniques depends on the degree to which these influences can be minimized.

A field research study was designed to develop and evaluate techniques for estimating agronomic parameters, such as leaf area, over corn and soybeans. The major objectives are (1) to identify transformations of Thematic Mapper multispectral data which essentially eliminate the soil as a significant factor in remote sensing of crops, but which respond in a relatively sensitive manner to crop development; (2) to determine the effect of moisture stress on agronomic parameters and plant water relations; (3) to test the model of Badhwar and Henderson (1980a, 1981) for estimating corn development stage; (4) to develop a statistical base for designing future experiments and (5) to compare field measurements with model predictions by Cupid.

2. THEORY AND REVIEW OF LITERATURE

2.1 Thermal Radiation

Radiation is a form of energy that continuously emanates from all matter as a result of oscillating magnetic and electrostatic fields. Thermal radiation is that portion of the electromagnetic spectrum which is produced as a result of the internal energy of a given material. In the equilibrium state, this internal energy is proportional to the temperature of the material. The wavelengths at which thermal radiation is emitted range from about 0.1 to about 1000 µm. This region is referred to as the thermal region or the infrared region (Siegel and Howell, 1981).

For convenience in discussing the radiation properties of materials having large temperature differences, the infrared region is often divided into the ultraviolet (0.1-0.38 μm), visible (0.38-0.72 μm), near infrared (0.72-1.30 μm), middle infrared (1.30-3.0 μm) and far infrared (7.0-15.0 μm) regions. Special terms are not normally applied to the 3.0-7.0 μm or 15.0-1000 μm regions. The 7.0-15.0 μm range is often referred to as the thermal region. Physically, however, thermal radiation is a term that applies to the 0.1-1000 μm waveband. Hence, the term far infrared is more precise. Other imprecise terms are reflective infrared and emissive infrared since all objects both emit and reflect infrared radiation in all wavelengths, although the relative magnitudes of emitted energy at any wavelength depends on relative temperature differences (Silva, 1978) (Table 2.1).

2.1.1 Thermal Radiation Theory

Before the theoretical developments proposed by Planck, experiments were conducted by Lummer and Pringsheim (1901) to measure the frequency distribution of thermal radiation. Rayleigh and Jeans proposed a theoretical model that conformed to the experimental results for long wavelengths, but which predicted infinite amounts of energy at short wavelengths. This discrepancy was called the ultraviolet catastrophe (Barr, 1960; Love, 1968).

The Rayleigh-Jeans model is not without merit, however, and was important in Planck's theory. Rayleigh and Jeans showed that the monochromatic energy density E(f) may be expressed as:

$$E(f) = 8\pi f^2 kT/c_0^3 \quad \text{(energy/volume)} \tag{2.1}$$

where f = frequency; k = Boltzmann's constant = universal gas constant/Avogadro's number; T = temperature (°K); c_0 = speed of light in a vacuum. Inspection of this equation shows that the energy predicted at the higher

Table 2.1 Sources dealing with the theory of radiation/heat transfer.

Barrett and Curtis (1976)	Remote sensing text
Silva (1978)	Radiation theory and remote sensing
Williams (1972)	Definition of thermography
Wiebelt (1966)	Radiation theory
Sparrow and Cess (1966)	Radiation theory
Love (1968)	Radiation theory
Siegell and Howell (1981)	Radiation theory
Kreith and Black (1980)	Radiation theory and applications
Harrison (1960)	Radiation theory
Planck (1959)	Radiation theory
Kruse et al. (1962)	Infrared radiation measurement technology

frequencies increases very rapidly.

Planck postulated that this model failed to consider the statistical nature of natural radiation. Using Einstein-Bose statistics, he concluded that natural radiation is the result of a field of ideal linear oscillators (Love, 1968). The energy of an ideal oscillator is the sum of the potential and kinetic energy at any given instant. Planck described the microscopic state or "phase plane" of an ideal oscillator in terms of displacement versus momentum and concluded that the area of the phase plane enclosed by the displacement versus momentum curve would be a constant, now known as Planck's constant (h). This theory limits the energy associated with a single oscillator, at a given frequency, to a multiple of hf.

Lewis (1973) discusses the derivation of Planck's law. Love (1968) presented a simplified outline of Planck's theory. Planck's theory states that as a result of the "elemental chaos" of natural radiation, the number of ideal oscillators required to produce a radiation wave is proportional to the energy of the oscillators:

energy of one radiation wave	ideal number of oscillators required
0	A
hf	A exp(-bhf)
2hf	A exp(-2bhf)
3hf	A exp(-3bhf)
.	.
.	.

The total number of oscillators (N) can be calculated by evaluating the infinite series:

$$N = A + A\exp(-bhf) + A\exp(-2bhf)\ldots = A/[1-\exp(-bhf)]$$

where b is a constant not yet defined. The total energy of the system (E) is the sum of the products of all the energy waves and the number of oscillators:

$$E = 0 + hfA\exp(-bhf) + 2hfA\exp(-2bhf)\ldots = hfA\exp(-bhf)/[1-\exp(-bhf)]^2$$

The average energy of a single oscillator (e) is thus equal to E/N:

$$e = hf\ \exp(-bhf)/[1-\exp(-bhf)] = hf/[\exp(bh)-1] \qquad (2.2)$$

Rayleigh and Jeans had also shown that the number of stationary electromagnetic waves per unit volume (N) of a radiation field is:

$$N = 8\pi f^2/c^3$$

where c is the speed of light in a given medium. The radiant energy per unit volume E(f) at a given frequency is the product eN:

$$E(f) = 8\pi hf^3/(c^3[\exp(bhf)-1]) \qquad (2.3)$$

Since the Rayleigh-Jeans expression is valid at low frequencies, the limit of (2.3) as hf goes to 0 should equal eq. (2.1). The limit of (2.3) can be evaluated by evaluating the limit of (2.2) as hf goes to 0. Replacing the exponential with its polynomial expansion:

$$\lim_{hf\to 0} e(f) = hf/(1+bhf+(bhf)^2/2'\ldots.(bhf)^n/n') = 1/b$$

Therefore, the limit of eq. (2.3) as hf goes to 0 is:

$$\lim_{hf\to 0} [E(f)] = 8\pi f^2/c^3b$$

Equating this limit with eq. (2.1):

$$8\pi F^2/c^3b = 8\pi f^2KT/c^3$$

therefore, $b = 1/kT$.

Planck (1959) showed that the relationship between E(f), energy per unit volume, and I(f), energy emitted per unit time per unit area per steradian, is $E(f) = 4\pi I(f)/c$. Thus, the monochromatic intensity of emitted radiation is:

$$I(f) = 2hf^3/(/c^2\ [\exp(hf/kT)-1])\ df \tag{2.4}$$

The monochromatic intensity can also be expressed as a function of wavelength (λ) using the relationships:

$$\lambda = c/f \text{ and } d\lambda = -c/f^2\ df$$

As a result of the minus sign in $d\lambda$, absolute values must be used in relating I(f) with $I(\lambda)$. The energy emitted per unit time per unit area per steradian in an interval $d\lambda$ is thus:

$$I(\lambda) = 2hc^2/(\lambda^5\ [\exp(hc/k\lambda T)-1])d\lambda \tag{2.5}$$

The speed of light in a given medium (c) can be related to the speed of light in a vacuum (c_0) by the index of refraction n. Therefore:

$$I(\lambda) = 2\ hc_0^2/(n^2\lambda^5\ [\exp(hc_0/nkT\lambda)-1])d\lambda \tag{2.6}$$

Since the index of refraction is approximately 1 for the atmosphere, it is generally not used in calculating $I(\lambda)$. Note that all terms are constant except λ and T. Thus:

$$I(\lambda) = 2c_1/(n^2\ \lambda^5\ [\exp(c_2/\lambda T)-1])d\lambda \tag{2.7}$$

where $c_1 = hc_0^2 = 0.59544(10)^{-16}$ W/m^2 and $c_2 = hc_0/k = 14388$ µm°K. When integrated over an entire hemisphere (π steradians) the hemispherical energy emitted per unit time per unit area at a wavelength λ is:

$$I_b(\lambda) = 2\pi\ c_1/(\lambda^5\ [\exp(c_2/\lambda T)-1]) \tag{2.8}$$

Equation (2.8) thus describes the theoretical energy that can be emitted at a given wavelength into a hemisphere in a vacuum (the index of refraction n has been dropped) by an object at temperature T. Equation (2.8) is known as Planck's spectral distribution of emissive power for a black body. Objects that emit energy according to eq. (2.8) are known as black bodies. This one equation is sufficient to describe the theoretical thermal radiation emitted by all objects.

Few objects emit as much energy as predicted by eq. (2.8), however. The ratio of the energy actually emitted to that predicted by eq. (2.8) is called the emissivity (ε). Thus, for real objects:

$$I(\lambda) = \varepsilon(\lambda) 2\pi C_1 / \lambda^5 \, [\exp(c_2/\lambda T)-1] \tag{2.9}$$

Note that emissivity is a function of wavelength. Equation (2.9) can be easily integrated between two wavelengths only if emissivity is assumed constant between those two wavelengths:

$$I = \overline{\varepsilon} \int_{\lambda_1}^{\lambda_2} 2\pi c_1 / (\lambda^5 \, [\exp(c_2/\lambda T)-1]) d\lambda \tag{2.10}$$

where $\overline{\varepsilon}$ is the average emissivity between λ_1 and λ_2. At a given wavelength, the absorptivity equals the emissivity. If emissivity, or absorptivity, is assumed independent of wavelength, the object is called gray (Love, 1968).

Equation (2.10) can be evaluated by a transformation of variables where v = $c_2/\lambda T$:

$$I_{\lambda_1-\lambda_2} = \overline{\varepsilon}\, \pi \int_{\lambda_2}^{\lambda_1} \left(\frac{c_2}{\lambda T}\right)^5 \left(\frac{T}{c_2}\right)^5 \left[\; 2c_1 \quad (\exp[c_2/\lambda T]-1 \right] \left(\frac{\lambda T}{c_2}\right)^2 \left(-\frac{c_2}{T}\right) d\left(\frac{c_2}{\lambda T}\right)$$

$$= 2 \frac{\bar{\varepsilon} \pi c T^4}{c_2^4} \int_{\lambda_1}^{\lambda_2} \frac{v^3}{e^v - 1} dv \tag{2.11}$$

If $\lambda_1 = 0$ and $\lambda_2 = \infty$; the integral has a value of $\pi^4/15$ (Abramowitz and Stegun, 1965). Thus:

$$I_{total} = \frac{\overline{2} \varepsilon c_1 \pi^5}{15 c_2^4} T^4 = \bar{\varepsilon} \sigma T^4 \tag{2.12}$$

where $\bar{\varepsilon}$ is the average emissivity over all wavelengths and σ is the Stefan-Boltzman constant. Theoretical and experimental values of σ differ slightly. The experimental value of σ is 5.729×10^{-8} W/m^2 °K (Siegell and Howell, 1981). If the index of refraction is included, $I_{total} = \varepsilon n^2 \sigma T^4$.

It can now be seen why confusion concerning emissivity values in the literature may arise. The appropriate emissivity for eq. (2.12) is the average emissivity over all wavelengths (gray-body emissivity), yet the emissivity value used in many remote sensing studies is that determined by methods similar to Fuchs and Tanner (1966). Emissivities determined by this method are obtained with an infrared thermometer (IRT), which measures energy in discrete wavebands, such as 8-14 µm. Hence, emissivity values determined by this method are average emissivity values in the discrete waveband measured by the IRT.

The appropriate form of eq. (2.12) for discrete wavelength intervals is:

$$I_{\lambda_1 - \lambda_2} = \varepsilon' \sigma T^4 F \tag{2.13}$$

where ε' is the average emissivity between λ_1 and λ_2 and F is the fraction of σT^4 in the wavelength interval λ_1-λ_2 at temperature T (Siegell and Howell, 1981). This factor is included as part of the calibration of an infrared thermometer and, therefore, does not normally appear in remote sensing literature. Hence, although eq. (2.12) is generally written, theoretically it is eq. (2.13) that is used. It is important to remember that a finite band emissivity (ε') calculated by the methods of Fuchs and Tanner (1966) is not an average emissivity from 0 to ∞. Vegetation cannot be assumed gray, except over small wavelength intervals. Consequently, care should be taken to ensure that finite-band emissivities are not confused with gray-body emissivities when eq. (2.12) is used.

2.1.2 Radiation Geometry

Geometrical theory can be used to define the relationship between hemispherically emitted energy and directionally emitted energy for black bodies, since the intensity of emitted radiation from a black body is equal in all directions (diffuse) (Table 2.2).

2.1.3 Designing a Laboratory Black Body

To construct a cavity that will approximate blackbody emission for use in calibrating radiation detecting equipment (such as infrared thermometers) a cylindrical tube, with one end partially opened, can be used. The apparent emissivity of the bottom of the cavity is a function of the length of the tube, the emissivity of the cavity material and the diameter of the opening at the end of the tube (Table 2.3) (Siegell and Howell, 1981). High-emissivity black paint (greater than 0.9) could be used to coat the interior of a thin metallic cylinder so that thermal equilibrium of the cylinder with the changing temperatures of a water bath could be rapidly achieved (Blad and Rosenberg, 1976).

2.1.4 Emissivity Values of a Crop Canopy

Sutherland and Bartholic (1977) presented formulae for calculating effec-

Table 2.2 Relationships between hemispherically emitted spectral energy and directionally emitted energy for a black body (Siegell and Howell, 1981).

Symbol	Name	Definition	
$I(\lambda)$	hemispherical spectral emissive power	emission into hemispherical solid angle per unit surface area, wavelength and time	$2\pi C_1/\lambda^5(\exp(C_2/\lambda T)-1)$
$I'(\lambda)$	spectral intensity	emission in any direction per unit of projected area normal to that direction, and per unit time, wavelength and solid angle	$I(\lambda)/\pi$
$e(\lambda)$	directional spectral emissive power	emission per unit solid angle at a zenith angle θ per unit surface area, wavelength and time	$I(\lambda)\cos\theta/\pi$
$e'(\lambda)$	finite solid-angle spectral emissive power	emission in a solid angle per unit surface area, wavelength and time. θ is the plane angle meausre of the solid angle. ϕ is the circumferential angle of the solid angle. For a cone, ϕ is 2π	$I(\lambda)(\sin^2(\theta))\phi/2\pi$ $= I(\lambda)\sin^2(\theta)$ if the solid angle has a cone shape
I_{total}	hemispherical total emissive power	total emission, into all wavelengths, into a hemisphere per unit surface area and time	σT^4
I'_{total}	total intensity	total emission, into all wavelengths, in any direction per unit of projected area normal to that direction, per unit time and solid angle.	I_{total}/π
E_{total}	directional total emissive power	emission, into all wavelengths at a zenith angle θ per unit surface area, solid angle and time	$I_{total}\cos\theta/\pi$
E'	finite solid-angle total emissive power	emission in a solid angle per unit surface area, wavelength and time. θ is the plane angle measure of the solid angle. ϕ is the circumferential angle of the solid angle. For a cone, ϕ is 2π	$I_{total}(\sin^2\theta)\phi/2\pi$ $= I_{total}\sin^2\theta$ if the solid angle has a cone shape.

Table 2.3 Apparent emissivity of a cavity opening for a cylindrical cavity of finite length (L) and radius (R). The cavity is made of material with emissivity ε and has a diaphram covering the opening. The diaphram has a hole in the center with radius R_i (Siegell and Howell, 1981).

material emissivity		apparent emissivity		
ε	R_i/R	L/R = 2	L/R = 4	L/R = 8
0.25	0.4	0.916	0.968	0.990
	0.6	0.829	0.931	0.981
	0.8	0.732	0.888	0.969
	1.0	0.640	0.844	0.965
0.50	0.4	0.968	0.990	0.998
	0.6	0.932	0.979	0.995
	0.8	0.887	0.964	0.992
	1.0	0.839	0.946	0.989
0.75	0.4	0.988	0.997	0.999
	0.6	0.975	0.993	0.998
	0.8	0.958	0.988	0.997
	1.0	0.939	0.982	0.996

tive canopy emissivity (ε_c) as a function of canopy height (H), row spacing (W), soil emissivity (ε_s), leaf emissivity (ε_ℓ) and sky emissivity (ε_{sky}) in a narrow wavelength interval. The equation is:

$$\varepsilon_c = \frac{\varepsilon_s + \varepsilon_\ell(1-\varepsilon_s)F + \varepsilon_{sky}(1-\varepsilon_s)(1-F)}{1 + H/W} + \frac{\varepsilon_\ell + \varepsilon_{sky}(1-\varepsilon_\ell)}{1 + W/H} \tag{2.14}$$

where $F = (1 + H/W) - [1 + (H/W)^2]^{1/2}$.

Idso (1982) presented formulae for calculating ε_{sky} as a function of air temperature and vapor pressure. This model (eq. 2.14) shows that, once the ratio H/W exceeds approximately 1.0, cavity effects cause the effective canopy emissivity to become approximately constant (Fig. 2.1). The effective emissivity is around 0.01 to 0.02 greater than the leaf emissivity after this point. Before this point, canopy emissivity rapidly increases from the bare soil emissivity value to a maximum value at H/W of approximately 1.0. Idso et al. (1969c) reported an emissivity value of 0.944 for corn (Zea mays L.) leaves. Thus corn canopy emissivity should be about 0.964. This projected value agrees closely with the measured value of 0.97 by Gardner (1980) over a young corn canopy using the technique described by Fuchs and Tanner (1966).

2.1.5 Effect of Emissivity Errors on Canopy Temperature

Infrared thermometers are calibrated to measure the apparent black-body temperature of an object (T_{ab}). The energy sensed by an IRT originates as emitted radiation from the surface of interest and reflected radition from the surroundings. T_{ab} will depend on the true emissivity of the surface (ε_t) and, for field situations where trees or tall buildings are not present, on the effective radiative temperature of the sky (T_s) which is a function of the screen-level air temperature (Idso and Jackson, 1969). The apparent temperature sensed by an IRT is thus:

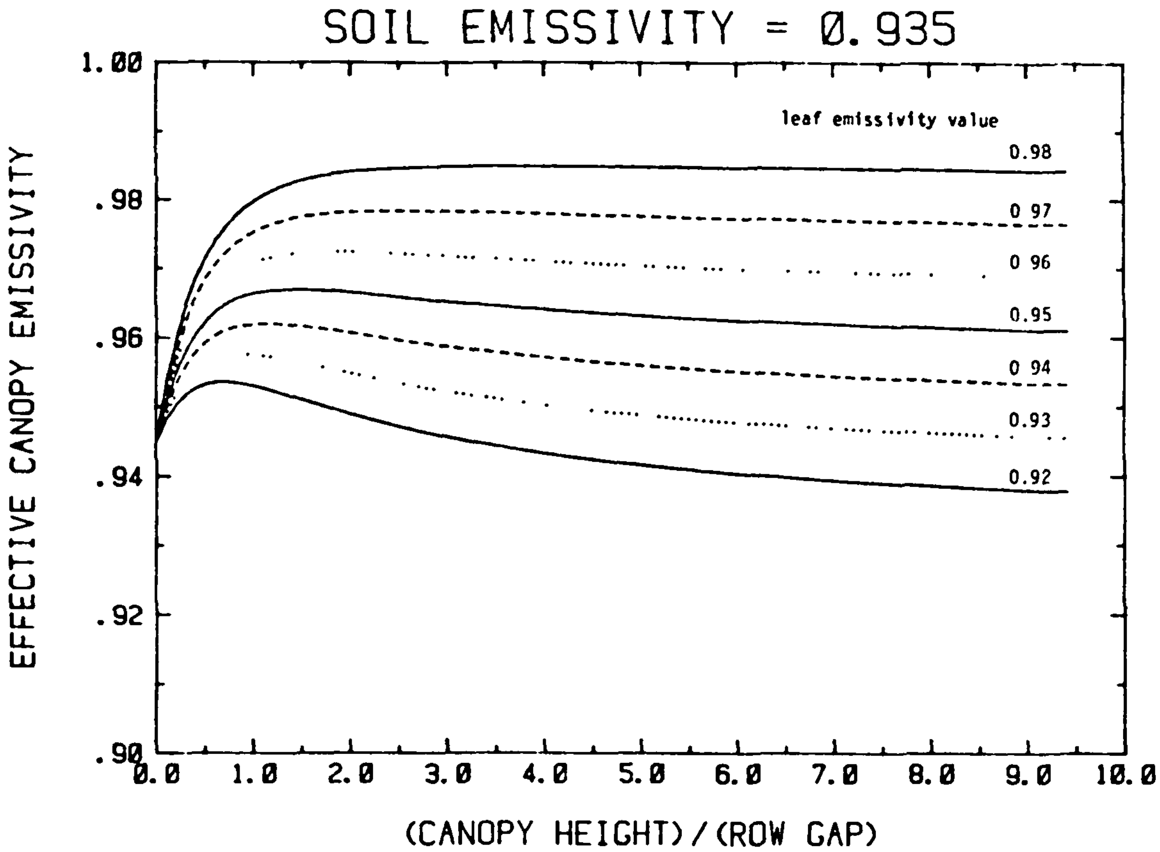

Fig. 2.1 Theoretical values of effective canopy emissivity as a function of leaf emissivity and the ratio (canopy height)/(row gap), where the row gap is the distance between canopy envelopes in adjacent rows (Sutherland and Bartholic, 1977).

$$T_{ab} = [\varepsilon_t T_t^4 + (1-\varepsilon_t) T_s^4]^{1/4} \quad (2.15)$$

where T_t is the true surface temperature. In practice, T_{ab} is measured, but ε_t and T_t are not known. True canopy temperature is normally estimated as:

$$T_c = [(T_{ab}^4 - (1-\varepsilon_e) T_s^4)/\varepsilon_e]^{1/4} \quad (2.15)$$

where T_c is estimated canopy temperature and ε_e is the estimated surface emissivity. Equation (2.14) can be used to calculate T_{ab} for a given set of conditions and then inserted into eq. (2.15) to estimate the true surface temperature. The difference between T_t and T_c represents error. This error is a function of the estimated emissivity and effective radiative sky temperatures (Idso and Jackson, 1968; Taylor, 1979) (Table 2.4). For example, if the true surface temperature is 30 C, the true surface emissivity is 0.96 and the effective radiative sky temperature is 273 K (0 C), then errors of 0.01 in emissivity will result in errors of less than 1 C (Fig. 2.2).

2.1.6 Radiation Geometry

In general, reflectance is defined as the ratio of reflected to incident radiation. It is important to understand the geometry involved in the incident and measurement beams if the reflectance calculation is to be properly understood (Table 2.5). Radiation beams may be directional, conical or hemispherical (Fig. 2.3).

The sun is essentially a directional radiation source, although some hemispherical (diffuse) radiation is also present as a result of atmospheric scattering. For practical purposes, instruments with fields of view less than 20° can be considered directional radiation detectors (Robinson and Biehl, 1979). Hemispherical solar radiation detectors include albedometers, net

Table 2.4 Papers dealing with the emissivity of soils, vegetation or longwave emissions from the sky (B*).

Taylor (1979)	Measured soil emissivity; emissivity induced errors $T_s = \frac{[T_\lambda^4 - (1-\varepsilon_\lambda)T_b^4]^{1/4}}{\varepsilon_\lambda}$
Idso and Jackson (1969b)	Formula for estimating B* using air temperature
Aase and Idso (1978)	Comparison of formula for B*
Idso and Jackson (1969a)	Soil emissivity data
Idso et al. (1969c)	Leaf emissivity data/measurement techniques
Idso (1972)	Measuring B* with net radiometers
Sutherland and Bartholic (1977)	Cavity effects in row crops on canopy emissivity
Idso and Jackson (1968)	Theory and emissivity data for several surfaces - effect of B* fluctuations $\sigma T_A^4 = \varepsilon\sigma T^4_{true} + (1-\varepsilon)\sigma T^4_{sky}$
Idso et al. (1976a)	Laboratory technique for measuring emissivity
Sutherland and Bartholic (1979)	Theory of instrument/emissivity responses
Buettner and Kern (1965)	Methods of evaluating emissivity
Idso (1982)	Formulae for narrow band sky emissivity values and estimating vapor pressure deficits with an infrared thermometer

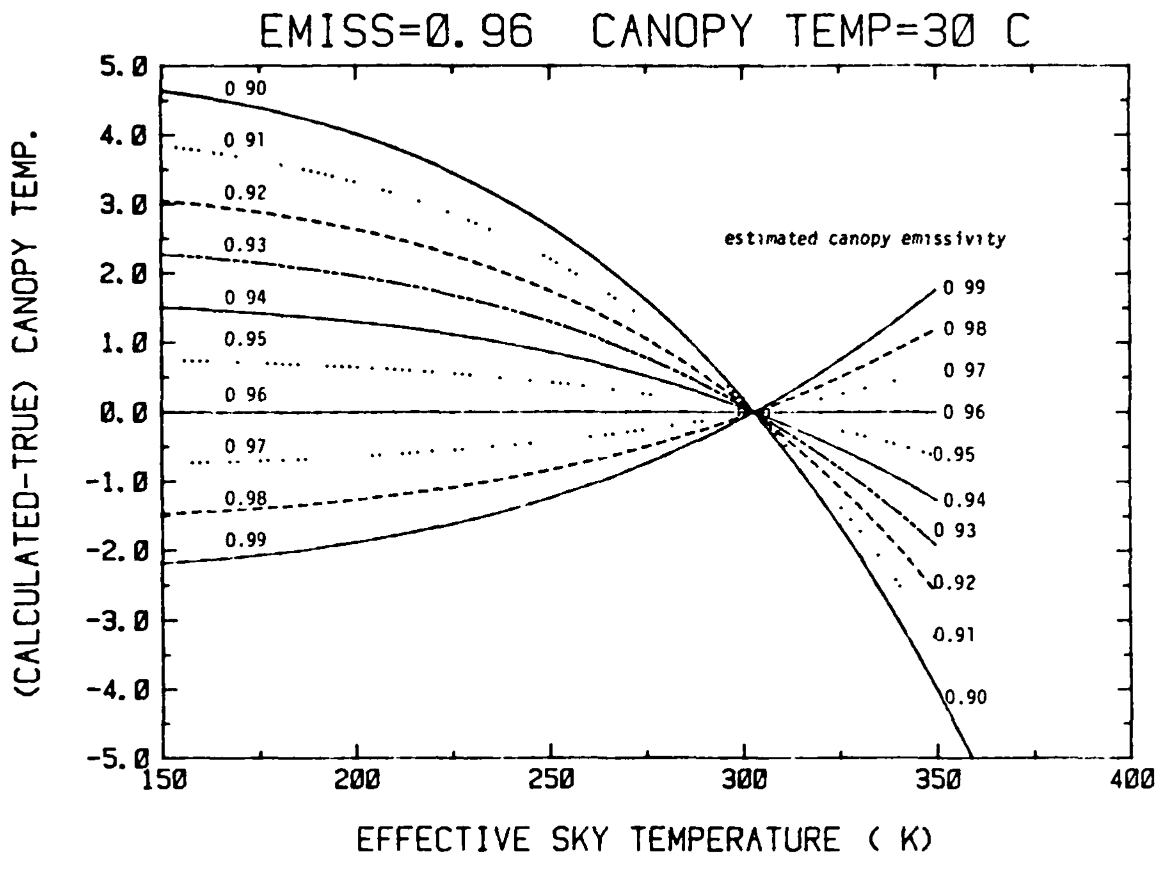

Fig. 2.2 Differences between estimated and true canopy temperatures as a function of radiative sky temperatures and estimated canopy emissivity. True canopy temperature was taken as 30°C, with a true emissivity of 0.96.

Table 2.5 Papers dealing with reflectance theory/definitions.

Judd (1967)	Terms and definitions
Spencer and Gaston (1975)	Definitions
Barr (1960)	History of infrared theory development
Billmeyer et al. (1971)	Reflectance properties of barium sulfate
Bunnik (1978)	Comprehensive discussion of reflectance modeling theory
Swain (1978)	Bidirectional reflectance theory and geometry
Sommerfeld (1954)	Optical theory
Meyer-Arendt (1968)	Radiometry units and conversion factors
Robinson and Biehl (1969)	Calibration procedures for measuring reflectance factors

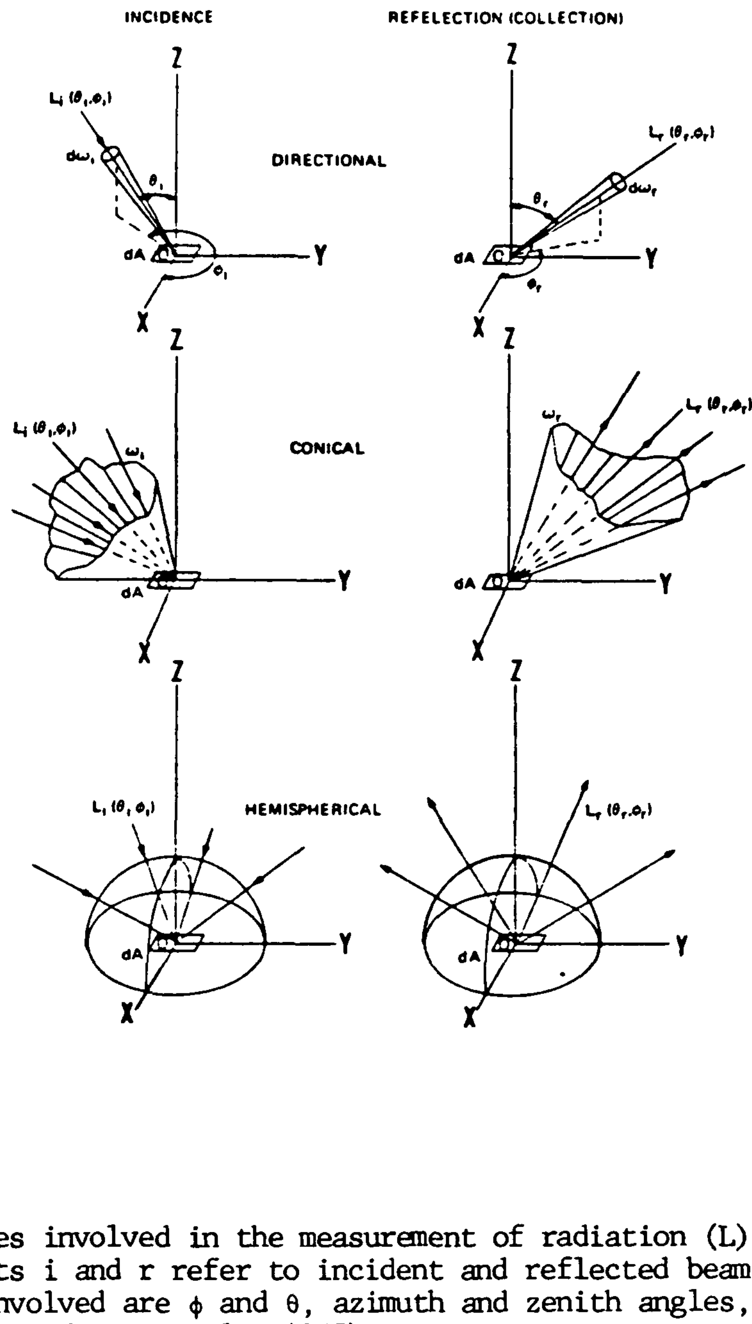

Fig. 2.3 Geometries involved in the measurement of radiation (L). The subscripts i and r refer to incident and reflected beams. The angles involved are ϕ and θ, azimuth and zenith angles, respectively (Nicodemus et al., 1977).

radiometers and pyranometers. Conical radiation detectors are instruments with a wide field of view (greater than 20°, but less than 180°). Nine reflectances can be defined from these geometries (Table 2.6) (Judd, 1967; Nicodemus et al., 1977; Siegel and Howell, 1981).

It is also important to understand the geometrical relationship between incident (I_o) and reflected (I_r) radiation from a perfectly diffuse surface. Spherical geometry can be used to show that $I_r = I_o/\pi$ (Nicodemus et al., 1977; Siegel and Howell, 1981).

2.2 Reflectance Definitions

In terms of incident solar radiation (I_o) and reflected radiation from a crop surface (I_r), the bidirectional distribution function (BRDF) is:

$$BRDF = I_r(\theta_i, \phi_i; \theta_r, \phi_r)/I_o(\theta_i, \phi_i; \theta_r, \phi_r) = fr$$

where θ and ϕ are zenith and azimuth angles and the subscripts i and r refer to incident and reflected radiation beams. The reflected beam is measured with a directional radiometer. The BRDF may take on any value from 0 to infinity. It is not easy to make sufficient measurements to characterize the entire BRDF of a canopy. Hence, it is desirable to define a standard radiation geometry. The geometry often selected to measure I_r is a zenith angle of 0°, thus making I_r independent of ϕ_r. Hence, the reflectance of a canopy can be defined as:

$$R = I_r(\theta_i, \phi_i)/I_o(\theta_i, \phi_i)$$

Thus canopy reflectance using this measurement geometry is dependent only on solar azimuth and zenith angles. It should be emphasized that measurement of I_r at a zenith angle of 0° fails to provide much information concerning the nature of canopy reflectance. Important information has been shown to exist

Table 2.6 Nine definitions of reflectance based on the bidirectional distribution function (f_r) and the geometry of the incident and reflected beams.

			Comments
1.	Bidirectional reflectance	$= f_r \, d\Omega_r$	incident and measured reflected beams are in a small solid angle
2.	Directional-conical reflectance	$= \int_{\omega_r} f_r \, d\Omega_r$	incident beam is in a small solid angle, measured reflected beam is in a large solid angle (cone)
3.	Directional-hemispherical reflectance (albedo)	$= \pi \, f_r$	incident beam is in a small solid angle, measured reflected beam is a hemisphere
4.	Conical-directional reflectance	$= (d \, \Omega_r/\Omega_i) \int_{\omega_i} f_r \, d\Omega_i$	inverse of number 2
5.	Biconical reflectance	$= (1/\Omega_i) \int_{\omega_i} \int_{\omega_r} f_r \, d\Omega_r \, d\Omega_i$	incident and measured reflected beams are in a large solid angle
6.	Conical-hemispherical reflectance	$= (1/\Omega_i) \int_{\omega_i} \int_{2\pi} f_r \, d\Omega_r \, d\Omega_i$	incident beam is in a large solid angle, measured reflected beam is a hemisphere
7.	Hemispherical-directional reflectance	$= (d\Omega_{r/\pi}) \int_{2\pi} f_r \, d\Omega_i$	inverse of number 3
8.	Hemispherical-conical reflectance	$= (1/\pi) \int_{2\pi} \int_{\omega_r} f_r \, d\Omega_r \, d\Omega_i$	inverse of number 6
9.	Bihemispherical reflectance	$= (1/\pi) \int_{2\pi} \int_{2\pi} f_r \, d\Omega_r \, d\Omega_i$	incident and measured reflected beams are hemispherical

Note that f_r is a function of the azimuth and zenith angles (ϕ and θ, respectively) of the incident and reflected beams. Thus, $f_r = f_r(\theta_i, \phi_i; \theta_r, \phi_r)$.

in the off-nadir directions (Vanderbilt et al., 1980).

2.2.1 Reflectance Factor Definitions

With many instruments, such as multiband radiometers, it is not convenient to measure I_o directly. Instead, the reflected energy from a reference surface is used as an indicator of I_o. One type of reference surface is composed of pressed barium sulfate powder. This type of surface is highly diffuse, differing no more than 3% from Lambertian (perfectly diffuse) for incident radiation zenith angles of 0-55° (Robinson and Biehl, 1979). Reflected energy from a diffuse reference surface is denoted I'. The ratio I_r/I' is termed a reflectance factor (RF). Since individual reference surfaces differ in their reflectance properties, RF is generalized by including the reflectance of the surface (R_p).

$$RF = I_r/(I'R_p) \tag{2.16}$$

R_p is a function of zenith angle.

Noting that $I' = I_o/\pi$ for a diffuse surface:

$$RF = \pi I_r/I_oR_p \tag{2.17}$$

Hence, the reflectance factor of a crop is approximately π times its bidirectional reflectance. This statement is only partially true, since crops are not entirely diffuse surfaces.

In eq. (2.17) reflected radiation is measured directionally. If the crop is assumed to be a diffuse surface, then the hemispherically reflected radiation is πI_r. If I_o can now be measured directly, the albedo of the crop can be defined:

$$\text{albedo} = (\pi I_r)/I_o = RF = I_r/(I_o/\pi)R_p \tag{2.18}$$

Hence, the reflectance factor of a crop and the albedo of a perfectly diffuse crop are theoretically the same. Consequently, numerical values of crop reflectance factors and albedo values can be expected to be similar.

2.2.2 Diurnal Albedo and Reflectance Factor Patterns

Although theoretically the same, albedo trends and reflectance factor trends are inversely related to each other. Albedo is maximum at low solar zenith angles and minimum at solar noon (Nkremdirim, 1972; Coulson and Reynolds, 1971). Reflectance factors are minimum at low solar zenith angles and maximum at solar noon (Kollenkark et al., 1981). This inverse relationship can be explained on the basis of the reflectance properties of leaves and canopies and the radiation measurement geometry involved in the two measurements.

Leaf and canopy reflectance patterns contain definite specular components (Wooley, 1971; Eaton and Dirmhirn, 1979). These specular components can be expected to be strongest at low solar elevation angles (Wooley, 1971). At low solar elevation angles, a hemispherical reflectance measurement should detect relatively high levels of radiation as a result of specular reflections. As the solar elevation angle increases, the canopy begins reflecting as an increasingly diffuse surface. Hence, the minimum albedo is reached at solar noon.

A directional reflectance measurement (made from the nadir direction) will not detect specular reflections from the canopy. Hence, the pattern of reflectance factor measurements can be expected to follow the same pattern as the incoming solar radiation intensity, since only diffuse radiation is detected. Consequently, reflectance factors reach a maximum at solar noon. Reflectance factors and albedo measurements will, therefore, be most similar in magnitude around solar noon.

2.3 Reflective Properties of Leaves

Reflectance properties of individual leaves are basic to understanding the reflectivity of an entire plant or vegetation canopy (Knipling, 1970) (Table 2.7). Between 0.4 (blue) and 0.7 (red) μm, the reflectance is very low. The peak at about 0.55 μm, which accounts for the perceived color of green, is caused by two chlorophyll absorption bands centered at approximately 0.45 and 0.65 μm (Hoffer, 1978). Carotenes and xanthophylls also absorb energy around 0.45 μm. Thus, changes in the pigmentations of a leaf will primarily affect the shape of the reflectance curve in the 0.4-0.7 region (Hoffer and Johannsen, 1969).

Between 0.7 and 1.4 μm, healthy green leaves are characterized by high reflectance (45-50%), high transmittance (45-50%) and low absorptance (less than 5%) (Hoffer, 1978). Knipling (1970) stated that the internal structure of leaves accounts for the similarity of the reflectance and transmittance spectra. Elimination of internal air cavities drastically reduced reflectance between 0.7 and 1.2 μm. Myers (1970) and Sinclair et al. (1971) showed that the reflectance spectra from healthy green leaves of various crops at similar moisture contents are different in magnitude but similar in shape. The differences in reflectance were attributed to differences in internal leaf structure. Allen et al. (1970b) associated reflectance measurements at 1.65 μm from nine field-grown types of leaves with the equivalent water thickness (D) and intercellular air spaces (N) in the leaf. They showed that as the ratio D/N increased, reflectance decreased.

2.3.1 Leaf Reflectance and Short-Term Water Stress

Leaves subjected to short-term stress, such as that experienced in controlled relative water content (RWC) experiments, increase in reflectance at all wavelengths with decreasing water content once the RWC is below 66-80%

Table 2.7 Papers dealing with leaf optical properties--theory or laboratory measurements.

Allen et al. (1973)	Ray tracing theory
Allen et al. (1971)	Equivalent water thickness of grapefruit, corn and cotton leaves
Allen et al. (1970b)	Optical properties of 13 leaf types including corn, sorghum and wheat
Al-Abbas (1974)	Effect of nitrogen deficiency on corn leaf reflectance
Breece and Holmes (1971)	Soybean and corn leaf reflectances
Carlson et al. (1971)	Leaf water effects
Chance and LeMaster (1977, 1978)	Canopy reflectance models for wheat and cotton
Colwell (1974a)	Dead and live leaf reflectances
Gausman et al. (1971a,b; 1973a,b; 1976; 1977a; 1978a,b; 1981; 1982)	Reflectance, absorption and transmission properties of many different leaves
Knipling (1970)	Theory and leaf spectra
Kumar and Silva (1978)	Light ray tracing theory
Meyers (1970)	Multiple NIR reflectance from leaf layers
Sinclair (1971)	Spectra from several different leaves
Sinclair (1973)	Hypothesis for diffuse reflectance pathway
Tucker (1980a)	Simulation model
Turrell (1936)	Internal exposed area of leaves
Wooley (1971)	Reflectance of several leaves irradiated at various angles
Wiegand et al. (1971)	Single leaf and infinite reflectance of 9 agricultural plant leaves

(Hoffer and Johannsen, 1969). Since wilting occurs when RWC is greater than 80%, it is probable that no detectable change in leaf or canopy reflectance would be detectable in leaves experiencing early stages of moisture stress. Short-term water stress will primarily influence leaf temperature, which may be detected radiometrically (Drake, 1976).

2.3.2 Leaf Reflectance and Long-Term Water Stress

Leaves from plants subjected to long-term or intermittant water stress develop more compact internal structure, thus exposing more inner surface to air per unit outer surface than in nonstressed leaves. The expected result is an increased reflectance at all wavelengths (Bidwell, 1979; Drake, 1979; Turrell, 1936). Idso et al. (1980) showed that, during the grain-fill period, wheat grown under moisture stress conditions exhibited higher visible reflectance than nonstressed wheat.

Tucker (1980a) used a stochastic leaf radiation model to predict leaf spectral reflectance as a function of leaf water content for a dicot leaf. He concluded that the 1.55-1.75 μm region was best suited for remote sensing of plant water status. Meyers (1970) showed that the difference in reflectance between stressed and nonstressed cotton leaves was maximal around 1.75 and 2.25 μm. The transmittance was correspondingly reduced.

2.3.3 Leaf Reflectance and Nitrogen Status

The shape of the reflectance curve for nitrogen-deficient sweet pepper leaves is similar to those of normal leaves (Meyers, 1970). The severity of the nitrogen deficiency affects the reflective properties of the leaf. An increase in reflectance around 0.5 μm was the result of lower chlorophyll contents in the nitrogen-deficient leaves. An increase in reflectance between 0.7 and 1.3 μm suggests that nitrogen-deficient leaves may have smaller and fewer cells within the leaf, resulting in an increase in internal air spaces.

Reflectance in this region usually increases as the number of internal air spaces increase (Allen et al., 1971; Gates et al., 1965; Gausman et al., 1969; Knipling, 1970). A decrease in reflectance between 1.3 and 2.5 μm suggested that nitrogen-deficient leaves contain more water than normal leaves. In this case, the severely deficient leaves contained 3% more water than the mildly deficient leaf.

2.3.4 Leaf Reflectance and Plant Maturity

Gausman et al. (1970) reported that cotton leaves increased in near infrared reflectance as they developed during the first ten days after emergence. The changes in reflectance were related to increases in the intercellular air spaces caused by increased cell size. Sinclair et al. (1971) showed that the reflectance spectra of corn, soybeans, sorghum and sudan grass leaves increased at all wavelengths as the plants matured and the leaves senesced. Gausman et al. (1976) showed that near infrared infinite reflectance (R_∞) in corn leaves decreased as the leaves senesced. Two leaf layers resulted in R_∞ for dead leaves while eight leaf layers were required for live leaves.

2.3.5 Reflectance of Leaf Components

Gausman (1977a) concluded that refractive index discontinuities in leaves, other than air-cell interfaces, contribute significantly to the reflectance of near infrared light. If a leaf is assumed to reflect 40% of incident radiation at 0.8 μm, then non-air-cell interfaces can account for up to 20% of the reflected energy.

The cellular structure of some leaf components is relatively large when compared to the wavelengths found in solar radiation. Palisade cells are on the order of 15 μm x 60 μm; spongy parenchema and epidermal cells may measure 18 μm x 15 μm x 20 μm. Chloroplasts may be 5-8 μm in diameter, clearly of the same dimensions as mid-ir solar radiation. Thus, the grana may produce considerable scattering of incident radiation (Gates, 1965).

2.3.6 Surface Reflectance of Leaves

Visible reflectance from maize and soybean leaves contains distinctly specular components. The reflectance pattern for corn is affected by the orientation of the leaves to the incident radiation. The reflectance from the lower (dorsal) surface of a soybean leaf is much greater than from the upper (ventral) surface at all viewing angles. A 5-20° shift of the specular component away from the angle of incidence was attributed to the effect of surface irregularities. The leaves of maize and soybean do not begin closely approximating diffuse surfaces until the angle of incidence of the radiation is less than 15° from the normal. However, when the viewing angle is 0° from the normal (nadir), the reflectance in that direction is nearly identical when the angle of incidence ranges between 15° and 45° (Wooley, 1971).

2.4 Leaf Area Index and Biomass

Thomas et al. (1977) found that the clearest contrast between soil and vegetation for leaf area index estimations was in the 0.7-1.1 μm band. They concluded that the 1.1-2.5 μm region was best suited for observing plant moisture stress.

2.4.1 Multiple Leaf Layer Effects

The near infrared reflectance from multiple layers of leaves may be up to 85% greater than the reflectance of a single leaf (Meyers, 1970). This phenomenon is known as multiple reflectance. Radiation from the top layer of leaves is approximately equally transmitted and reflected (Hoffer, 1979). The maximum reflected (R_∞) is reached when the number of leaf layers reaches between 6 and 8 (Meyers, 1970; Gausman et al., 1976).

In field situations, the effective number of leaf layers is often less than that required to produce R_∞. Hence, near infrared reflectance (1.0-1.4 μm) of a crop canopy can be expected to increase continuously as LAI increases. This reflectance value will be biased by the reflectance characteristics of the soil. Minor multiple reflectance effects are also present in 1.6-1.9 μm range (Meyers, 1970). This range is also a strong water absorption region. R_∞ is reached by 3 leaf layers in this waveband. Hence, relationships between canopy reflectance and LAI will likely involve the 1.0-1.4 μm waveband. Multiple reflectance in the 1.6-1.9 μm band may likewise be important for crops with low leaf area indices.

2.5 Spectral Transformation Indices

Remote detection of crop water stress depends on selection of the right spectral index. The use of a spectral index or transformation provides for the possibility of "canceling" soil background effects. Several such transformations have been developed for Landsat multispectral scanner (MSS) bands (Table 2.8). Blad et al. (1982a) concluded that the Kauth and Thomas (1976) greenness index and the ratio of MSS4/MSS2 (RVI) were the best suited of these transformations for monitoring moisture stress. Note that the TVI transformation is approximately equal to log (RVI).

Tucker et al. (1979) used the RVI and TVI to relate to agronomic variables such as crop canopy cover, plant height and drought stress. The following conclusions were reached:

a. Significant relationships exist between spectral measurements and agronomic variables.

b. Asymptotic (logarithmic) relationships limit the usefulness of spectral data for estimating agronomic variables at high amounts of canopy cover or biomass.

c. Transformations involving the 0.63-0.69 μm and 0.75-0.80 μm wavebands

Table 2.8 Transformations of MSS Data.

Greenness[a] = -0.48935 x Band 4 - 0.61249 x Band 5 + 0.17289 x Band 6 + 0.59538 x Band 7

Brightness[a] = 0.32362 x Band 4 + 0.48521 x Band 5 + 0.56304 x Band 6 + 0.59538 x Band 7

TVI[c] = (Band 7 - Band 5)/(Band 7 + Band 5) ≈ $\log_{10}$ (Band 7/Band 5)

TVI6[c] = TVI with Band 7 replaced by Band 6 ≈ $\log_{10}$ (Band 6/Band 5)

DVI[b] = 2.4 x Band 7 - Band 5

AVI[b] = 2 x Band 7 - Band 5 if AVI < 0, then AVI = 0

RVI[b] = Band 7/Band 5

PVI[b] = $[(S_2 - \text{Band } 2)^2 + (S_4 - \text{Band } 7)^2]^{1/2}$

where S_2 = 0.851 x Band 5 + 0.355 x Band 7

S_4 = 0.355 x Band 5 + 0.148 x Band 7

PVI6[b] = $[(S'_2 - \text{Band } 5) + (S_3 - \text{Band } 6)]^{1/2}$

where S'_2 = -0.498 + 0.543 x Band 5 + Band 2 + 0.498 x Band 6

S_3 = 2.734 + 0.498 x Band 5 + 0.457 x Band 6

where Band 4 = 0.5 - 0.6 μm

Band 5 = 0.6 - 0.7 μm

Band 6 = 0.7 - 0.8 μm

Band 7 = 0.8 - 1.1 μm

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[a]Ranson, K. J., M. M. Hixson, V. C. Vanderbilt and M. E. Bauer. 1980. Estimation of corn and soybean development stages from spectral measurements. Field Research on the Spectral Properties of Crops and Soils. AgRISTARS JR-PO-04022. Purdue Univ., Laboratory for Applications of Remote Sensing, West Lafayette, IN.

[b]Richardson, A. J. and C. L. Wiegand. 1977. Distinguishing vegetation from soil background information. Photog. Engr. and Remote Sensing 43:1541-1552.

[c]Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing Environ. 8:127-150.

respond to the amount of photosynthetically active vegetation present in the canopy.

Wiegand et al. (1979) related leaf area index measurements of winter wheat (Triticum aestivum L.) to three vegetation indices: TVI, greenness and PVI. They found that all indices responded to changes in LAI from the time LAI exceeds 0.2 until the plants senesce. All the indices performed approximately the same, with the exception of the TVI. They concluded that spectral estimations of LAI and biomass are based on sound optical principles. They stated that more research is needed concerning the effects of differing leaf angles among cultivars and planting configurations. They also concluded that these effects would be small and that precision in LAI measurements would be necessary to detect them.

Aase and Siddoway (1980) found no general relationship between LAI and the PVI, PVI6, TVI and TVI6. The slopes of linear regression lines depended on the initial seeding rate of their plots. The reason for these differences was not given, but one possible explanation is that shadow effects caused by different density stands were responsible. It is possible that these findings are also related to the measurement technique, i.e., measurements were conducted at 0930 (solar time) while the observer stood on a platform 0.20 m above the ground. They concluded that further studies should be conducted to determine if a general relationship between LAI and vegetation indices exists. Visual inspection of their data shows that these transformations are logarithmically related to LAI when seeding rate is ignored. This observation agrees with the findings of Tucker et al. (1979a)--that these indices respond asymptotically to LAI--and suggests the need to reevaluate the data in terms of an index that responds linearly to LAI.

Bauer et al. (1979b) acquired spectral and agronomic measurements over spring wheat in Kansas, North Dakota and South Dakota during a three year period. The spectral measurements were made from a height of 6 meters with an Exotech 20 C spectrometer. Agronomic variables included percent soil cover, leaf area index, fresh biomass, dry biomass and plant water content. Linear correlation analysis was conducted between the agronomic variables and reflectances in the four Landsat MSS bands and the six Thematic Mapper (TM) bands. The results indicate that MSS and TM bands have a similar response to percent soil cover and leaf area index, but that the TM bands have a superior response to fresh biomass, dry biomass and plant water content. The highest correlations were found in the 1.55-1.75 and 2.08-2.35 µm bands, indicating that these bands contain significant information concerning canopy structure.

Maxwell et al. (1980) used six spectral vegetation indices to estimate green biomass. Spectral data were obtained from Landsat bands 2, 3 and 4. The analysis used 23 crop fields (corn, sugarbeet, pinto bean and alfalfa), 24 rangeland fields and six irrigated hay fields. None of the spectral indices had a linear relationship with biomass. Hence, log and square root transformations were applied to the biomass data. The most linear relationsip appeared to be between TVI and the square root of biomass.

Markham et al. (1981) used transformations of three Thematic Mapper bands (TM3, TM4, TM5) to relate to accumulated dry matter and dry grain yield in corn. They concluded that the ratio of TM4/TM3 provided the highest and most consistent correlations. The integration of this ratio over several dates improved the correlations.

Idso et al. (1980) used the TVI6 ratio to correlate with grain yield and yield reductions in moisture-stressed wheat and barley. They stated that the TVI6 ratio is highly indicative of green leaf area. Thus, it is responsive to the loss of chlorophyll as wheat turns brown during senescence. Differences in TVI6 between stressed and nonstressed wheat are due to differences in senescence rates. No stress-related differences were observed in TVI6 before heading.

Chappelle et al. (1980a) correlated reflectance in 15 spectral bands with the weight of plant water per unit area and the crop-air temperature differential (T_c-T_a) above a wheat canopy (Table 2.9). The bands at 1.425 and 1.940 µm exhibit a relatively high correlation with water status and T_c-T_a, but they are not on the Thematic Mapper. Several bands appeared suitable for correlating with crop-water status and crop-air temperature differences, however.

Chappelle et al. (1980a) also examined a stress index, defined as:

$$SI = (\text{middle IR} \times \text{red})/\text{near IR} \cong \frac{TM5 \times TM3}{TM4}$$

where middle IR = 1.66 µm, near IR = 0.870 µm, red = 0.67 µm. The stress index was found to be very highly correlated with percent canopy water content. They concluded that further study of this and other "adjustor" indices is warranted.

Gardner et al. (1982) showed that several spectral transformations of thematic mapper reflectance data were necessary in order to obtain the maximum predictability for various agronomic parameters of corn, soybeans and wheat. They concluded that the Thematic Mapper bands 1.55-1.75 µm and 2.08-2.35 µm provide information concerning the water condition of the canopy.

2.6 Soil Reflectance

Soil reflectance properties result from cumulative effects of the heterogeneous combination of mineral, organic and fluid matter constituting the soil. The spectral reflectance patterns of soils are distinctly different from that exhibited by leaves. While leaves exhibit absorption maxima at 0.47

Table 2.9 Reflectance relationships in 15 spectral bands to plant water content and stress degrees (canopy temperature (T_c) minus ambient air temperature (T_a). Wavelengths with an asterisk indicate they are included on the thematic mapper (Chappelle et al., 1980a).

Wavelength (μm)	Reflectance vs. Plant Water/M		Reflectance vs. (T_c-T_a)	
	Slope	r^2	Slope	r^2
0.400	-0.61	0.66	0.32	0.62
*0.560	-1.41	0.69	0.19	0.61
*0.670	-2.38	0.86	1.68	0.69
0.720	-3.27	0.37	0.40	0.17
*0.870	5.47	0.88	-2.77	0.50
0.985	2.84	0.67	-1.68	0.74
1.220	0.36	0	-0.48	0.20
1.275	0.109	0.01	-0.48	0.22
1.425	-3.68	0.79	1.69	0.69
*1.660	-2.78	0.76	1.00	0.42
1.774	-2.98	0.81	1.11	0.50
1.780	-3.13	0.69	1.24	0.46
1.940	-3.61	0.74	1.71	0.71
*2.220	-4.49	0.85	1.84	0.61
*2.250	-4.16	0.83	1.74	0.62

μm (blue) and 0.68 μm (red), with a reflectance peak at 0.55 μm (green), soils generally tend to increase continuously in reflectance between 0.4 and 1.4 μm. Iron oxide contents can reverse this trend, however (Stoner and Baumgardner, 1981). At 1.45 and 1.95 μm, strong water absorption bands appear in moist soils (Meyers and Allen, 1968).

The spectral reflectance of soils is influenced by sixteen soil factors, as well as nonsoil residues that may cover the soil surface. The soil factors are: cation exchange capacity, color, drainage class, erosion, geographic location, iron oxide content, mineralogical composition, moisture regime, organic matter content, parent material, taxonomic classification, particle size, texture, topographic position (slope), vegetation growing on the soil, and yield potential (productivity rating) (Davidson, 1980; Stoner et al., 1980) (Table 2.10). Another factor that may affect the spectral reflectance of soils is surface crusting, which may make a soil appear dry when it is really wet (Hoffer and Johannsen, 1969). Recently cultivated soils reflect less than undisturbed soils because of their generally higher surface moisture content. Tillage also causes decreasing reflectance as the sun elevation increases (Coulson and Reynolds, 1971).

Stoner and Baumgardner (1981) summarized the reflectance curves from 485 soil samples from the United States and Brazil. Five distinct spectral curve forms were identified, depending on the presence or absence of absorption bands and the predominance of soil organic matter and iron oxide composition. These curve forms were then associated with soil taxonomic subdivisions. Davidson (1980) concluded that no information exists concerning the yield potential/ reflectance relationship of soils.

2.7 Relationship Between LAI and Canopy Reflectance

The canopy reflectance model of Allen and Richardson (1968) was used to

Table 2.10 Papers dealing with soil reflectance properties.

Beck et al. (1976)	Moisture, carbon and clay content interactions
Baumgardner et al. (1969)	Organic matter effects on soil reflectance
Blanchard et al. (1974)	Soil moisture effects on reflectance
Bowers and Hanks (1965)	Soil moisture and particle size relationships to reflectance
Bowers and Smith (1972)	Soil moisture estimation
Gerbermann et al. (1979)	Effect of clay and sand percentages on reflectance
Condit (1970)	Reflectance spectra of 160 soils
Stoner et al. (1980)	Physiochemical and reflectance properties of 246 soils
Stoner and Baumgardner (1980)	Atlas of reflectances from 246 soils
Stoner and Baumgardner (1981)	Summary of reflectance properties of 485 soil samples
Coulson and Reynolds (1971)	Crop and soil reflectances
Gausman et al. (1975)	Crop residue effects
Gausman et al. (1977b)	Disked and non-disked soil and straw effects

predict the general shape of the LAI versus canopy reflectance relationship (Fig. 2.4). More theoretically complete models exist for predicting canopy reflectance (Table 2.11). The predicted trends from Allen and Richardson's model are similar to observed trends in several field canopy reflectance studies.

The relationship between LAI and canopy reflectance in the visible region is logarithmic, decreasing to a constant value after LAI exceeds approximately 1.0. Before this point, canopy reflectance is primarily a function of the soil background reflectance.

In the near infrared region, canopy reflectance increases curvilinearly with LAI and is a function of soil reflectance throughout the entire life of the canopies with LAI less than about 8.0. (Fig. 2.4). For the LAI range from 0 to 5, if soil background reflectance is not extremely variable, then a virtually linear relationship between LAI and canopy reflectance can be expected in the near infrared region (Ahlrichs and Bauer, 1982; Bauer et al., 1980; and Daughtry, 1980).

2.8 Landsat Satellites

In 1967, NASA began launching a sequence of six satellites. The sensors on Landsats 1-4 include a four-band multispectral scanner (0.5-0.6 μm, 0.6-0.7 μm, 0.7-0.8 μm and 0.8-1.1 μm). These four bands are designated channels 4-7, respectively. Landsat 4 also included an additional sensor, the Thematic Mapper (TM).

The Thematic Mapper is a seven-band multispectral scanner (Table 2.12). The TM has a spatial resolution of 30-40 m, compared to 240 m for the MSS scanner. The thermal band on the TM has a spatial resolution of 120 m (Lintz and Simonett, 1976).

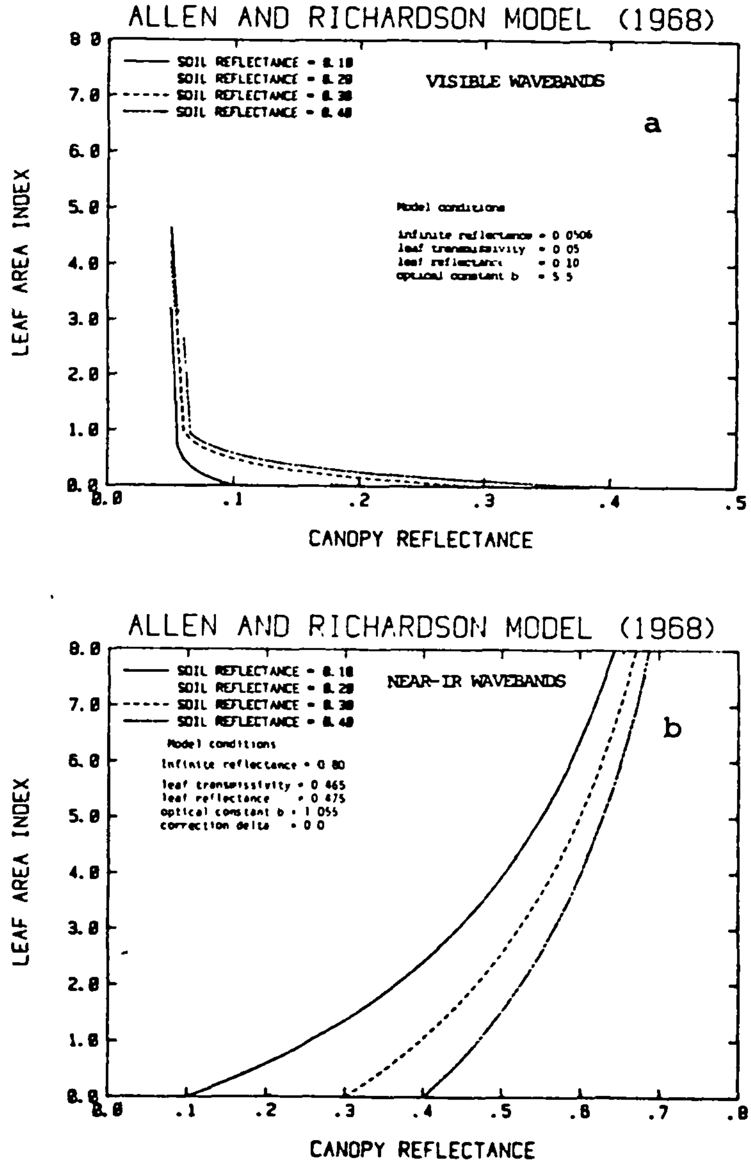


Fig. 2.4 Theoretical relationship between canopy reflectance and leaf area index (LAI) in the visible and near infrared wavebands based on the model of Allen and Richardson (1968).

Table 2.11 List of references relating to canopy reflectance.

A. Models

Allen and Richardson (1968)	Norman, J. M. (1979)
Allen and Richardson (1970a)	Richardson et al. (1975a, b, 1977)
Chance and LeMaster (1978)	Suits (1972a, b, 1981)
Colwell (1974)	Suits and Safir (1972)
Kimes et al. (1980)	Tucker (1980a)
LeMaster et al. (1980)	

B. Estimating Biomass/LAI--Canopy Reflectance Trends

Aase and Siddoway (1980	effect of planting density (wheat)
Ahlrichs and Bauer (1982)	(wheat)
Bauer et al. (1977, 1978, 1979a,b,c, 1980, 1981)	(corn, wheat, soybeans)
Gardner et al. (1982a, b)	(corn, soybeans, wheat)
Cipra et al. (1980)	(forage)
Daughtry et al. (1980a,b, 1982a)	(wheat)
Holben et al. (1980)	(soybean)
Idso et al. (1977a,b, 1980)	(wheat and barley) (yields)
Kanemasu (1974)	(wheat, sorghum, soybeans)
Leamer et al. (1978, 1980)	(wheat)
Markham et al. (1981)	(corn)
McDaniel and Haas (1982)	(mesquite-grass)
Nkremdirim (1972)	(potatoes, cabbage, green beans, peas) (albedo)
Pinter et al. (1981a)	(wheat and barley) (grain yield predictions)
Thomas et al. (1977)	(corn)
Tucker et al. (1980)	
Tucker (1977a, b, 1978, 1979a, b)	(grass, corn, soybean)
Walburg et al. (1982)	(corn)
Wiegand et al. (1979)	(wheat)
Kreibel (1978b)	(savannah, bog, pasture)
Coulsen and Reynolds (1971)	(soil, balcktop, alfalfa, surgar beets, bluegrass, rice, sorghum)
Rao et al. (1979)	(oats, grass, corn)

C. Phenology/Crop Emergence

Badhwar (1980a, b; 1981, 1983)	(corn, wheat, barley)
Ranson et al. (1980)	(corn, soybeans)

Table 2.11 (con't)

D. Measurement Procedures/Conditions

Eaton and Dirmhirn (1979)	(instrument view angle)
Daughtry et al. (1982b)	(instrument height requirements) (corn and soybeans)
Jackson et al. (1979a, b)	(canopy geometry, solar azimuth and elevation)
Kreibel (1978a)	(effect of insolation fluctuations)
Pinter et al. (1981b)	(dew and vapor pressure effects on reflectance) (wheat)
Robinson and Biehl (1979)	(calibration procedures/theory)
Robinson et al., (1979)	(multiband radiometer description)
Tschuida (1979)	(boom truck system for field radiometers)

E. Moisture Stress/Crop Discrimination

Blad et al. (1982)	(moisture stress detection--corn, soybeans) (Landsat MSS bands)
Collins (1978)	(crop discrimination--narrow band measurements)
Dale et al. (1982)	(moisture stress detection--corn) (broad band) (hemispherical IR measurements)
Rao et al. (1978)	(cereal crop discrimination) (narrow band)
Thompson and Wehmann (1979)	(moisture stress detection using Landsat) (large scale estimation)

Table 2.12 Applications of Thematic Mapper Data, band by band (Erickson and MacDonald, 1982)

TM1--0.45-0.52 μm

Soil-vegetation separation (urban areas, roads, harvested fields); field separation is poor; minor forest discrimination; coastal water mapping; chlorophyll absorption band.

TM2--0.52-0.60 μm

Vegetation separation; vegetation vigor (green reflectance peak between two chlorophyll absorption bands); harvested areas difficult to observe; city and roads are distinct (contrast is better in TM1, however).

TM3--0.63-0.69 μm

No discrimination between vegetation classes; vegetated and non-vegetated discrimination (urban areas, roads, harvested areas); chlorophyll absorption band.

TM4--0.76-0.90 μm

Vegetation density; general vegetation separation; soil/crop contrasts; harvested fields are distinct; water is observable but confused with low vegetation patterns.

TM5--1.55 1.75 μm

Crop types show up well; separation of vegetated and urban areas; crop stage separation is observable; ponds/wet areas very distinct; possible soil moisture patterns; harvested fields are apparent, but not as distinct as in TM4; crop water content.

TM6--10.4-12.5 μm

Cannot tell city from harvested regions; vegetated/non-vegetated regions are discernable; vegetation classification; soil moisture discrimination; thermal properties of vegetation and other thermal related mapping.

TM7--2.08-2.35 μm

Urban and harvested areas are apparent, as are roads and forests; vegetation discrimination is possible; important in the discrimination of rock type and for hydro-thermal mapping; crop water content.

2.9 Procedures Used to Distinguish Vegetative from Nonvegetative Targets

2.9.1 Frequency Distribution Method

When radiative data is collected by a moving sensor (such as a multispectral scanner on an aircraft) over a relatively homogeneous surface, the detected energy tends to be normally distributed. When more than one distinctively different surface is represented in the data, then a multimode frequency distribution will result. One mode will be present for each surface type present in the data. This technique appears very useful for classifying data points into general categories. Carter and Jackson (1976) used this technique to separate reflectance data collected by Landsat into water, urban and vegetational classes. Thomas et al. (1977) presented evidence that the reflected radiation from a known row crop could be separated into bare soil, soil-vegetation and vegetation components with this technique. It should be apparent that this technique relies heavily on statistical procedures (Swain, 1978). The major difficulty of using the frequency distribution method to analyze data collected in the field is the requirement of having sufficient data points to conduct the statistical tests. This requirement can be met by mounting the radiation sensor on a moving platform.

2.9.2 The Clustering Method

Multispectral scanners normally collect radiative energy in a small number of discrete wavelength intervals or channels. The clustering method consists of examining the relationship between the various channels of emitted and reflected energy in a data set. These relationships can be defined in multidimensional (channel) space. Data points from different surfaces will tend to cluster in different locations of this multidimensional space. Clustering analysis has been used to classify the source of radiative data to discriminate between crops (Landgrebe, 1978) and to identify cloud and noncloud data points in Landsat data (Wiegand et al., 1981). Swain (1978) discusses mathematical techniques for performing cluster analysis.

2.9.3 The Tasseled Cap

Kauth and Thomas (1976) showed that soil reflectance lies in a region (plane of soils) near the four-dimensional diagonal of the four Landsat channels. The diagonal is the four-dimensional analog of the 1:1 line. Richardson and Wiegand (1977) stated that the slope of the line of soils appears constant from one overpass date to another and that the intercept term is not significantly different from 0. Stated alternatively, the relative relationship between visible and near infrared reflectance from bare soil is approximately constant for a large number of soil types and soil moisture contents. However, the absolute value of visible and near infrared reflectances from bare soil will be very different, depending on soil type and moisture content.

Kauth and Thomas (1976) showed that reflectance from developing vegetation occurred perpendicular to the line of soils. The trajectory of the reflectance was calculated using the Gram-Schmidt orthogonalization procedure. The trajectory of reflectance from green vegetation was termed the greenness index. As a crop grows, greenness values increase from their initial value on the plane of soils to a maximum, that is similar for similar crops regardless of soil background. Stated alternatively, an emerging crop initially "looks" like the soil it is growing on, but a mature crop "looks" the same no matter what the soil type. The curving trajectory from a given soil greenness value (the base of a cap) to similar greenness values for mature canopies was said to resemble the shape of a tasseled woolly cap.

It is important to realize that the tasseled cap (greenness index) does not remove the effects of soil background reflectance, but rather quantifies the bias of a given soil. Hence, analysis of satellite data using this index requires multitemporal analysis techniques. Essentially this means that the same fields must be observed throughout the season. It should be apparent that identification of the same fields from one satellite overpass to the next is technically difficult (but not impossible). Cloud-cover problems often make it impossible to observe the same field on many occasions throughout a season. Although the greenness number is important and valuable, it seems desirable to develop alternative data analysis techniques that do not require multitemporal analysis in order to effectively assess vegetation condition or density.

2.10 Plant Responses to Moisture Stress

Hsaio (1973) summarized plant responses to water stress, including reductions in the transporation rate, CO_2 assimilation and respiration rate, cell size, plant-water potential, growth rate, total protein synthesis and stomatal aperture diameter. Leaf temperature, mesophyll resistance and total free amino acids increased with stress. These responses to moisture stress seem to represent general patterns of modulation in plants under adversity and may be of little value in determining the underlying causes or mechanisms. For example, in many plants water stress causes chemical changes similar to changes induced by nutrient deficiencies. Hsaio concluded that the effects of water stress must be evaluated in terms of the severity and duration of the stress and the plant species involved.

2.10.1 Stomatal Response

Ehrler and van Bavel (1967) stated that the regulation of transpiration by leaf stomata is of specific importance to water use and its efficiency in crop production. They theorized that as leaf water deficits develop, stomata close, leading to decreases in transpiration and increases in leaf temperature. With severe water stress Glover (1959) reported that sorghum stomata remained slightly open through the day, but corn stomata were open for only a short period in the morning. Stomatal activity following irrigation returned to normal sooner in sorghum than in corn. He concluded that evaluation of stomatal response to moisture stress requires a knowledge of the moisture history of the plant.

Sullivan (1974) found that sorghum stomata closed when plants were exposed to moisture stress for the first time, but failed to close completely when subsequently stressed.

Turner (1974) showed that the leaf turgor potential of corn, sorghum and tobacco could decrease from 11 bars to less than 1 bar before stomatal resistance incresed significantly. The critical leaf water potential--that at which stomatal resistance showed a large increase--was lowest in sorghum and highest in tobacco.

Clark (1973) stated that stomatal resistance in peas increased as moisture stress developed, resulting in increased leaf temperatures. He concluded that the status of water in plants represents an integration of the atmospheric demand, soil-water potential, rooting density and distribution and other plant characteristics. Thus, for a true measure of plant moisture deficit, measurements should be made on the plant instead of the soil or atmosphere. Gardner et al. (1981b) suggest that crop temperatures provides one such sensitive indicator of moisture stress.

2.10.2 LAI and Grain Yield Relationships

Linear relationships between corn canopy LAI and grain yield have been reported for maximum LAI values between 3.0 and 4.0 (Nunez and Kamprath, 1969; Scarsbrook and Doss, 1973; Prior and Russell, 1976). Thus, it can be expected that grain yields will increase with increasing LAI or plant population until an optimum LAI or plant population is reached. After this optimum is reached, grain yields will plateau and eventually decrease, probably as the result of increasing numbers of barren ears (Williams et al., 1968; Prior and Russell, 1976; De Loughery and Crookston, 1979).

The implications of these agronomic studies are of major importance in efforts to assess corn grain yield via remote sensing techniques. Similar grain yields may be produced under nonstress conditions at high and low peak LAI values. The effect of moisture stress on the LAI-grain yield relationship further complicates efforts to estimate grain yield as a direct function of LAI. DeLaughery and Crookston (1979) show that maximum yields occur at lower plant densities (LAI) as water stress occurs.

Mauer (1981) showed that plants subjected to moisture stress only during the vegetative growth period (before tasseling) achieved yields similar to plants that were not stressed throughout the entire season. Mauer's (1981) results emphasize the point that maximum canopy LAI is not a good indicator of grain-yield production. High or low grain yields may be produced at high or low LAI values, depending on the timing and severity of stress. Thus, remote sensing estimates of grain yield based solely on maximum LAI (reflectance) values will be subject to serious error.

Mauer's (1981) data also show that moisture stress during the pollination and grain-fill period is the most critical in terms of grain yield. One agronomic result of moisture stress during the grain-fill period is an increased rate of leaf senescence. Leaf senescence rates can be inferred from remotely sensed data. Relative reflectance changes as the grain-fill period progresses will be related to leaf senescence rates. It should be emphasized that this type of information provides inferences about relative grain yields but does not give absolute grain yields.

Substantial grain-yield losses can be incurred if stress occurs only during the relatively short tasseling/pollination period (Denmead and Shaw, 1960). This means that canopies with similar maximum LAI (biomass) and leaf senescence rates can produce very different grain yields. The only remote sensing technique known, at present, for assessing short-term water stress is midday canopy temperature data. This means that accurate remotely sensed estimates of corn grain yield will require midday canopy temperature measurements.

2.11 Factors Affecting Leaf Temperatures

Leaf temperature is a function of air temperature, radiation intensity, wind velocity, leaf dimension, leaf thickness and the angle of leaf orientation with respect to impinging radiation (crop geometry) (Ansari and Loomis, 1959; Thofelt, 1975). Other important factors are sensible heat exchange, vapor pressure gradient (Ehrler and van Bavel, 1967), transpiration (Wiegand and Namken, 1966) and leaf position on the plant (Waggoner and Shaw, 1952).

Wolpert (1962) summarized important variables in the heat balance of leaves and derived formuli that relate steady-state leaf temperatures to wind velocity, evaporation rate, leaf size and pubescence. He concluded that the temperature of a typical plant leaf is dominated by convection under calm conditions and by evaporation under windy conditions. Gates (1964) calculated that a reduction of 70 w/m^2 in the effective radiation load due to transpirational cooling would reduce leaf temperature 5 C in still air and 1 C in a strong wind.

Ehrler (1973) stated that long-term leaf temperature measurements are an indirect indication of stomatal behavior. Ehrler et al. (1978a) demonstrated that canopy temperature in wheat increased as plant water potential decreased. Differences in canopy temperature between stressed and nonstressed wheat plants were shown to be a reliable indicator of plant moisture stress.

Moisture-stressed leaves have been consistently reported as being warmer than nonstressed leaves. Reported differences between stressed and nonstressed leaves for various crops range from +2 to +8 C (Palmer, 1965; Wiegand and Namken, 1966; Millar et al., 1971; Bartholic et al., 1972; Clark and Hiler, 1973; Sumayao et al., 1977; Ehrler et al., 1978; Gardner et al., 1981a, b, c).

2.12 Canopy Temperature Studies

Monteith and Szeicz (1962) and Tanner (1963) were among the first to use infrared thermometers to measure crop moisture stress. Monteith and Szeicz (1962) demonstrated the dependence of surface temperatures on stomatal resistance. They suggested that IRT measurements could be used to evaluate the effective stomatal resistance of field crops. Tanner (1963) observed 3 C temperature differences between irrigated and nonirrigated potato canopies (*Solanum tuberosum*).

Wiegand and Namken (1966) found a linear relationship between cotton leaf temperature and relative turgidity when air temperature and solar radiation were approximately constant. Millar et al. (1971) observed that canopy temperature differences between stressed and nonstressed barley closely followed differences in leaf water potential and relative water content.

Bartholic et al. (1972) used an airplane-mounted thermal scanner to measure the canopy temperatures of stressed and nonstressed cotton plots. Differences in canopy temperature were significantly related to differences in leaf water potential (LWP) and relative water content (RWC) between stressed and nonstressed plots.

Idso et al. (1977b) showed that crop temperature measurements were related to final grain yields in wheat, provided that temperature measurements were acquired during the period between head emergence and the cessation of head growth. The initiation of head emergence was detected by changes in the albedo of the crop.

Heerman and Duke (1978) measured predawn water potentials for corn as well as midday IRT temperatures. They found plant water potential measurements did not give a quantitative measure of water stress. The midday canopy temperature difference between stressed and nonstressed plots was inversely related to the soil water content of the stressed plot. The average temperature elevation of the crop was linearly related to grain-yield reductions in the stressed area. Their results at oblique IRT angles are nearly identical to those of Gardner et al. (1980, 1981c) (Fig. 2.5). These and other studies of crop temperature measurements are summarized in Table 2.13.

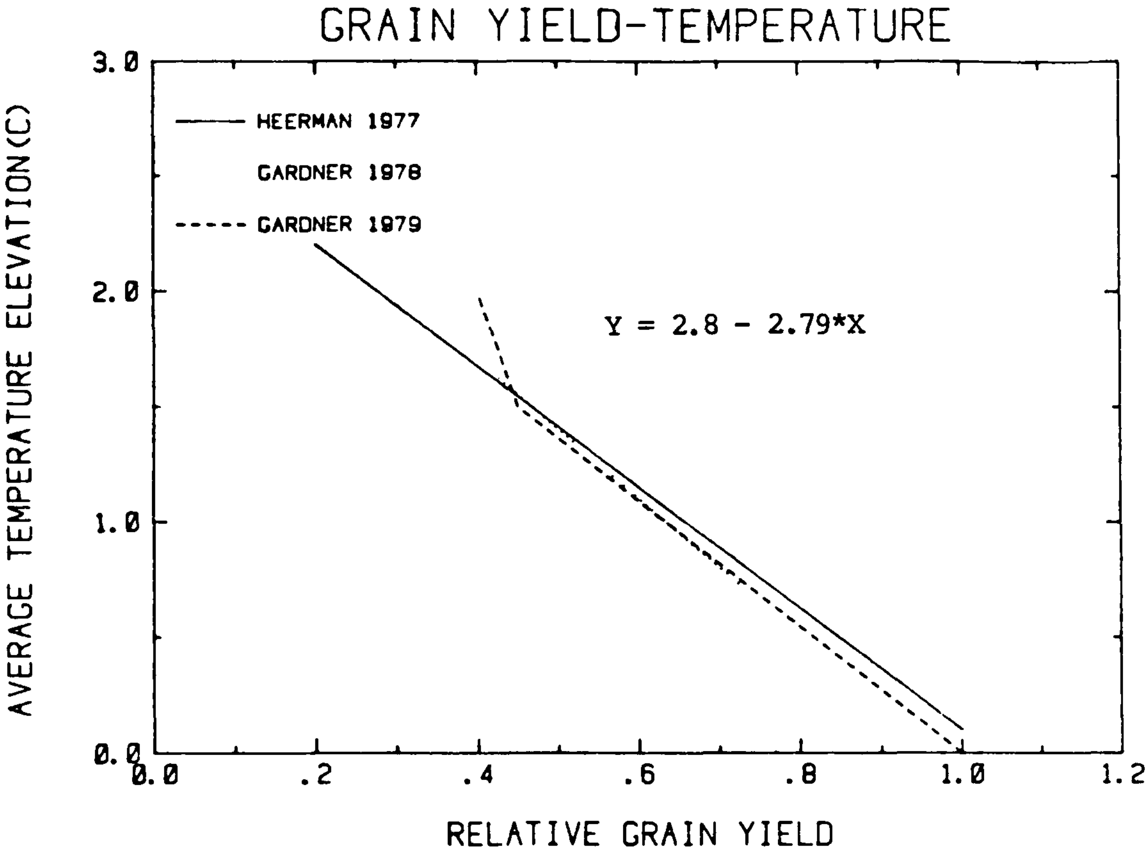


Fig. 2.5 Relationship between average daily temperature elevation and relative grain yields from three studies. The average temperature elevation was calculated as the sum of mid-day canopy temperatures between tasseling and the end of the grain-fill period divided by the number of days between these two end-points.

Table 2.13 Papers dealing with agricultural studies of infrared thermometry/leaf thermocouples.

Reference	Comments
Aston and van Bavel (1972) (Nixon and van Bavel, 1973)	Theory. Hypothesis of canopy temperature variability with stress
Ansari and Loomis (1959)	Leaf thermocouple data of stressed leaves
Aston et al. (1969)	Role of radiation exchange in controlling leaf temperatures
Bartholic et al. (1972)	Thermal scanner detection of water stress in cotton
Blad et al. (1978)	White mold detection in beans
Blad and Rosenberg (1976a)	Comparison of leaf thermocouple and infrared radiometer measurements
Blad and Rosenberg (1976b)	Evaluation of ET models using canopy temperature
Blad et al. (1981)	Thermal imagery and leaf thermocouple detection of stress in sorghum and corn
Byrne et al. (1979)	Theory/effect of percent ground cover on canopy temperature
Kimes (1981)	Azimuthal canopy temperature patterns in wheat
Hatfield (1979)	Zenith angle versus percent ground cover and canopy temperature in wheat. Leaf thermocouple versus IRT for beans.
Clawson and Blad (1982)	Irrigation scheduling in corn
Clark and Hiler (1973)	Leaf temperatures of water stressed peas
Gardner et al. (1981a,b,c)	Moisture stressed corn and soybean--grain yield, ET and phenology relationships
Heilman et al. (1981)	Cover effects on canopy temperature--barley
Idso et al. (1977a, 1981a)	Grain yield estimates in wheat
Idso et al. (1982)	Humidity estimates from IRT data
Jackson et al. (1977)	Evapotranspiration/soil water (wheat)

Table 2.13 (con't)

Millard et al. (1978)	Thermal scanner detection of moisture stress in wheat
Heilman et al. (1976)	ET estimation from thermal data (soybean, sorghum, millet)
Heerman and Duke (1978)	Grain yield estimates in moisture stressed
Fuchs and Tanner (1966)	IRT measurement theory
Fuchs et al. (1967)	Viewing angle effects on canopy temperature
Jackson (1982)	Literature review, theory and experimental results
David (1969)	Literature review and theory
Chilar (1976)	Remote sensing bibliography

3. MATERIALS AND METHODS

3.1 Experimental Site

This experiment was conducted in 1982 at the University of Nebraska Sandhills Agricultural Laboratory, located near Tryon, Nebraska (41° 37' N; 100° 50' W and 975 m above mean sea level). This site is appropriate for moisture stress studies since rainfall is almost always inadequate to meet evaporative demands of agricultural crops during much of the growing season and the sandy soils (Valentine fine sand-Typic Ustipsament) at the site do not store large quantities of soil water. Field capacity and available water percentages are typically 20% and 12%, respectively. The experimental site is divided in four distinct areas (A, B, C and D) (Fig. 3.1). This experiment was conducted on corn and soybean plots located in C and D areas.

3.2 Experiment Design--Overview

Moisture stress can be defined as active or cumulative. Active moisture stress responses are those directly observable by an experimenter. These responses include relative leaf water content, stomatal diffusion resistance, plant water potential, visible wilting and leaf canopy temperature.

Cumulative canopy responses to moisture stress include reductions in leaf area, either as a result of decreased vegetative growth or in increased senescence rates; changes in canopy color/reflectance due to reductions in nitrogen availability (nitrogen availability is a function of soil moisture status); and grain-yield reductions. Grain yield is the agronomic parameter frequently selected to indicate cumulative stress effects (Turner ana Burch, 1983).

Two questions are of fundamental importance in the remote sensing of crop canopies: 1) can leaf area and phytomass be reasonably estimated regardless of whether or not the canopy is or has been stressed? and 2) can the presence

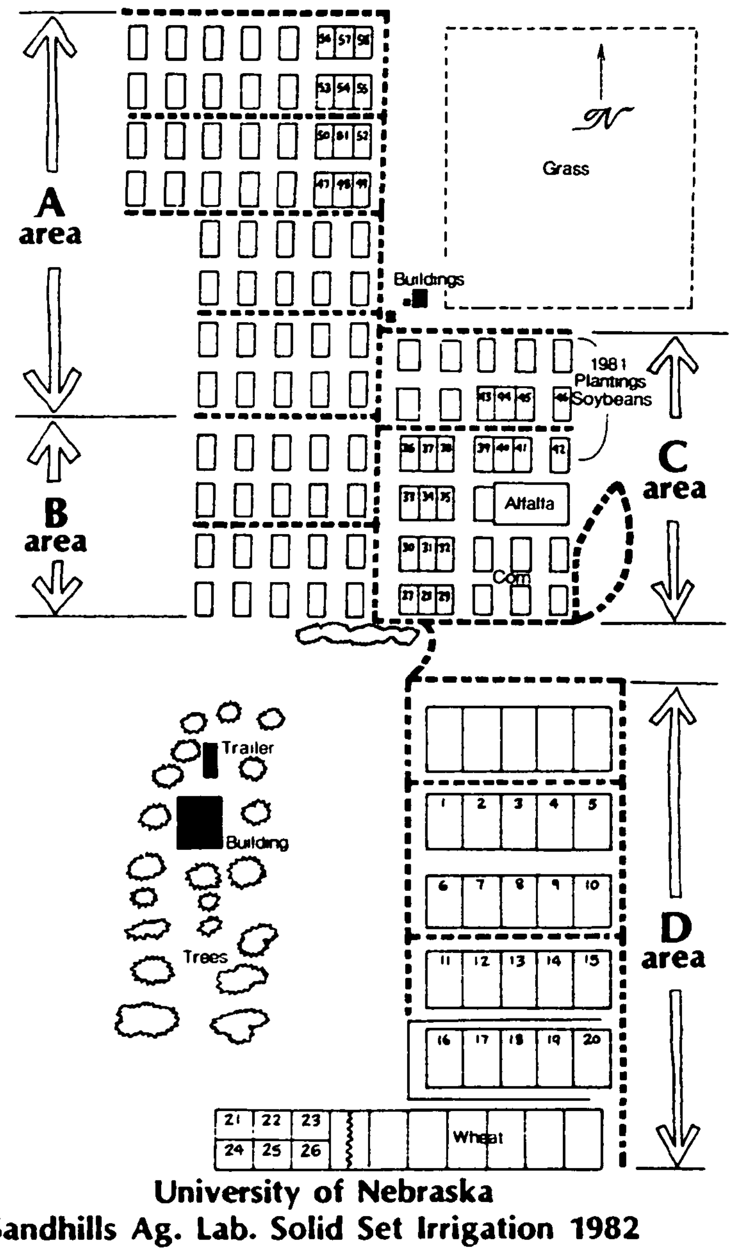


Fig. 3.1 Solid set irrigation area of the Sandhills Agricultural Laboratory showing the locations of the plots used in this study.

and level of moisture stress be detected with reflectance measurements? One experiment that can provide information in both areas cannot be easily designed. In order to answer the first question, it is necessary to create significant vegetative differences caused by water stress among the various plots. The second question cannot be resolved with this type of data since uncertainties will exist as to whether reflectance differences are caused by moisture stress differences or by vegetative differences. Question 1 will be addressed in this report. An experiment is planned for 1983 to address the second question.

3.2.1 Experiment Design--Corn

Three irrigation treatments were applied to the corn in D area: III, GII and GGG (Fig. 3.2). GII plots received gradient (G) irrigations between growth stages 0 to 5.0 and were fully irrigated thereafter. GGG plots received gradient irrigations throughout the entire season. III plots were fully irrigated the entire season. Each plot was divided into four six-row segments. It was assumed the gradient was relatively uniform within each segment. The average irrigation rate within each segment, during a gradient irrigation, was assumed to be 100%, 66%, 33% and 0% of the maximum. Smaller segmenting of the gradient could not be done since the radiometer spot sizes covered about three rows. A border of approximately three rows between segments was used. Two corn hybrids, Pioneer 3901 and B73XMo17, were grown. All row widths were 0.76 m. All planting directions were north to south except in plots 21-26, where the row directions were east to west. The planting rate was 76000 plants/ha. The crop was planted on May 17-18.

The irrigation treatments used in C area were whole plot treatments that lasted throughout the entire season. The four treatments used corresponded to the four irrigation levels on a gradient plot: 100%, 66%, 33% and 0% of maxi-

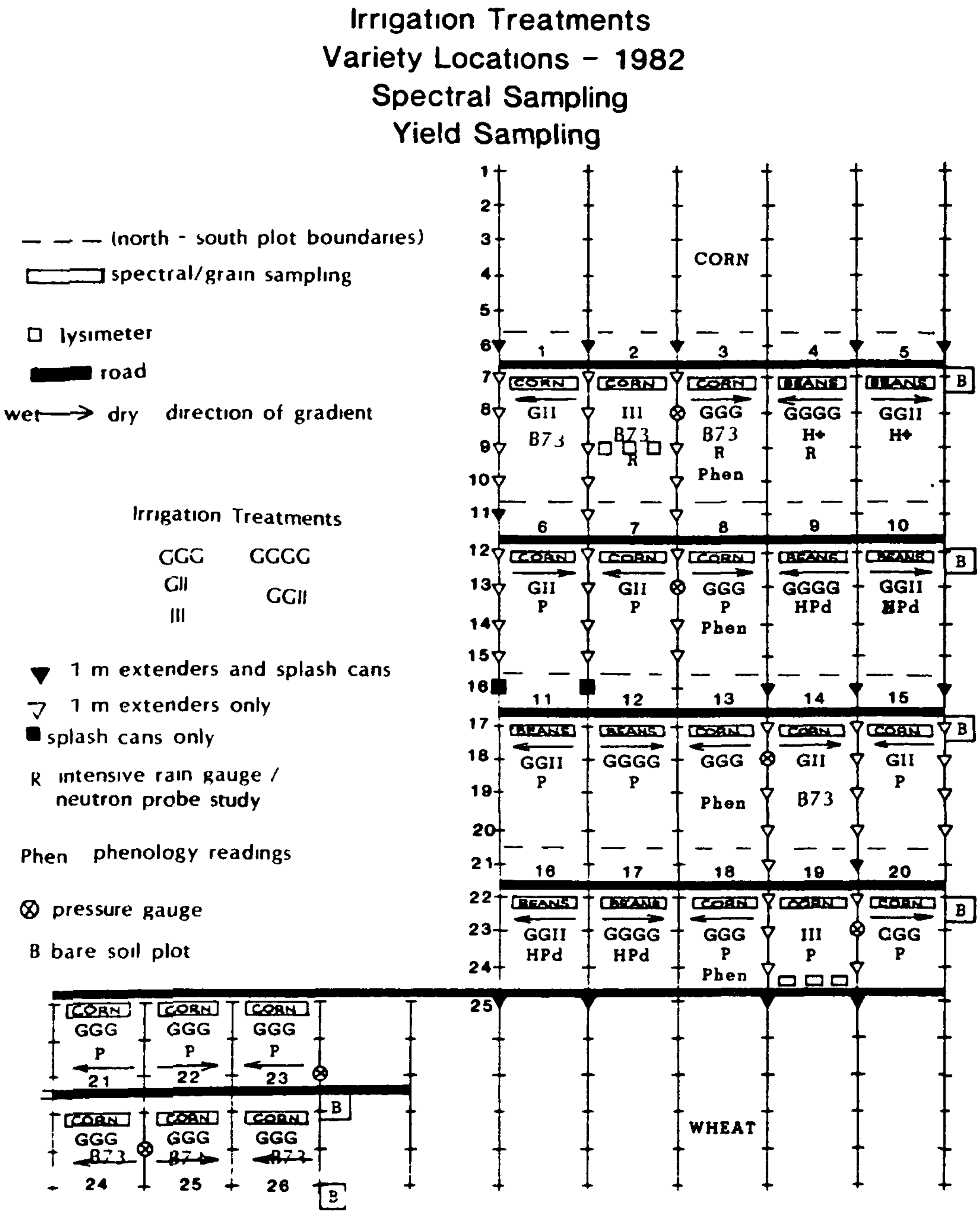


Fig. 3.2 Plot map of D area in 1982.

mum irrigation requirements. These treatments were selected since they produce a wide range in stress conditions from plot to plot (Fig. 3.3).

Pioneer 3901 was selected for this experiment since it has a planophile (horizontal) leaf architecture and is adapted for this area. B73XMo17 has an erectophile (vertical) leaf architecture and produces more phytomass than Pioneer 3901. Reflectance data from two geometrically and vegetatively different hybrids help to clarify the extremes in responses that may be encountered in satellite observations of corn.

3.2.2 Experiment Design--Soybeans

The soybean design was similar to that of the corn (Fig. 3.2). Since the phenological progression of soybeans is described differently from that of corn, the irrigation treatments were designated GGII and GGGG. A GGII plot received a gradient irrigation during vegetative growth, then was fully irrigated for the remainder of the season. GGGG plots received gradient irrigations throughout the entire season. Whole plot water treatments of 0%, 33%, 66% and 100% were established on soybeans in C area.

Three isogenic cultivars of the Harosoy line were planted. These cultivars differed only in the amount of pubescence present. Normal (H_+), dense (H_{pd}) and sparse (H_{ps}) pubescent cultivars were used. The dense pubescent isoline has about 400% more trichomes on leaf and stem surfaces than the normal parent (Bernard and Singh, 1969).

3.2.3 Sampling Design

The design of all reflectance and plant sampling areas was similar (Fig. 3.4). In C area and D area, 2 and 4 neutron tubes and rain gauges were installed per plot, respectively, except for plots 3-5. Plots 3-5 were designated as intensive neutron/raingauge areas. 12 neutron tubes and rain gauges were placed symmetrically behind the reflectance areas in order to

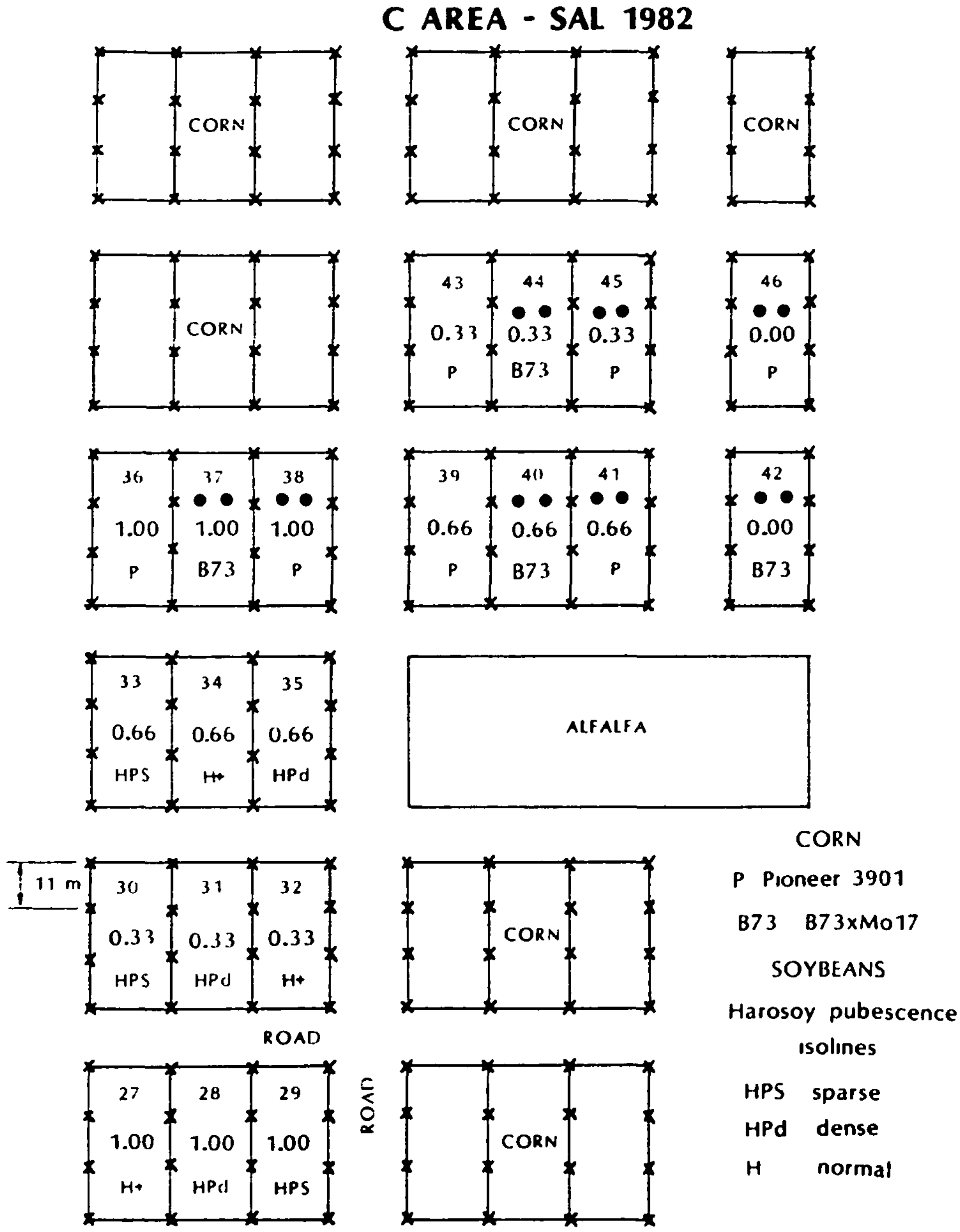
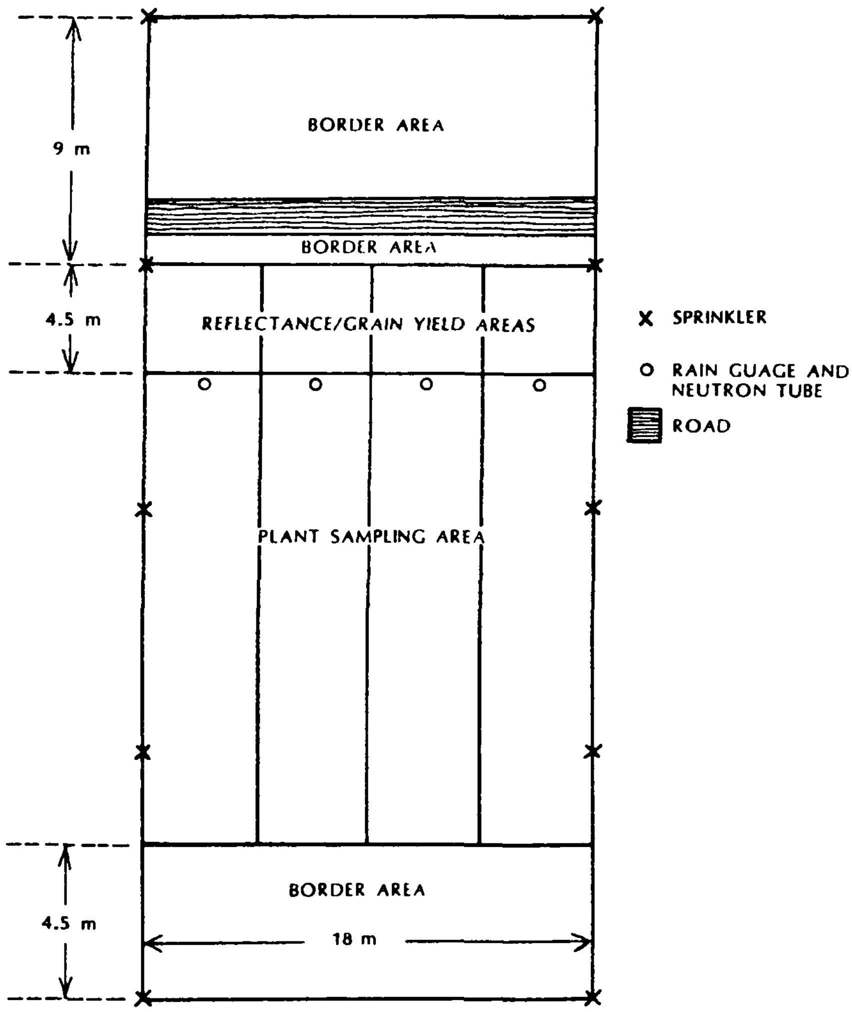


Fig. 3.3 Plot map of C area in 1982.



PLOT GEOMETRY 1982

Fig. 3.4 Sampling geometry for reflectance and plant sampling measurements for most plots in C and D areas at SAL in 1982. The only significant difference among the plots were the use of two plant and neutron sampling areas in C area instead of four, as in D area.

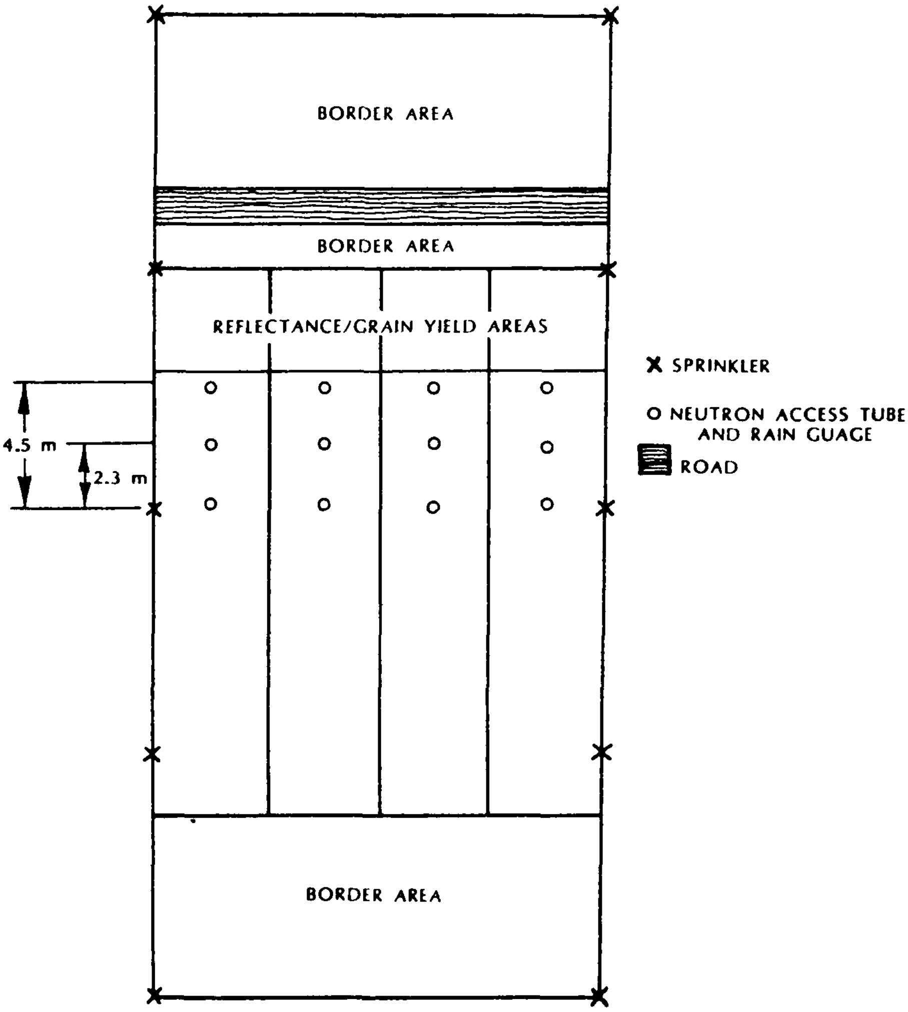
obtain data on the variability of within-plot soil moisture contents and irrigation amounts (Fig. 3.5). Although plot 5 was planted to soybeans, data from this plot was included in the analysis of the intensive neutron and rain gauge data.

Four areas for measuring reflectance and grain yield were selected for each plot. The radiometer spot sizes were located entirely within each grain-yield sampling area. Neutron tubes and rain gauges were located 1-2 m south of and marked the center of a group of three rows. Plant sampling was conducted from south to north on this group of rows until the reflectance area was reached. Plant sampling in C area was conducted only on the two middle groups of rows. No plant samples were taken from plots 2 and 19.

3.2.4 Leaf Area, Phytomass, Phenological and Physiological Measurements

Leaf area measurements were obtained approximately weekly through destructive sampling of 1.83 m of row for corn and 0.92 m for soybeans from the three-row sampling area. The leaves were then removed from the plants. LAI was measured on a LICOR-3100 leaf area meter, for the first 1 m^2 of leaf area for corn and 0.5 m^2 for soybeans. The ratio of area/dry leaf weight was then used to calculate leaf area for the remainder of the sample. This necessitated the separate weighing and drying of two leaf measurements per sample: the leaf area subsample and the rest of the leaves. Wet leaf weights for the entire sample were also recorded.

A similar sampling scheme was used to obtain dry stalk weights. The wet weight of all sampled corn stalks was measured directly on a triple beam balance. The stalk from 1 plant per sample was then dried to estimate stalk moisture content. The lack of oven space precluded the drying of all the stalk samples. The developing ear was included as part of the stalk. All phytomass samples were dried for 5-6 days at 76 C. A summary of leaf area and



PLOT GEOMETRY FOR INTENSIVE NEUTRON ACCESS TUBE EXPERIMENT

Fig. 3.5 Sampling geometry for reflectance and plant sampling from plots 3-5 at SAL in 1982.

phytomass calculations is in Table 3.1. For soybeans all stalks were dried and weighed.

Phenological data were collected biweekly from 10 plants located 1-2 m directly south of the neutron tubes in plots 3, 8, 13 and 18, using the corn scales of Hanway (1971) and soybean scales of Fehr and Caviness (1977).

Grain yields of corn and soybeans were sampled on October 14 from 13.7 m of row within each reflectance sampling area. The grain was shelled and wet weights obtained. Subsamples for percent moisture contents were also obtained and dried. Corn grain yield was calculated at 0% moisture content and soybeans at 13% moisture.

In addition to the above measurements, data were collected over well-watered and dryland soybeans throughout the day on seven days and between 1200 and 1500 hours solar time on nine other days. These data included canopy temperature, leaf temperature, stomatal resistance, total water, osmotic and pressure potentials of sunlit leaflets near the top of the canopy.

Canopy temperatures were measured obliquely and recorded for each of the four cardinal directions with a hand-held Telatemp infrared thermometer. A spot size of approximately 0.06 m^2 was viewed by the IRT. The average of the four directions was assumed to be the average canopy temperature. Stomatal resistance and transpiration of both the adaxial and abaxial leaf surface was measured with a LI-COR model LI-1600 steady-state porometer. Total leaflet stomatal resistance was computed assuming parallel resistance between the two surfaces. Total leaflet transpiration was computed as the sum of the transpiration from the two surfaces. Leaflet temperature, measured with a thermocouple in the sensing heat of the porometer, was also recorded simultaneously. Total leaf water potential was measured by the pressure chamber technique (Scholander et al., 1976). Leaves used in making the water poten-

Table 3.1 Summary of the phytomass calculations used in 1982.

Row width = 0.76 m = ℓ_w

Row length (LAI, leaf, stalk samples) = 1.83 m = ℓ_b

Row length (grain yield) = 13.7 m = ℓ_g

All weights are in kg

$Larea_s$ = leaf area of the leaf sub-sample

$dryleaf_s$ = dry leaf weight of the leaf sub-sample

$dryleaf_t$ = total dry leaf weight (includes the sub-sample)

$wetstalk_s$ = wet weight of the stalk sub-sample (1 stalk, 1 ear)

$drystalk_s$ = dry stalk weight of the stalk sub-sample

wetstalk = wet stalk weight (includes the ear, includes the sub-sample)

$grain_w$ = total wet weight of the grain sample

$grain_{ws}$ = wet weight of the grain sub-sample

$grain_{ds}$ = dry weight of the grain sub-sample

LAI = $(Larea_s/dryleaf_s)*dryleaf_t/(l_w*l_b)$

dry stalk weight = $(drystalk_s/wetstalk_s)*wetstalk/(l_w*l_b)$ (g/m^2)

grain yield (g/m^2) = $grain_{ds}/grain_{ws})*grain_w/(l_w*l_b)$

tial measurements were subsequently frozen for later measurement of osmotic potential by dewpoint thermocouple psychrometry. Pressure potential was calculated as the difference between osmotic and total water potential. Dilution of the leaf osmotic solution by apoplastic water was not accounted for since comparison of both osmotic and pressure potentials between isolines grown under identical water treatments was desired. This procedure assumed that no difference in apoplastic water content existed between isolines in the same water treatment.

The data were subjected to appropriate analyses of variance and linear regression procedures. Observed diurnal trends were plotted and differences determined. Observations obtained between 1200 and 1500 hours solar time were pooled and analyzed with variance and regression tests.

3.2.5 Soil Water Content Measurements

Soil moisture measurements were made once per week with a Troxler model 3222 moisture depth gauge that was calibrated for the soils at SAL. Readings were taken at 0.15, 0.30, 0.60, 0.90, 1.20 and 1.80 m. Volumetric soil moisture content (θ) was calculated as:

$$\theta = -0.01810 + 0.4416*CR \qquad \text{for depths less than or equal to 0.15 m}$$

$$\theta = 0.025 + 0.4181*CR \qquad \text{for depths greater than or equal to 0.30 m}$$

where CR is the count ratio: (counts at depth x)(standard counts).

The effective sampling radius (R) of each neutron measurement was taken as 0.225 m for the 0.15 and 0.30 m readings. R was taken as 0.30 m for all other depths. Soil moisture content at any level was taken as the product θR. Total soil moisture content at any tube location was calculated as the sum of all θR products.

3.2.6 Irrigation Scheduling

The weekly soil moisture readings from all 100% irrigation areas were used to schedule irrigations. The amount of irrigation was calculated as the amount needed to bring the average soil moisture content at each level in the profile back to 19% volumetric soil water content. Plots 1-10, 11-20 and 21-26 in D area and all of C area corn were scheduled separately. Differences in required irrigation amount for fully irrigated areas between these locations were generally small (Table 3.2).

3.3 Irrigation System

The irrigation system used at SAL is a modification of the line source system developed by Hanks et al. (1976) and is described in detail in Maurer et al. (1979), Gilley et al. (1980) and Blad et al. (1981). Two solid-set irrigation lines are used (Fig. 3.6). When a plot is fully irrigated (I treatment) both lines are operated. An approximately linearly decreasing water gradient can be applied to a plot (G treatment) by operating only one line (treatment line).

Proper operation of the irrigation system is essential if the water gradients are to be properly applied. The radius of throw of low application rate sprinklers are relatively insensitive to nozzle pressure fluctuations, but application rates and patterns are strongly dependent on nozzle pressure (Table 3.3, Fig. 3.7). If the nozzle pressure is too low, a sinusoidal application pattern results. If the pressure is too high, the gradient will become nonlinear. Pump pressures of 483 KPa (70 p.s.i.) are optimum for the system at SAL. This corresponds to nozzle pressures of 310-345 KPa (45-50 p.s.i.).

Pump pressures were checked every 2-3 hours throughout all irrigation periods. More frequent monitoring was not feasible since most irrigations were conducted between 10:00 p.m. and 6:00 a.m. This time period is generally used for irrigating gradient plots since winds at SAL are generally calm (less

Table 3.2 Irrigation requirements for fully irrigated corn--1982. Units are in mm.

Day of Year	Month/ Day	North D Area	South D Area	Dogleg	C Area
188	July 7	--	20.32	20.32	19.05
196	July 14	19.05	25.40	38.10	25.40
201/2	July 20/21	38.10	40.64	50.80	44.45
209	July 28	50.80	50.80	63.5	50.80
216	August 4	20.32	21.59	38.10	40.64
225	August 13	44.45	50.80	44.45	45.72
230	August 18/19	22.86	20.32	25.40	25.40
245	Sept. 2	25.40	19.05	19.05	15.24
252	Sept. 9/10	7.62	31.75	25.40	25.40

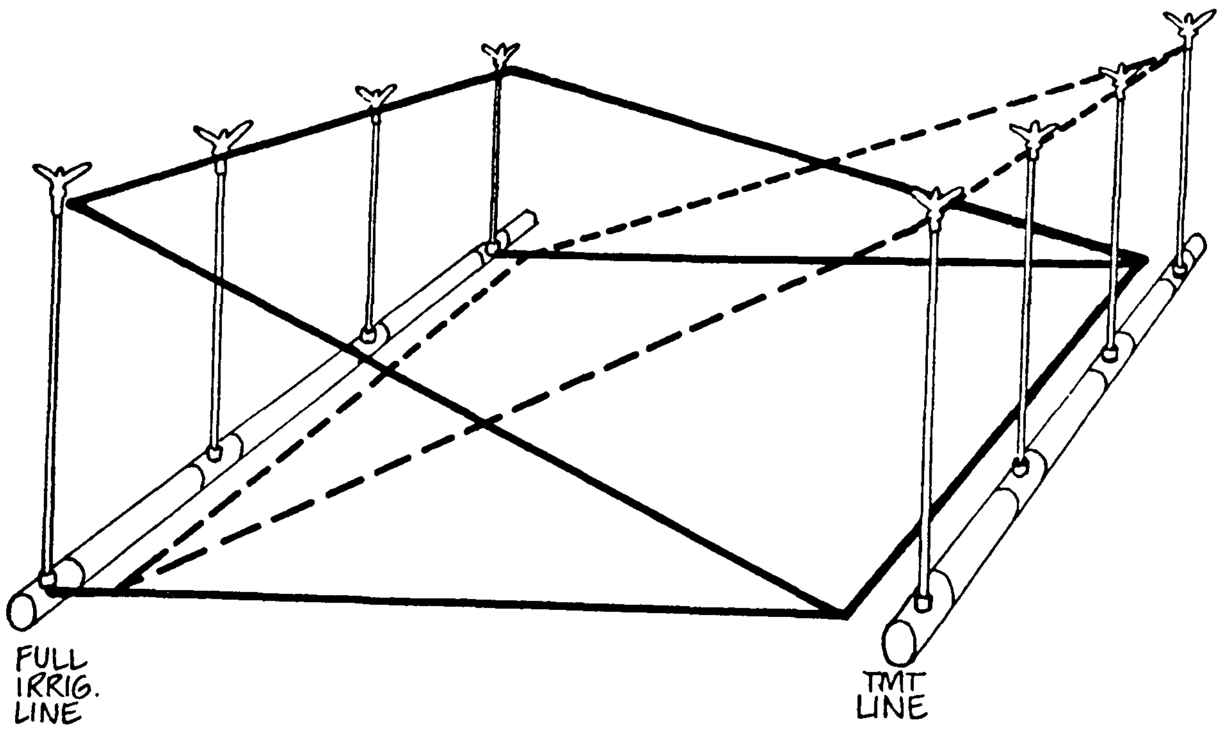


FIg. 3.6 Schematic of water application patterns from two solid-set irrigation lines. The plot is fully irrigated when both lines are used. A gradient treatment is applied when the treatment line is shut off. Total water application is the sum of the amounts from the individual patterns (Maurer et al., 1979).

Table 3.3 Operating characteristics of the Rainbird 30H 4.76 mm x 2.38 mm-7° (3/16" x 3/32"-7°) and 30W 4.76 mm (3/16") sprinklers. These sprinklers are similar to those installed in D and C areas, respectively. (Rainbird Manufacturer's Catalogue, 1981).

Operating pressure		radius of throw		delivery rate		D area application rate	
p.s.i.	KPa	feet	meter	gallons per min	liters per min	inches per hr	mm per hr
			30H 4.76 mm x 2.38 mm-7°				
25	172.5	42.5	12.96	6.31	23.85	0.34	8.8
35	241.5	47.0	14.34	7.52	28.42	0.40	10.2
45	310.5	49.0	14.95	8.57	32.39	0.46	11.6
50	345.0	50.0	15.25	9.04	34.17	0.48	12.2
55	379.5	50.5	15.40	9.46	35.76	0.51	12.9
65	448.5	51.5	15.71	10.26	38.78	0.55	13.9
75	517.5	52.5	16.01	10.99	41.54	0.59	14.9
			30W x 4.76 mm			C area application rate	
25	172.5	42.5	12.96	5.09	19.24	0.27	6.9
35	241.5	47.0	14.34	6.02	22.76	0.32	8.2
45	310.5	49.0	14.95	6.83	25.82	0.37	9.3
50	345.0	50.0	15.25	7.20	27.22	0.39	9.8
55	379.5	50.5	15.40	7.55	28.54	0.40	10.3
65	448.5	51.5	15.71	8.20	31.00	0.44	11.1
75	517.5	52.5	16.01	8.81	33.30	0.47	12.0

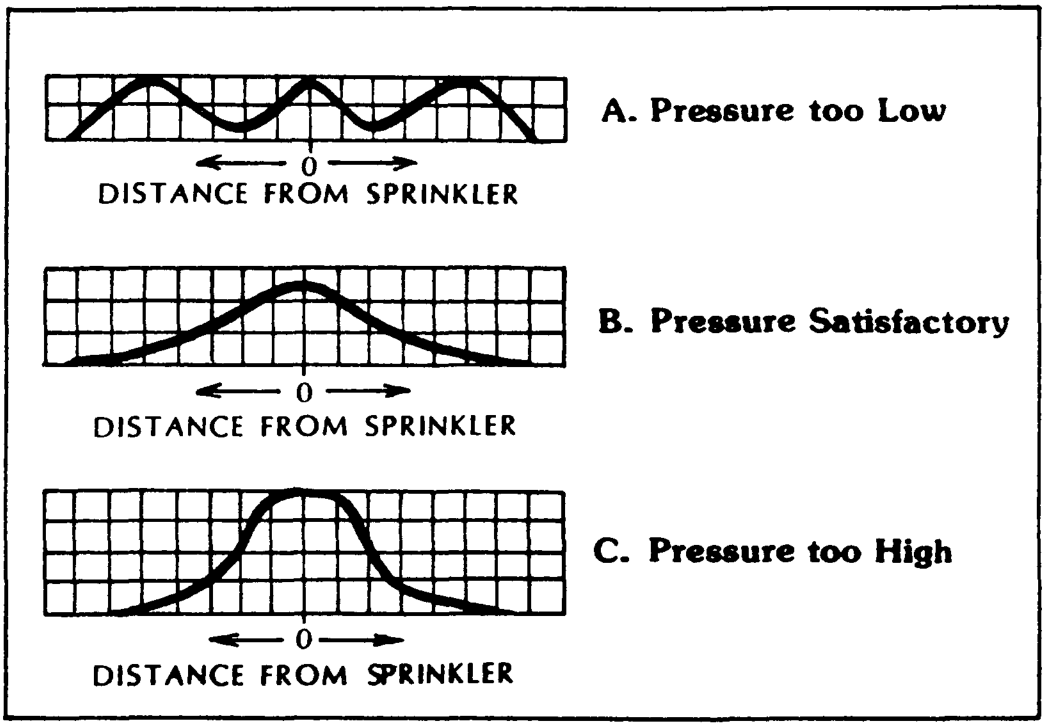


Fig. 3.7 Expected water application patterns from a solid-set irrigation system as a function of nozzle pressure (J. R. Gilley, private communication). (Based on data from Christiansen, 1942.)

than 2.2 m/sec [5 mph]) only during this time interval.

3.3.1 Irrigation and Rainfall Measurements

Adjustable 102 mm diameter rain gauges were used to measure irrigation and precipitation. At the beginning of the season, the gauges were set at a height of 1 m. As the corn grew, they were adjusted to keep them slightly above the top of the canopy.

The volume of collected water in each gauge was measured the morning after an irrigation. Water volume in 20-30 gauges located throughout A, C and D areas was measured after a rain. All gauges were emptied before an irrigation if there had been rain since the last irrigation (Table 3.4).

Eisenhauer (1979) made the following statement concerning rain gauges: "Sprinkler delivery and efficiency cannot be adequately measured by rain gauges. Even six-inch (15 2.4 mm) diameter gauges will show a wide variety of readings under what are supposed to be the same conditions. They can be used as a check but do not use them as a complete replacement of other measuring devices and techniques."

One technique for estimating irrigation amounts on whole plot treatments comes from sprinkler irrigation theory:

$$Q = [Kq/\ell*w]*t \qquad (3.1)$$

where Q is the applied irrigation amount, k is a units conversion factor, q is the sprinkler flow rate, t is the time of delivery, l is the distance between sprinklers along a single lateral and w is the distance between 2 laterals. Q will be measured in cm if q is measured in liters/min, t is measured in hours and ℓ and w are measured in meters and k=6. Q will be in inches if q is measured in gallons per minute and l and w are measured in feet and k=96.3. q is obtained from manufacturer's specifications for the sprinklers being used.

Application amounts on gradient plots can be estimated as:

Table 3.4 Rainfall amounts during the 1982 growing season at the Sandhills Agricultural Laboratory. Phenological growth stages of two corn varieties are included for comparison.

Day of Year	Rainfall (mm)	Stage of Growth Pioneer 3901	Stage of Growth B73xMo17
155	0.2	emergence	emergence
156	1.9	emergence	emergence
166	4.8	0.8	0.6
168	0.5	1.0	0.8
169	9.2	1.1	0.8
172	1.0	1.3	1.0
175	20.4	1.5	1.2
178	0.2	1.8	1.3
182	3.9	2.1	1.6
187	4.6	2.5	1.9
188	1.2	2.6	2.0
194	1.7	3.1	2.4
210	35.1	4.4	3.6
211	0.2	4.5	3.7
215	0.5	4.9	4.0
217	1.0	5.1	4.1
222	7.7	5.5	4.6
223	0.6	5.6	4.6
224	0.2	5.7	4.7
225	0.5	5.8	4.8
226	15.6	5.9	4.9
232	7.0	6.5	5.4
236	27.2	6.9	5.8
239	6.4	7.2	6.1
242	13.7	7.5	6.3
256	19.2	8.9	7.8
257	4.5	9.1	7.9
261	3.0	9.5	8.3
274	13.2	10.9	9.7
279	8.5	11.0	10.4
Total	213.7		

$$Q = Q_{max} * (R-d)/R \quad (3.2)$$

where Q_{max} can be estimated from eq. (3.1) or from a rain gauge located near the lateral sprinkler. R is the radius of throw of the sprinkler and d is the perpendicular distance from the sprinkler lateral of the location of interest.

Although measured irrigation amounts were used in water balance estimates, eqs. (3.1) and (3.2) were used to estimate irrigation amounts on all corn gradient plots in D area. Comparison with measured irrigation amounts indicate no significant difference between the two methods of estimating irrigation (Fig. 3.8a). The data are inconclusive as to which of the two methods is more accurate.

Equation (3.2) was used to estimate irrigation amounts of the 0.00, 0.33 and 0.66 areas of the GGG corn plots in D area. Q_{max} was estimated as the amount of measured irrigation at the 1.00 area of each plot. The results indicate a definite tendency for areas receiving 30-60 m of water per irrigation (0.66 areas) to receive more water than theoretically expected (Fig. 3.8b). This suggests that the 0.66 level would be relatively nonstressed and that gradients should be curvilinear. This conclusion is supported by vegetative height and grain-yield patterns (Fig. 3.9); it strongly suggests that the sprinkler pressure used at SAL during 1982 was too high (see Fig. 3.7). It is recommended that pump pressures be reduced by at least 69 KPa (10 p.s.i.) when irrigating in the future.

3.3.2 Homogeneity of ET and Rain Gauge Estimates--Fully Irrigated Conditions

The homogeneity of soil moisture content measurements with a neutron probe in a fully irrigated area was investigated. Weekly volumetric soil moisture contents were measured in twelve symmetrically placed tubes in plot 2. Rain gauges were also located at each tube. The weekly evapotranspiration

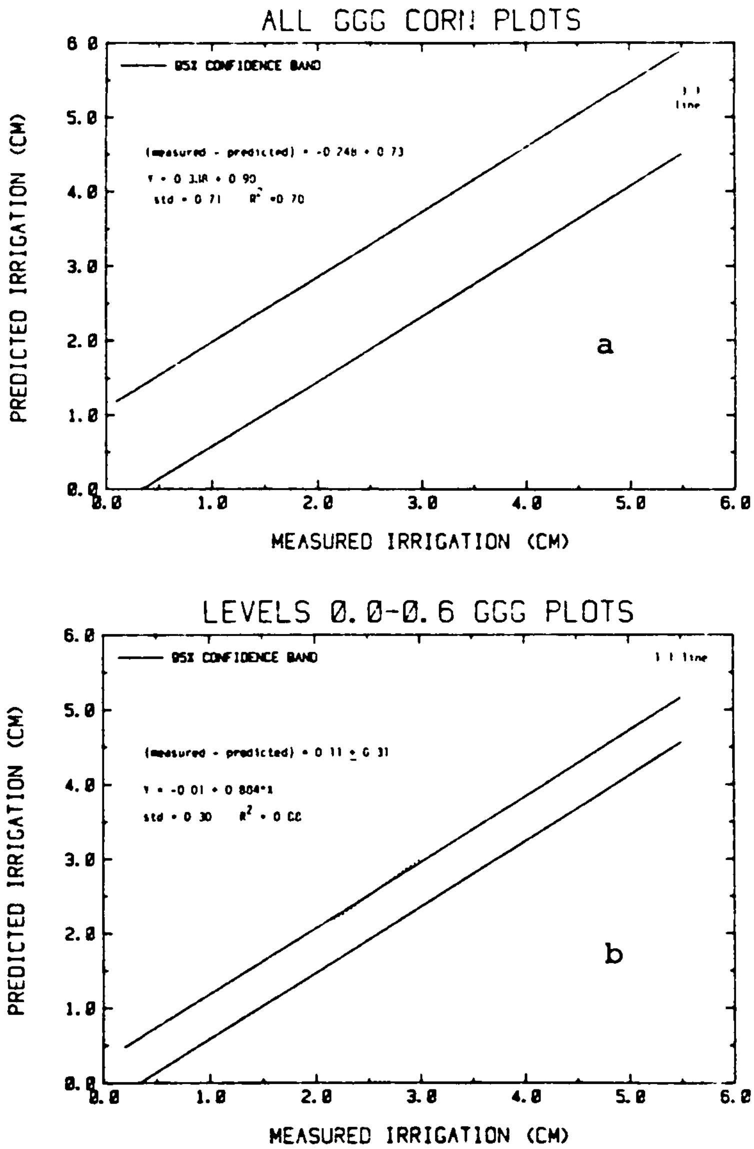


Fig. 3.8 Relationship between measured irrigation amounts and a) predicted irrigation on all corn gradient plots and b) predicted irrigation on all whole plots which were not fully irrigated at SAL in 1982.

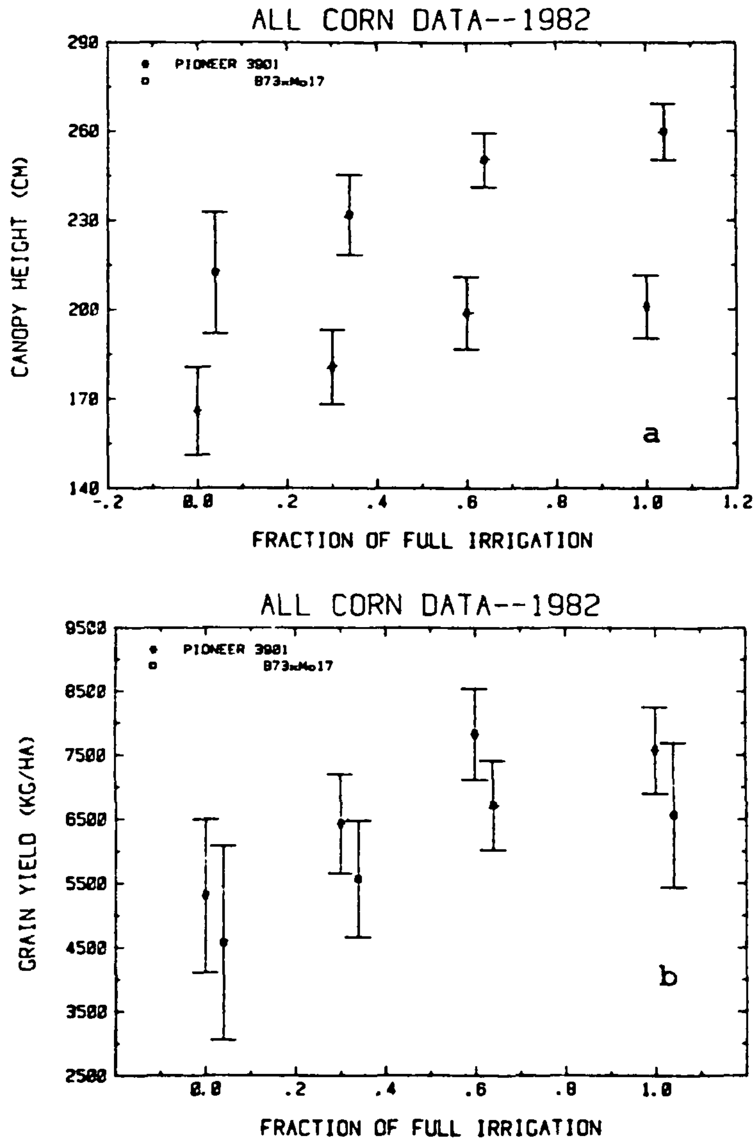


Fig. 3.9 Relationship between fraction of full irrigation and a) canopy height after tasseling and b) grain yield. The irrigation fraction is defined as the ratio (irrigation applied)/(irrigation required).

(ET) was then calculated using a water balance program developed by Bill Kranz and Roberto Mauer of the Agricultural Engineering Department at the University of Nebraska-Lincoln. The weekly average irrigation and ET value for each tube was then compared with the weekly mean:

$$D_j = \left[\sum^{n} \left(\frac{\sum_{i=1}^{12} x_i}{12} - x_j \right) \right] \Big/ n$$

where x_j is the weekly ET or irrigation amount for tube j and n is the number of weeks for which data were collected. t-test calculations on D_j indicate the average difference in irrigation amounts between any tube and the plot mean was less than 4 mm per week and generally less than 1 mm. The average difference in ET estimates was less than 5 mm per week and generally less than 1 mm. No statistically significant differences were found (Table 3.5).

3.3.3 Homogeneity of ET and Rain Gauge Estimates--Gradient Irrigation

Only three tubes per irrigation level were available for estimating the variability of ET or irrigation estimates in gradient-irrigated areas (plots 3 and 4). The maximum difference between these three tubes was formed. The results indicate that the maximum difference in irrigation amounts between tubes within an irrigation level was less than 2 mm per week, and generally less than 1 mm per week. Similarly, the maximum difference in ET amounts was 3.5 mm per week, and generally less than 2 mm per week (Table 3.6). Thus, in the gradient plots, one neutron tube and rain gauge is sufficient to characterize the water balance at any irrigation level.

3.3.4 Evapotranspiration Calculations

Crop evapotranspiration (ET) was calculated on a weekly basis using the water balance equation:

Table 3.5 Average weekly difference between irrigation or ET amounts and the weekly average for twelve tubes in plot 2 for 15 weeks:

$$D = \sum_{j=1}^{15} \left(\sum_{i=1}^{12} (\bar{x}_j - x_i) \right) \Big/ 15$$

where x_i is the weekly irrigation or ET amount for tube i and $\bar{x}_j$ is the average weekly irrigation or ET amount for the plot. All amounts are measured in mm. No differences were statistically significant.

Tube Number	D (irr.) (mm)	D(ET) (mm)
1	-0.7	2.6
2	4.7	3.6
3	5.3	2.6
4	0.2	0.4
5	-1.3	-0.2
6	-2.4	-1.8
7	0.3	-0.3
8	-4.8	-3.7
9	-3.3	-3.0
10	-0.9	-1.7
11	4.2	-0.4
12	-1.4	1.0

Table 3.6 Maximum difference in mean weekly ET or irrigation amounts recorded at three locations within each irrigation level on two gradient irrigation plots in 1982. Plots two and three were planted to a corn hybrid, B73xMo17. Plot four was planted to a soybean cultivar, Harosoy normal pubescence. No differences were statistically significant.

	Irrigation Level			
	1.0	0.66	0.33	0.0
	Maximum Weekly ET Differences (mm)			
Plot 3	1.8	3.5	2.2	0.7
Plot 4	2.2	2.9	1.1	1.6
	Maximum Weekly Irrigation Amount Differences (mm)			
Plot 3	0.6	1.7	1.3	0.2
Plot 4	2.3	1.1	1.0	0.7

$$ET = (S_1 - S_2) + I + R$$

where S_1 = soil moisture content at the beginning of the week; S_2 = soil moisture content at the end of the week; I = irrigation amounts during the week and R = total rainfall amounts during the week. Deep percolation was assumed insignificant. Previous studies indicate no significant runoff occurs at SAL except in the case of heavy rain (Ghali, 1983).

3.3.5 Gradient Irrigation Systems

The gradient irrigation system used in this study limits the opportunities of an experimenter to randomize treatments. Randomization can be accomplished to a limited extent with the locating of varieties, but even this cannot often be done since variety and water treatments are frequently closely coupled. This situation is a cause of concern statistically. "Systematic designs...often result in either underestimation or overestimation of experimental error. Also, they can result in inequality of precision in the various comparison among the treatment means...Until futher study of systematic designs has been made, it would seem advisable to avoid their use" (Steel and Torrie, 1980). The statistical analysis is confounded by the fact that adjacent plots tend to behave more similarly than plots separated by some distance. Hence, error components tend to become correlated, thus making invalid the usual tests of significance (Steel and Torrie, 1980).

Another factor is of statistical concern in the analysis of gradient irrigation and moisture stress experiments. Moisture stress levels cannot be applied in the same sense that other agronomic treatments are applied. However, it is possible to properly randomize and statistically analyze non-irrigation treatments, such as fertilizer levels (Hanks et al., 1980).

The vagaries of the weather may rapidly alter any preplanned moisture application level. Plot-to-plot differences in soil moisture holding capacities, compaction, irrigation application patterns and runoff patterns may result in significantly different amounts of water being available to plants that are theoretically treated the same. Hence, what is the stress treatment of a given plot?

If the applied treatments were a controllable quantitative variable, such as fertilizer, then all plots treated with the same fertilizer levels would be grouped together for statistical purposes, i.e., homogeneous groups exist in terms of the experimental treatments. What are the homogeneous groups for grouping the results of moisture stress research?

The answer to these questions depends on the purpose of the research. One common agronomic indicator of stress is grain-yield production. If two plots yield at a maximum rate, then does it matter whether one was dryland and the other was fully irrigated? Both plots can be considered nonstressed in terms of production. Any theoretical water treatment may be found in virtually any yield class (Table 3.7).

The grouping of data into homogeneous yield or vegetative classes also has the advantage of introducing randomness into an otherwise systematic design. Since grain yield is one of the parameters of interest in this study, the data will be analyzed by grain-yield class. Vegetative variability within any given yield class is expected.

3.4 Statistical Analysis Methods

Several statistical procedures are available for the analysis of data. Among these are a) multiple comparison procedures; b) orthogonal contrasts; c) analysis of variance; and d) regression analysis. An understanding of the appropriateness of a given procedure for a given set of experimental data is critical to a proper interpretation of the results (Petersen, 1977).

3.4.1 Multiple Comparison Procedures

Table 3.7 Grain yield data from corn plots at the Sandhills Agricultural Laboratory in 1982. Data are arranged in order of increasing yield and identified by plot, applied water treatment and hybrid. Arbitrary "yield categories" are defined in approximately 1000 kg/ha intervals. Treatment 1.0 was 100% of required irrigation, as determined by a neutron probe. Treatment 0.66 was 66%, treatment 0.33 was 33% and treatment 0.00 was 0% of treatment 1.00.

Pioneer 3901

Yield Class 1 (2500-4000 kg/ha)

Plot	TRT	Yield
18	0.00	3710
20	0.00	3872

Yield Class 2 (4000-5000 kg/ha)

Plot	TRT	Yield
22	0.00	4104
18	0.33	4425
23	0.00	4467
8	0.00	4475
21	0.00	4698

Yield Class 3 (5000-6000 kg/ha)

Plot	TRT	Yield
46	0.00	5242
43	0.33	5558
43	0.33	5687
46	0.00	5713
43	0.33	5894
43	0.33	5941
46	0.00	5942
46	0.00	5947

Yield Class 4 (6000-7000 kg/ha)

Plot	TRT	Yield
45	0.33	6176
19	1.00	6354
45	0.33	6419
8	0.33	6493
15	0.00	6610
6	0.33	6647
36	1.00	6653
45	0.33	6663
7	0.00	6680
18	0.66	6786
15	0.33	6796
20	0.33	6802
8	0.66	6836
41	0.66	6839
7	1.00	6860
7	0.33	6900
6	0.66	6901
6	1.00	6906
22	0.33	6929
18	1.00	6986

Table 3.7 (con't)

Yield Class 5 (7000-8000 kg/ha)

Plot	TRT	Yield
45	0.33	7090
20	1.00	7097
38	1.00	7102
7	0.66	7108
23	0.33	7159
19	1.00	7199
19	1.00	7298
19	1.00	7319
21	0.66	7413
6	0.00	7486
38	1.00	7643
8	1.00	7702
21	0.33	7721
36	1.00	7740
15	1.00	7768
20	0.66	7803
38	1.00	7910
39	0.66	7934

Yield Class 6 (8000-9000 kg/ha)

Plot	TRT	Yield
41	0.66	8033
39	0.66	8056
36	1.00	8103
36	1.00	8198
22	0.66	8214
39	0.66	8237
41	0.66	8250
39	0.66	8404
23	1.00	8417
15	0.66	8528
21	1.00	8550
22	1.00	8613
38	1.00	8643
41	0.66	8827
23	0.66	8886

B73xMo17

Yield Class 1 (2500-4000 kg/ha)

Plot	TRT	Yield
3	0.00	2605
13	0.00	2802
42	0.00	3305
42	0.00	3615

Yield Class 2 (4000-5000 kg/ha)

Plot	TRT	Yield
13	1.00	4270
13	0.66	4421
3	0.66	4553
42	0.00	4564
42	0.00	4634
14	0.33	4800
24	0.00	4801
14	0.66	4997

Yield Class 3 (5000-6000 kg/ha)

Plot	TRT	Yield
25	0.33	5329
44	0.33	5333
13	0.66	5338
13	1.00	5439
1	0.33	5470
2	1.00	5529
3	1.00	5574
2	1.00	5593
25	0.00	5762
44	0.33	5815
2	1.00	5844
3	0.66	5923

Table 3.7 (con't)

Yield Class 4 (6000-7000 kg/ha)			Yield Class 5 (7000-8000 kg/ha)		
Plot	TRT	Yield	Plot	TRT	Yield
44	0.33	6190	40	0.66	7077
14	1.00	6210	26	0.33	7373
26	0.66	6221	25	0.66	7428
1	1.00	6340	24	1.00	7437
24	0.66	6365	37	1.00	7813
1	0.00	6550	40	0.66	7624
2	1.00	6707	24	0.66	7710
40	0.66	6838	37	1.00	7733
1	0.66	6866	40	0.66	7808
25	1.00	6934	37	1.00	7836
26	0.00	6981	26	1.00	7922
			37	1.00	7964

Multiple comparison tests were developed to permit "data snooping" among sample means after an experiment has been conducted. Their purpose is to detect possible groups among a set of unstructured treatments. They are not intended as a substitute for regression analysis or orthogonal comparisons which can be defined before an experiment is conducted.

Multiple range tests should be used only when the treatment structure is not well understood--as in the case of "treatments" of fertilizers, varieties or insecticides, in which the researcher desires to "pick a winner" from among a set of qualitative treatments (Petersen, 1977). They should not be used when a) the treatments have an obvious structure; b) the means come from quantitative treatments such as rates of fertilizer, plant density, seeding rate or time; or d) when the treatments have a factorial structure (Chew, 1980; Buxton, 1982).

3.4.2 Orthogonal Contrasts

These procedures also apply to qualitative treatments or groupings of data. In this case, the qualitative factor contains several "levels," although no meaningful numerical value can be assigned. Examples include "levels" of varieties and soil types. Orthogonal tests, not multiple range tests, are performed on interesting or relevant contrasts as long as the contrasts have not been suggested by the data (Chew, 1976).

Examples of orthogonal contrasts that could be performed on our data set include contrasting varietal differences in leaf area index on a single day, varietal differences in grain yield or differences in reflectance patterns between corn and bare soil. It should be pointed out that the information from all of these contrasts with the exception of the grain-yield tests, can be summarized through ANOVA and regression analysis (Petersen, 1977).

3.4.3 Analysis of Variance/Regression Analysis

Analysis of variance (ANOVA) is often treated as being different from general regression. The realization that a model exists for all ANOVA situations and that it alone is the basis for all ANOVA results leads to the conclusion that ANOVA and regression analysis are equivalent, although separate computation procedures exist. Regression and ANOVA procedures are powerful tools only if the proper model has been identified.

3.5 Calibration of Infrared Thermometers and MMR Thermal Band

The PRT-5, Telatemp and MMR thermal bands were calibrated using the procedures described in Blad and Rosenberg (1976). Instrument responses were recorded while they viewed a copper cone that was immersed in a water bath. The temperature of the water bath ranged from 10 to 56 C in 2-4 C increments. Water temperature was measured with a mercury thermometer. A calibrated thermocouple was attached directly to the black body. Readings were taken when the thermocouple temperature stabilized. The mercury thermometer readings were used as the basis for the calibration equations.

The calibration equations for the PRT-5 and Telatemp were calculated directly, using a second order equation. The MMR thermal band calibration requires two separate calculations, however. First, the chopper temperature must be calculated. The factory calibration of the thermocouple which measures chopper temperature was used. The voltage response of the MMR thermal band is based on the difference in temperature between the target temperature and the chopper temperature. Hence, the following equation must first be calculated:

Thermal band (volts) = a + b (Blackbody temp. - Chopper temp.)

The coefficients a and b are then used to define the calibration equation for field data:

Target temperature = Chopper temp. + (Thermal band (volts) - a)/b

(Barrett Robinson, personal communication) (Table 3.8).

3.6 Bare Soil Emissivity

Bare soil emissivity values were determined the night of 9 June, using the techniques of Fuchs and Tanner (1966). The instrument used was the Telatemp Ag-42 infrared thermometer. Radiative sky temperatures were estimated as the average of 50 IRT observations made in several azimuth and zenith directions. Ten observations were made over wet and dry bare soil. Emissivity (ε) was calculated as:

$$\varepsilon = (T_a^4 - T_{sky}^4)/(T_b^4 - T_{sky}^4)$$

where T_a is the apparent soil temperature (degrees Kelvin), T_{sky} is the average radiative sky temperature and T_b is the "black" soil temperature. Dry soil emissivity was calculated as 0.935. Wet soil emissivity was calculated as 0.951.

3.7 Reflectance Factor Calculations

All measured voltages were first corrected for fluctuations in instrument electronics before calculating reflectance factors:

$$V_c = V_r - V_d$$

where V_c is the corrected response voltage over the calibration standard or the crop canopy in any given waveband, except the far infrared. V_r is the "raw" voltage response and V_d is the response of the instrument when a black cover was placed over the instrument optics.

Two algorithms were used to calculate reflectance factors (Bauer et al., 1981). Algorithm 1 uses a linear interpolation of "before" and "after"

Table 3.8 Calibration equations for the PRT-5, Telatemp, MMR Thermal band and a reference thermocouple.

March 23, 1982 Calibration Equations

Instrument Reponse (C)	Intercept	x	x^2	x^3	units	R^2
PRT-5 (high scale)	20.0257	11.712	-0.0036	n/a	volts	0.999
PRT-5 (mid-scale)	-10.402	10.548	-0.1145	n/a	volts	0.999
Telatemp	- 0.0553	1.000	0.00097	n/a	C	0.999

January 25, 1983 Calibration Equations

Instrument Reponse (C)	Intercept	x	x^2	x^3	units	R^2
PRT-5 (high scale)	20.401	11.217	0.2203	n/a	volts	0.998
PRT-5 (mid-scale)	- 9.426	9.468	0.101	n/a	volts	0.998
Telatemp	- 1.273	1.044	0.00042	n/a	C	0.999
Thermocouple	- 0.003818	25.985	-0.725	0.0205	mv	0.999

MMR Calibration Equations

Chopper Temperature = -1.4583 + 14.583 (chopper voltage)
(Chpt) (C)

Thermal band (volts) = 1.957 + [0.03325*(black body temp - Chpt)]

MMR Equation for Field Data

Thermal band (C) = Chpt + [Thermal band (volts)-1.957]/0.03325 calibration panel reflectance readings to estimate the barium sulfate plate reflectance at the time canopy reflectance was measured:

$$RF = (V_{cc}/V_{cp})100$$

where V_{cc} is the corrected response voltage measured over the crop and V_{cp} is the corrected response voltage over the barium sulfate plate at the time V_{cc} was measured. V_{cp} was calculated as:

$$V_{cp} = [V_{cpb} + (V_{cpa}-V_{cpb})*(t_c-t_b)/(t_a-t_b)]/R_p$$

where V_{cpb} is the plate response before canopy reflectance was measured and V_{cpa} is the plate response afterward; t_a and t_b refer to the times V_{cpb} and V_{cpa} were measured; t_c is the time crop reflectance was measured. R_p is the plate reflectance at the zenith angle at the time of measurement. R_p was determined in laboratory calibrations at the Laboratory for Applications of Remote Sensing (LARS) at Purdue University (Tables 3.9-3.11) (Fig. 3.10). Algorithm 1 was used throughout the season, except on infrequent occasions when (t_a-t_b) exceeded 30 minutes. In this event, algorithm 2 was used:

$$RF = [(V_{cc}/V_{cpb})\sin(sea)_b R_p/\sin(sea)_c]100$$

where sea_b is the solar elevation angle at the time the reflectance of the barium sulfate plate was measured and sea_c is the solar elevation angle at the time canopy reflectance was measured.

3.8 Solar Illumination Conditions

Solar illumination conditions ranged from 0 to 50% cloud cover. Generally, reflectance observations were not made if cloud cover exceeded 30%. The majority of observations were taken with less than 10% cloud cover (by visual estimate). The majority of readings were taken between 1000 and 1400

Table 3.9 Reflectance values for the 1.2 m x 1.2 m barium sulfate reference panel used at SAL in 1982. The plate was calibrated at the Laboratory for Applications of Remote Sensing (LARS) at Purdue University.

Band (μm)	Radiance Zenith Angles					
	10°	20°	30°	40°	50°	55°
0.5-0.6	94.1	90.8	88.7	87.6	84.7	83.6
0.6-0.7	93.9	90.4	88.3	87.5	84.3	83.6
0.7-0.8	93.3	89.5	87.6	87.1	83.7	83.4
0.8-0.11	92.0	87.9	86.1	85.7	83.0	82.3
0.45-0.52	94.3	92.0	89.0	88.0	85.0	84.0
0.52-0.60	94.1	90.7	88.7	87.7	84.8	83.6
0.63-0.69	93.9	90.4	88.3	87.5	84.3	83.5
0.76-0.90	92.8	88.9	86.8	86.6	83.5	83.1
1.15-1.30	90.2	85.7	84.1	84.0	81.4	81.1
1.55-1.75	85.7	81.2	79.4	79.5	77.4	76.9
2.08-2.35	75.7	71.2	69.7	69.6	68.1	67.7

Table 3.10 Equations used in 1982 for estimating the reflectance of the barium sulfate plate, as a function of illumination zenith angle (ZA).

R^2	waveband (μm)	Reflectance
0.997	0.5-0.6	102.028-1.127*ZA+0.0402*ZA**2-0.000694*ZA**3+4.08x10^{-6}*ZA**4
0.993	0.6-0.7	104.0957-1.522*ZA+0.0614*ZA**2-0.00115*ZA**3+7.510x10^{-6}*ZA**4
0.988	0.7-0.8	106.571-2.058*ZA-0.0899*ZA**2-0.00175*ZA**3+1.199x10^{-6}*ZA**4
0.993	0.8-1.1	104.166-1.813*ZA+0.0719*ZA**2-0.00128*ZA**3+7.951x10^{-6}*ZA**4
0.992	0.45-0.52	96.169-0.0961*ZA-0.0118*ZA**2+0.000347*ZA**3-3.171x10^{-6}*ZA**4
0.997	0.52-0.60	102.50-1.200*ZA+0.0431*ZA**2-0.000730*ZA**3+4.163x10^{-6}*ZA**4
0.993	0.63-0.69	103.87-1.479*ZA+0.0587*ZA**2-0.00108*ZA**3+6.94x10^{-6}*ZA**4
0.986	0.76-0.90	104.833-1.803*ZA+0.0729*ZA**2-0.00133*ZA**3+8.59x10^{-6}*ZA**4
0.990	1.15-1.30	105.102-2.276*ZA+0.0953*ZA**2-0.00175*ZA**3+1.144x10^{-6}*ZA**4
0.991	1.55-1.75	98.343-1.844*ZA+0.0690*ZA**2-0.00114*ZA**3+6.58x10^{-6}*ZA**4
0.996	20.8-2.35	88.239-1.837*ZA+0.0693*ZA**2-0.00116*ZA**3+6.871x10^{-6}*ZA**4

Table 3.11 Solar illumination conditions for spectral data at SAL during the 1982 crop season and the number of data points collected over corn. All angles are in degrees.

Date	Day of Year	Number of Observations Corn	Number of Observations Soybeans	Time Period (solar time)	Solar Elevation Angle Range	Solar Azimuth Angle Range	Solar Declination Angle	Percent Cloud Cover
5/29	149	72	32	1000-1230	59.8-70.0	123-204	21.7	0-1
6/16	167	72	32	1030-1230	64.0-72.0	127-193	23.4	0-5
6/21	172	72	44	0945-1215	57.0-71.0	113-167	23.5	0-30
6/23	174	115	105	0945-1630	33.0-72.0	158-273	23.5	0-5
6/28	179	116	113	1000-1600	59.0-71.0	117-230	23.3	0
7/13	194	47	32	1030-1200	63.0-70.0	132-172	21.8	5-30
7/14	195	44	36	1400-1500	46.0-53.0	249-257	21.7	5-20
7/15	196	132	116	1030-1430	53.0-70.0	164-249	21.5	0
7/19	200	36	36	1330-1415	55.0-58.0	237-243	20.8	0-30
7/20	201	128	68	0845-1200	48.0-69.0	106-172	20.6	0-5
7/23	204	48	81	1215-1500	48.0-59.0	233-252	20.0	0
7/31	212	72	32	1030-1130	59.0-65.0	132-156	18.1	20-50
8/1	213	116	116	0830-1130	44.0-65.0	106-163	17.9	5-10
8/8	220	117	115	0930-1400	55.0-64.0	138-231	15.9	0-1
8/17	229	116	68	1200-1530	55.0-64.0	213-264	13.1	5-50
8/18	230	116	152	1100-1715	57.0-25.0	180-252	12.7	0-10
8/23	235	116	116	0800-1200	32.0-58.0	104-158	11.0	0-10
9/1	244	116	116	0930-1400	42.0-55.0	123-207	7.6	0-5
9/2	245	144	96	0730-1630	22.0-56.0	101-259	7.3	0-10
9/9	252	164	148	0930-1515	33.0-53.0	128-243	4.5	0-5
9/18	261	71	80	0915-1115	42.0-48.0	140-162	0.9	0
9/29	272	116	117	1200-1415	45.0-38.0	179-215	-3.5	0

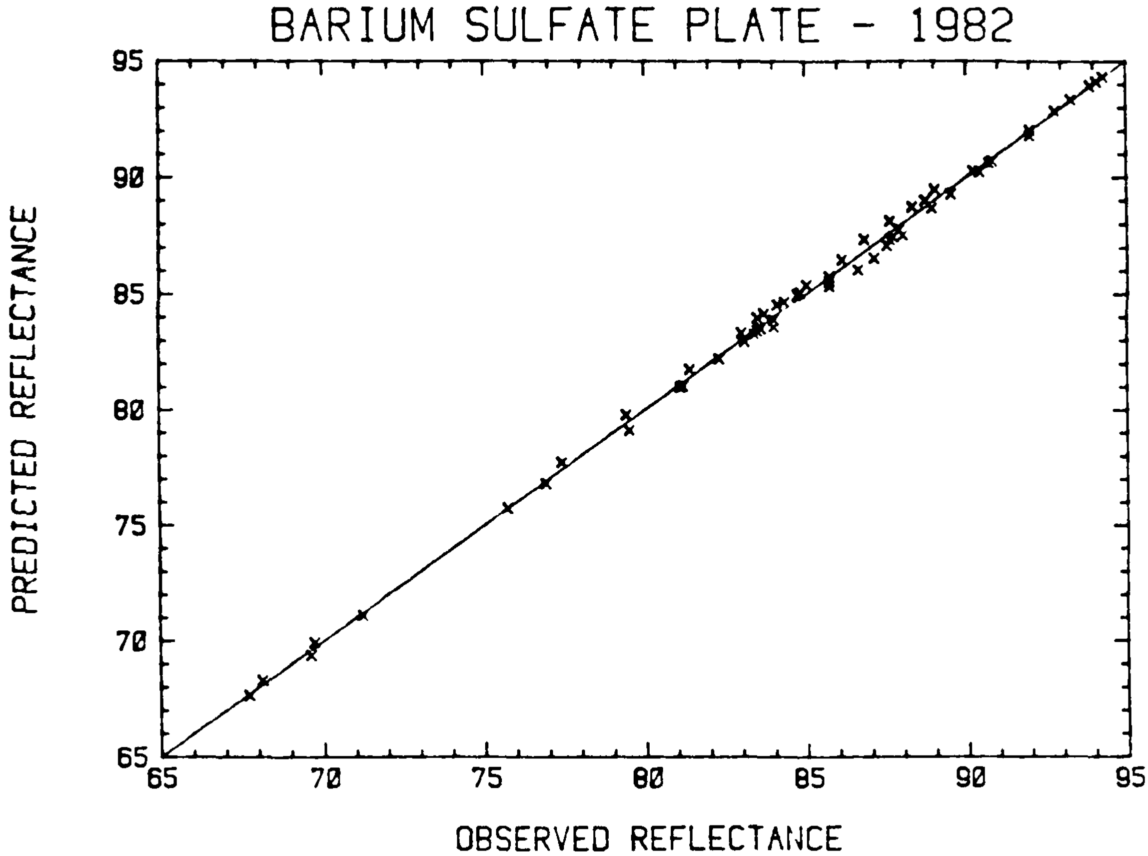


Fig. 3.10 Predicted versus observed reflectance for the barium sulfate plate used at SAL in 1982, for all zenith angles and wavelength combinations. Zenith angles ranged from 10 to 55 degrees.

solar time, although other times are presented. Solar elevation angles ranged from 22 to 71 degrees. The rapid development of clouds during a run caused many data runs to be aborted before they were completed (Table 3.11).

3.9 Soil Reflectance Characteristics

Dry soil at SAL is highly reflective in all wavebands. In general, however, soil reflectance is a strong function of moisture content. The extremes of bare soil reflectance encountered throughout the season are illustrated by data collected on 19 July over a 10 m diameter plot. The sandy soil was very dry on this date (by visual and tactile inspection). Reflectance readings were taken over this plot; then the plot was thoroughly wetted and reflectance readings were again taken. The time between measurements was less than 1 minute. Reflectance values decreased by around 100% in the visible and near infrared bands and by 329% in the middle infrared band 2.08-2.35 μm.

Bare soil reflectance was also monitored throughout the season. Bare soil plots measuring approximately 10 m by 10 m were located directly to the east of the reflectance areas of plots 5, 10, 15, 20, 23 and 26. These plots were read during each data run through these areas (Table 3.12).

3.10 Radiation Instrumentation

Radiation readings were made 8.5 m above the soil from the end of a boom assembly mounted on a four-wheel-drive truck after the design of Tsuchida (1981) (Figs. 3.11-12). At intervals of 30 minutes or less, radiation readings were also taken 1.4 m above a barium sulfate plate.

The instruments mounted on the boom were a Barnes Model 12-1000 multiband radiometer (MMR), an Exotech-100A radiometer, a Barnes PRT-5 infrared thermometer and a motor-drive Nikon 35 mm camera (Table 3.13). In addition, an

Table 3.12 Bare soil reflectance statistics for 6 bare soil plots at SAL during 1982 and a wet-dry study conducted at 1200 solar time on July 19.

	1982 Season		July 19		
Waveband (μm)	Mean	Coefficient of Variation %	Wet Soil Mean	Dry Soil Mean	Percent Difference
0.45-0.52	7.19	51.9	4.55	9.83	116
0.52-0.60	8.93	53.4	5.55	12.20	119
0.63-0.69	11.83	52.2	7.45	16.20	117
0.76-0.90	16.88	46.3	11.35	22.40	97
1.15-1.30	24.35	42.7	17.00	31.70	86
1.55-1.75	29.12	58.8	17.00	41.23	148
2.08-2.35	24.21	88.0	9.15	39.27	329

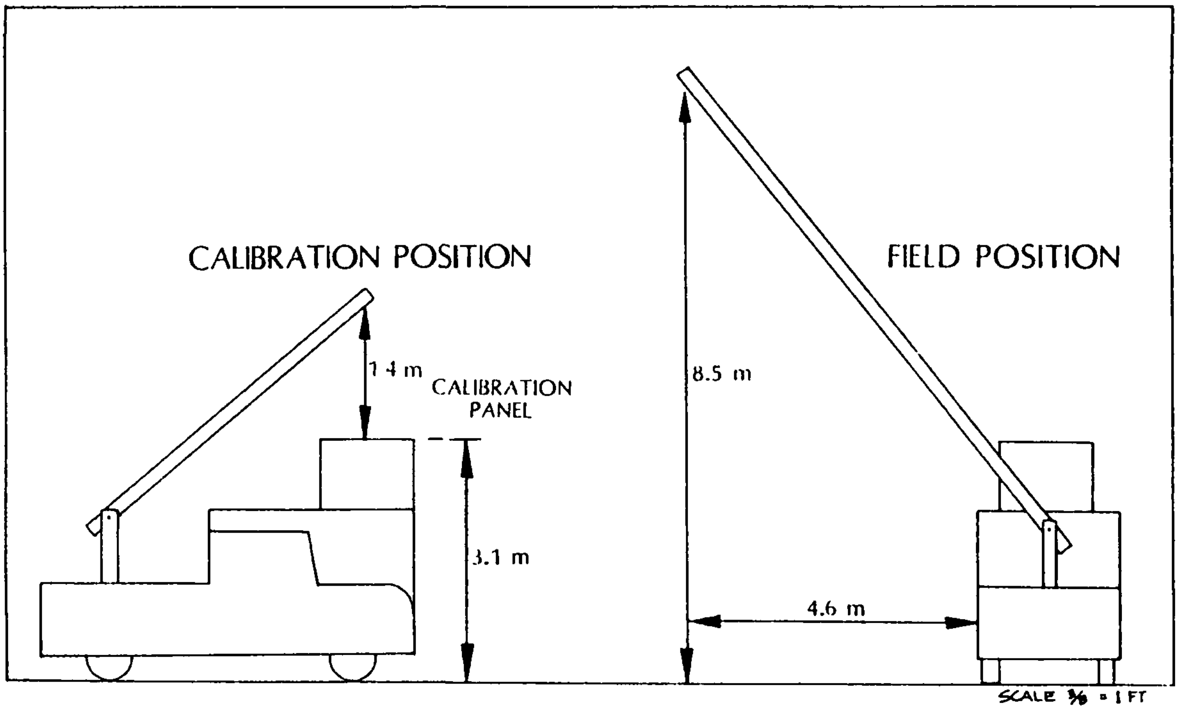


Fig. 3.11 Schematic of the boom truck system used at SAL in 1982.

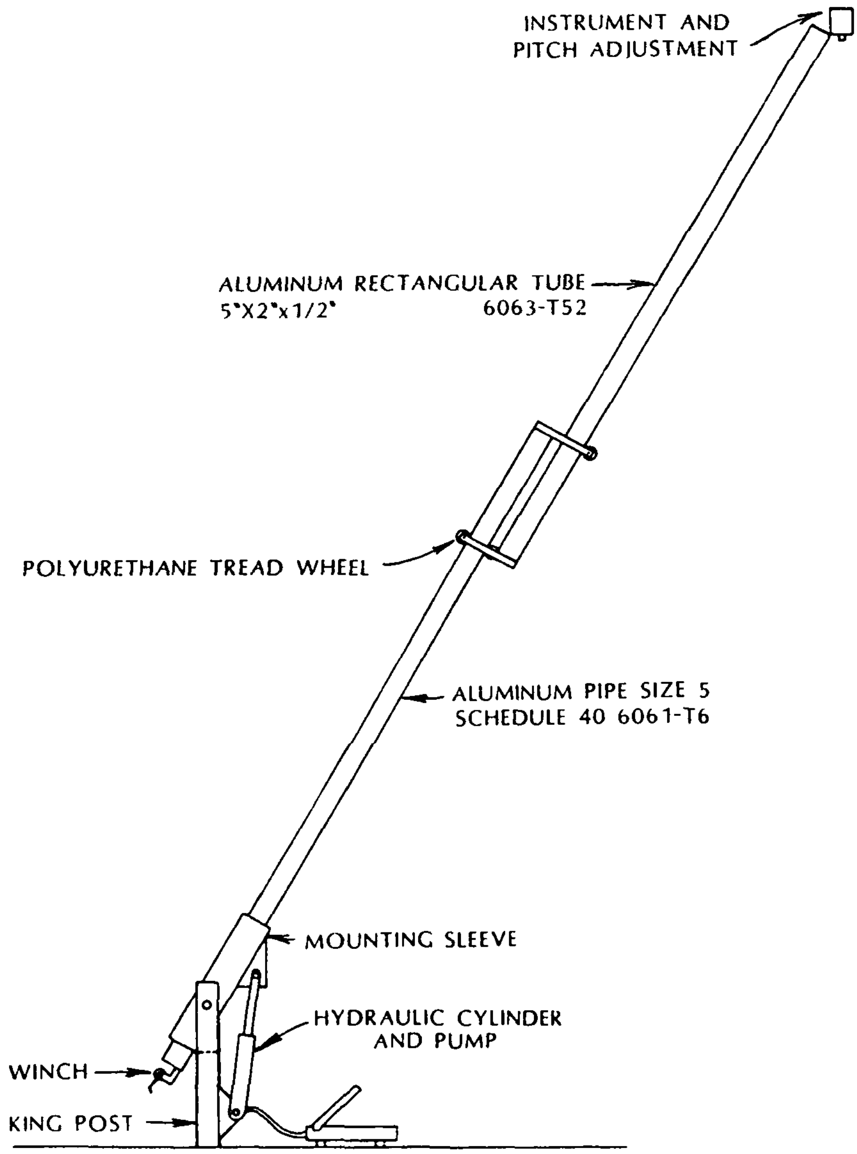


Fig. 3.12 Schematic of the boom assembly used in 1982 for making radiation measurements.

Table 3.13 Spectral bands measured and associated fields of view for the radiation instruments used at SAL during 1982. Acronyms for each radiation band are also given. TM refers to the Thematic Mapper wavebands. MMR refers to the Barnes modular multiband radiometer 12-1000. MSS refers to the multispectral scanner used on Landsat satellites.

Acronym	Wavelengths Measured (μm)	Field of View (degrees)
	BARNES 12-1000	
TM1	0.45-0.52	15
TM2	0.52-0.60	15
TM3	0.63-0.69	15
TM4	0.76-0.90	15
MMR5	1.15-1.30	15
TM5	1.55-1.75	15
TN7	2.08-2.35	15
TM6	10.4-12.5	15
	EXOTECH 100-A	
MSS4	0.5-0.6	15
MSS5	0.6-0.7	15
MSS6	0.7-0.8	15
MSS7	0.8-1.1	15
	BARNES PRT-5	
--	8.0-14.0	2
	TELATEMP AG-42	
--	10.5-12.5	5

observer, sitting on the calibration platform, also operated a Telatemp Ag-42 infrared thermometer. All radiation measurements were logged on a battery-operated Omnidata Polycorder. Photographs were taken of each reflectance sampling area approximately weekly throughout the season.

3.11 Walburg Corn Canopy Reflectance Data Base

Walburg et al. (1982) summarized the results of a remote sensing study of corn canopy reflectance/nitrogen nutrition experiment at the Purdue Agronomy Farm. The study was conducted during 1978 and 1979.

The soil type used was a Raub soil loam (Aquic Arguidoll). A randomized, complete block design was used, with three replications of each nitrogen treatment. The treatments used were 0, 67, 134 and 202 kg/ha, applied in the spring. Identical rates have been applied to the same plots continuously since 1965. Atrazine was applied after planting for weed control. Each plot consisted of six rows of corn plant 0.71 m apart in an east-west orientation. Corn hybrid Beck 65x was planted on 31 May 1978 at a population of 54000 plants/ha and Pioneer 3183 was planted on 10 May 1979 at 66000 plants/ha.

Spectral reflectance between .4 and 2.4 μm in 0.01 μm intervals was measured with an Exotech 20 C spectroradiomter mounted on the boom of a mobile aerial tower. Spectral data were acquired on 11 dates during 1978 and 12 dates during 1979. Measurements were made looking straight down from an altitude of 9.1 m over the center of a plot. With a 15° field of view, the instrument viewed 2.3 m diameter ground area. All spectral measurements were made on cloudless or near cloudless days when the solar elevation angle was greater than 45° and prior to solar noon. Each spectral data set required no more than 1.5 hours to collect. The response of a barium sulfate reference panel was measured in approximately 20-minute intervals throughout the data acquisition period.

Agronomic variables were measured and observed throughout each season on the same dates as the spectral measurements. These data included: development stage (Hanway, 1971), leaf area index, percent soil cover, fresh and dry biomass, leaf chlorophyll concentration and leaf nitrogen content. Grain yields were also collected.

In early 1982, these data were provided to the University of Nebraska Agricultural Meteorology group by the Laboratory for Applications of Remote Sensing (LARS) at Purdue University. The reflectance data was provided in integrated form over the Thematic Mapper wavelengths. These data will be referred to in this report as the Walburg data set.

3.12 Stoner Bare Soil Data Base

Stoner and Baumgardner (1981) summarized the results of an intensive reflectance study of samples from 246 soil series from 481 sites within the continental United States and 4 sites in Brazil. For the U.S. soil series, duplicate samples were obtained at a site 1 to 30 km from the first site. The soil series used in this study were selected at random within climatic strata from among a list of more than 1300 benchmark U.S. soil series. The resulting collection of soil samples covers a well-distributed geographical pattern, encompassing 17 continental U.S. climatic zones including soils from 28 suborders of 9 soil taxonomic orders (Soil Survey Staff, 1975; Thornthwaite, 1948).

Reflectance measurements between 0.4 and 2.4 μm were made in 0.01 μm intervals on samples that had equilibrated for 24 hours at 0.1 bar moisture tension on asbestos tension tables. This procedure expedited the establishment of a standardized moisture condition, thus avoiding the fluctuating uncontrolled environmental conditions of air-dry soil samples.

Spectral directional reflectance factors were measured with an Exotech Model 20 C spectroradiometer (Lemeur et al., 1973) adapted with an artificial illumination source for indoor use. Pressed barium sulfate was used as a calibration standard to account for fluctuations in the 1000W tungsten-iodide lamp used as an illumination source. Reflectance measurements for all of the soil samples were placed in a digital data base together with soil taxonomic and laboratory analysis data. In early 1983, the reflectance data were integrated over the Thematic Mapper and Landsat MSS wavebands and provided to the University of Nebraska Agricultural Meteorology group, together with the soil taxonomic and analysis data by the LARS (Biehl, L. L., personal communication). These data will be referred to in this report as the Stoner soil data.

4. RESULTS AND DISCUSSION

4.1 Development of Predictive Models for Assessing Phytomass and Moisture Stress in Corn

Three general mathematical models can be used to describe data: a) functional models; b) control models; and c) predictive models.

If a known functional relationship exists between a response variable and independent variables, then an experimenter can, theoretically, understand and predict the response. In practice, functional models are difficult to evaluate. All the independent variables may not be measurable or controllable. Functional models are often complicated and difficult to interpret and use, and are usually nonlinear. Thus, linear regression procedures cannot generally be applied to these models.

The purpose of control models is the controlling of a response variable in situations in which all the independent variables are under the control of an experimenter. These models are often used in industry and laboratory work, but have little application to field situations.

Predictive models do not necessarily provide information concerning functional relationships between variables, but can reproduce the main features of the behavior of the response under study. Multiple regression techniques are one of main tools for developing predictive models. These techniques can identify important variables that should be studied in relation to a response variable (Draper and Smith, 1966). The purpose of this chapter is to describe the development of predictive models for estimating leaf area index, grain yield and moisture stress in corn using reflectance and thermal data acquired from the Thematic Mapper wavebands.

4.2 Agronomic Relationships

The physical structure of a canopy determines the phytomass parameters which are directly related to canopy reflectance. For most agronomic crops, radiation is intercepted primarily by the leaves, although stems and stalks may also be important. The agronomic measurement that most appropriately characterizes the radiation interception qualities of a canopy is leaf area index (Norman, 1979). Other agronomic measurements to characterize the reflectance properties of a canopy may include wet and dry leaf weights or stalk weights.

The importance of LAI measurements in relationship to reflectance data can be determined through multiple regression. The model used is (in SAS notation):

reflectance = LAI wetleaf dryleaf wetstalk drystalk

where wetleaf and dryleaf are total wet and dry leaf weights and wetstalk and drystalk are total wet and dry stalk weights. The variables are statistically considered in the order shown. The relative importance of a variable can be determined by calculating the ratio Type I SS/Total SS, where SS means sum of squares. Type I SS represent the variation attributable to a given term in a model.

The results show that only 1 to 3 percent of the variation in reflectance throughout the 1982 season is accounted for by agronomic terms other than LAI (Table 4.1). Note that the 1.15-1.30 μm waveband is not related to LAI. The reason for this is related to soil reflectance characteristics (Biehl, private communication) since the bands on either side of it are highly correlated (see Section 4.4).

The correlation matrix for the phytomass data (Table 4.2) shows that many

Table 4.1 Percent of the total variation in reflectance in a given waveband for the linear multiple regression of reflectance on four agronomic variables: leaf area index (LAI), wet and dry leaf weights and wet and dry stalk weights. R^2 for the entire model is also given.

Waveband	R^2	LAI	wet leaf weight	dry leaf weight	wet stalk weight	dry stalk weight
0.45-0.52	0.71	0.68	0.01	0.01	0.00	0.01
0.52-0.60	0.72	0.69	0.01	0.01	0.00	0.00
0.63-0.69	0.75	0.72	0.01	0.00	0.00	0.01
0.76-0.90	0.66	0.62	0.02	0.00	0.00	0.01
1.15-1.30	0.14	0.08	0.00	0.02	0.02	0.02
1.55-1.75	0.78	0.73	0.01	0.03	0.00	0.01
2.08-2.35	0.78	0.73	0.01	0.02	0.00	0.02

Table 4.2 Correlation matrix (r) for all agronomic variables measured in Pioneer 3901 and B73xMo17 corn hybrids during 1982.

	LAI	Wet leaf weight	Wet stalk weight	Dry leaf weight	Dry stalk weight	Total wet phytomass	Total dry phytomass	Leaf water content	Stalk water content	Canopy water content
LAI	1.0	0.94	0.74	0.94	0.51	0.81	0.61	0.92	0.78	0.84
Wet leaf weight		1.0	0.72	0.94	0.46	0.80	0.57	0.99	0.76	0.84
Wet stalk weight			1.0	0.82	0.89	0.99	0.93	0.67	0.99	0.98
Dry leaf weight				1.0	0.58	0.87	0.69	0.93	0.85	0.89
Dry stalk weight					1.0	0.85	0.99	0.41	0.82	0.78
Total wet phytomass = wet (leaf+stalk) weight						1.0	0.91	0.76	0.99	0.99
Total dry biomass = dry (leaf+stalk) weight							1.0	0.52	0.87	0.85
Leaf water content = (wet leaf)-(dry leaf)weight								1.0	0.72	0.80
Stalk water content = (wet stalk)-(dry stalk)weight									1.0	0.99
Canopy water content = (total wet phytomass)-(total dry phytomass)										1.0

parameters are intercorrelated. The effect of this situation on multiple regression models is clear. When one correlated parameter is entered first in a regression model, other correlated parameters are viewed as being statistically insignificant. In addition, any parameter that is a linear combination of other model parameters is not allowed, i.e., leaf water content would not be allowed in the same model as wet and dry leaf weight measurements, where leaf water content is calculated as the difference in the wet and dry leaf weight. Thus, the agronomic terms in multiple regression models should be in terms of basic measurements in order to minimize these statistical problems.

These results have important implications for remote sensing of moisture stress. In order to determine whether moisture stress causes changes in the reflectance pattern of corn (relative to a nonstressed canopy) it is necessary to eliminate LAI differences between the stressed and nonstressed canopies. Stress severe enough to cause leaf curling would result in reflectance differences due to canopy geometry changes and should thus be avoided. It is conceivable that these problems may be overcome by the use of very narrow waveband reflectance measurements. Gausman (1977) showed that stomata of Rhoeo R. discolor Hance reflect more in the 0.85 μm waveband when open than when closed.

4.3 Reflectance Relationships to LAI

Green vegetation generally has low reflectance around 0.45 μm and 0.65 μm as a result of chlorophyll absorption bands centered at these points (Hoffer, 1978). Consequently, a reflectance peak occurs around 0.54 μm. Thematic Mapper bands 1, 2 and 3 have been selected to incorporate these responses.

The relationship between TM bands 1-3 is inverse and non-linear (Fig. 4.1). Reflectance is highest over bare soil and decreases to an approximately constant value by an LAI of around 2.0. It is clear that these bands are

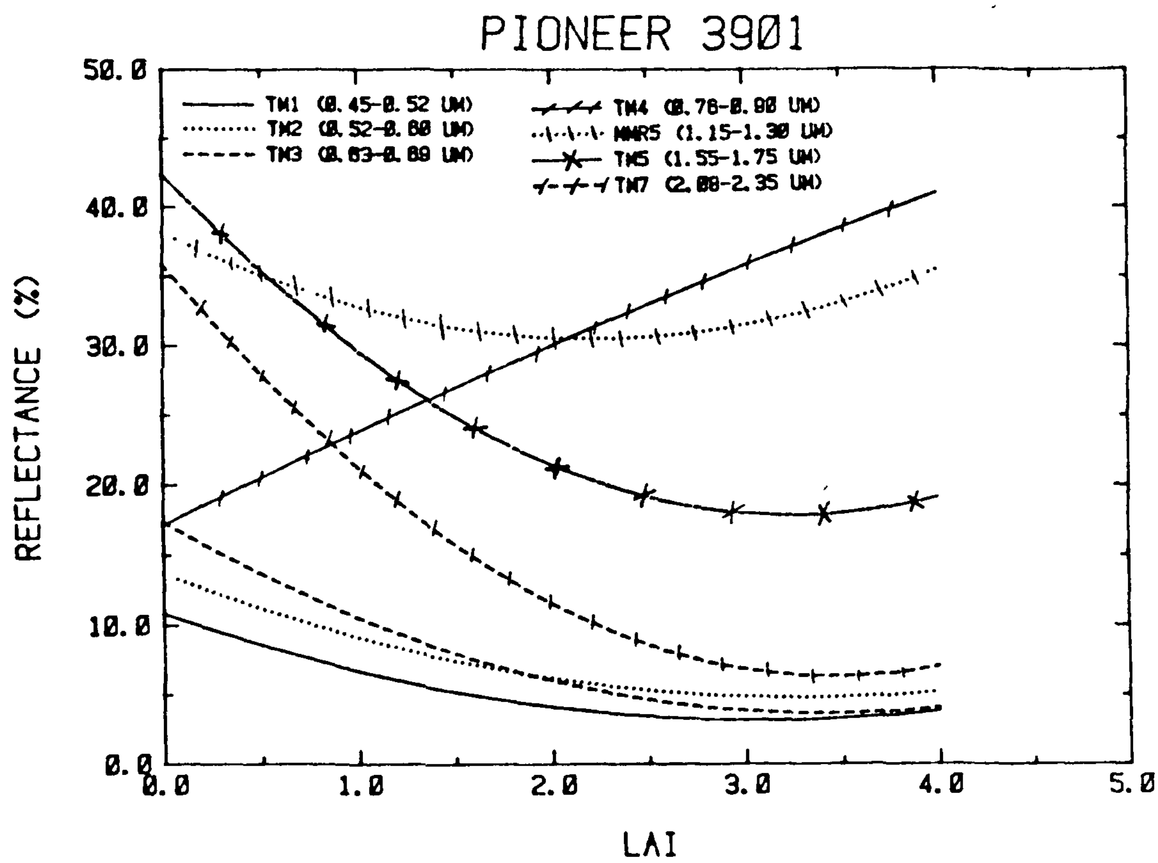


Fig. 4.1 Relationship between canopy reflectance and leaf area index (LAI) for several wavebands. Trend lines represent means from all plots of Pioneer 3901 measured in 1982.

responding to the percentage of bare soil present. But (1 -% bare soil) = % ground cover = % horizontal phytomass. Hence, these bands can be thought of as indicating the spatial distribution of phytomass.

Between 0.7 and 1.4 μm, healthy green leaves are characterized by high reflectance (45-50%), high transmittance (45-50%) and low absorptance (less than 5%) (Hoffer, 1978). These properties lead to the phenomenon known as multiple reflectance. As the number of layers of leaves increase, reflectance continues to increase. The reflectance from multiple leaf layers may be up to 85% greater than the reflectance from a single leaf in these wavebands (Meyers, 1970). Gausman et al. (1976) showed that multiple reflectance effects continue to be detectable through 8 layers of leaves. Based on this theory, TM4 and MMR5 should respond directly to changes in the number of layers of leaves in a canopy, i.e., vertical phytomass density. This theory accurately predicts the response of TM4 (0.76-0.90 μm) to LAI (Fig. 4.1) but does not predict the response of the 1.15-1.30 μm, as indicated in section 4.4.

TM5 (1.55-1.75 μm) and TM7 (2.08-2.35 μm) are both water absorption bands. Meyers (1970) showed that multiple reflectance effects were present in TM5 but to a lesser degree than in TM4. The water absorption effect acts in opposition to the multiple reflectance effect. Thus, multiple reflectance effects in TM5 are more likely to be found over lightly vegetated areas (such as rangelands) than in agronomic crops such as corn. Such was the case for our study. The response patterns of TM5 and TM7 were similar to the visible bands (Fig. 4.1). Thus, these bands can be said to indicate the horizontal or vertical density of canopy phytomass and/or canopy water content (Table 4.3).

4.3.1 Separation of Vegetation from Soil Data

The relative values of TM4 and MMR5 can be used to determine whether data

Table 4.3 Interpretation of the agronomic mechanisms resulting in observed reflectance patterns in selected wavebands.

Waveband (μm)	Agronomic mechansm	Additional agronomic sensitivity
0.45-0.52	Horizontal phytomass density	chlorophyll
0.52-0.60	Horizontal phytomass density	
0.63-0.69	Horizontal phytomass density	chlorophyll
0.76-0.90	Vertical leaf layers (density)	
1.15-1.30	Vertical leaf layers (density)	bare soil
1.55-1.75	Horizontal or vertical phytomass density	canopy water
2.08-2.35	Horizontal phytomass density	canopy water

comes from vegetated surfaces or from bare soil. Reflectance values are similar in TM4 and MMR5 over vegetated surfaces, but MMR5 is generally much greater than TM4 over bare soil (Table 4.4) (Bauer, personal communication). One major application of this relationship is found in the analysis of satellite data. Unvegetated data points can be easily identified.

4.4 Predicting LAI

The method used to relate spectral data to LAI is extremely important in terms of the generality of the resulting prediction equation. The predominating problem in developing generally applicable predictive models is the bias caused by soil reflectance differences from location to location and temporal changes in soil reflectance as a result of surface soil moisture changes (Colwell, 1974; Richardson et al., 1975; Richardson et al., 1977; Tucker et al., 1977; Rao et al., 1979).

The lack of response of the 1.15-1.30 μm waveband (MMR5) is interesting. Theoretically, this band should respond similarly to TM4 (0.76-0.90 μm). The lack of correlation of MMR5 with LAI is probably due to a similarity in reflectance values between corn and bare soil at SAL (Biehl, personal communication). In effect, in this waveband, corn and bare soil are virtually indistinguishable. This interpretation is supported by noting that mean canopy reflectances and dry soil reflectances were significantly different in all wavebands except MMR5 (Table 4.4).

The relationship between bare soil reflectance and mean canopy reflectance is strongly dependent on soil moisture content, however. Relative to wet soil at SAL, MMR5 over corn is very different. Hence, if the soil at SAL were wet throughout the entire season or (dark soil) then a stronger relationship between MMR5 and LAI should be evident.

The relative sensitivity of each waveband for estimating LAI can be

Table 4.4 Mean corn canopy reflectances (both varieties) throughout the 1982 season. Included for comparison is the reflectance of a 10 meter diameter (wet and dry) bare soil plot, as measured at 1200 (solar time) on July 19.

	Waveband (μm)	Mean canopy reflectance (n--1082)	Standard deviation	Wet soil reflectance	Dry soil reflectance
TM1	0.45-0.52	4.496	2.43	4.55	9.83
TM2	0.52-0.60	6.15	2.98	5.55	12.20
TM3	0.53-0.69	5.92	4.53	7.45	16.20
TM4	0.76-0.90	34.18	6.87	11.35	22.40
MMR5	1.15-1.30	33.15	3.08	17.00	31.7
TM5	1.55-1.75	22.36	7.96	17.00	41.23
TM7	2.08-2.35	11.93	9.52	9.15	39.27

readily assessed (Fig. 4.1). It is clear that TM4 (0.76-0.90 μm) is the most important band since it is linearly correlated with LAI. Although the visible (TM1-TM3) and middle IR (TM5, TM7) have the same curvilinear form, TM5 and TM7 exhibit much larger dynamic ranges. Thus, TM5 and TM7 are more sensitive indicators of canopy closure (horizontal phytomass) than are the visible bands. Improved resolution of LAI estimates before canopy closure (LAI less than about 2.5) can thus be expected by including TM5 and TM7 in LAI predictive models.

4.4.1 Minimizing Soil Background Effects

LAI models composed of reflectance in only TM4 could not be expected to be generally applicable, since soil reflectance varies strongly as a function of soil type and soil moisture (Fig. 4.2a). Thus, information from TM4 must be combined with information from the remaining wavebands in such a way as to reduce soil background fluctuations to a minimum (Fig. 4.2b). The general applicability of any given LAI model can thus be determined by studying its behavior over bare soil.

4.4.1.1 The Tasseled Cap Transformation

Figure 4.2a also represents the relationship of the Kauth and Thomas "tasseled cap" greenness transformation to soil reflectance. The Y axis is imagined to be a "plane of soils" from which all near-infrared reflectances (or greenness values) emerge. The greenness index is:

$$\text{Greenness} = K_1(\text{MSS4}) + K_2(\text{MSS5}) + K_3(\text{MSS6}) + K_4(\text{MSS7})$$

where K_1 to K_4 are constants depending on the type of instrument used to measure canopy reflectance. MSS4 and MSS5 are visible bands. The reflected radiation in these two bands rapidly becomes constant as the season progresses. The greenness index is, therefore, a linear function of near

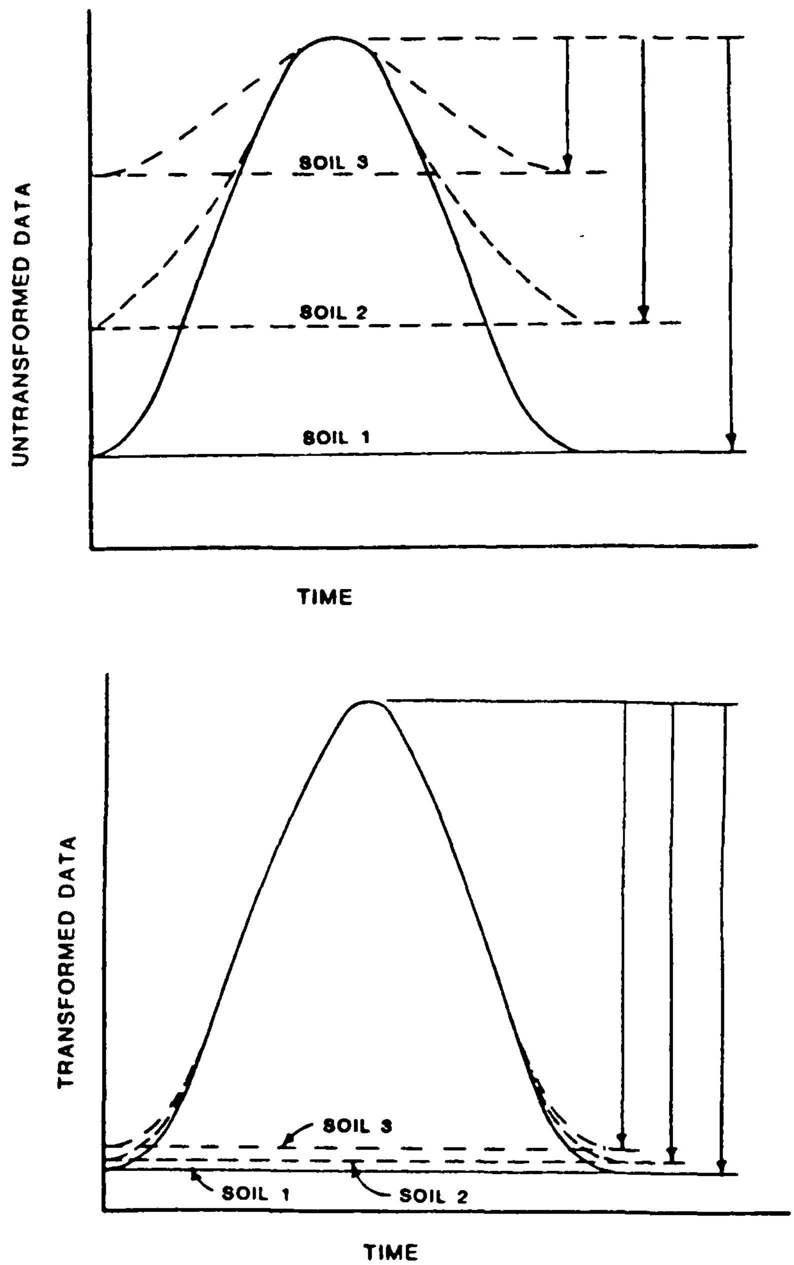


Fig. 4.2 Conceptual relationship between seasonal reflectance over a crop canopy in the near-infrared wavebands over three different soils, as compared to transformed data over the same soils. The transformation form is not defined.

infrared reflectance.

As the season progresses, near infrared reflectances emerge from the plane of soils (Y axis) and converge to a maximum value that is independent of soil type. As the canopy begins senescing, near infrared canopy reflectances return to near the bare soil reflectance values. If Fig. 4.2a were rotated, then the tasseled cap drawn by Kauth and Thomas (1976) would be outlined.

It should be clear that the greenness transformation does not remove any bias resulting from bare soil reflectance differences. Consequently, the only effective method of using this index to assess crop condition is to use temporal analysis. In effect, temporal analysis means that data from a given field must be examined each time remote sensing data is acquired. This means that, for satellite purposes, scene registration (finding the same fields time after time) is necessary.

By using temporal analysis, the seasonal pattern of crop development at a given location can be monitored. It should be remembered, however, that cloud-cover problems often limit data acquisitions over any specific site. It is highly desirable, therefore, to focus attention on data transformations that result in figure 4.2b. This would eliminate the need for temporal analysis of a scene and permit calculation of the behavior of all data points (pixels) from a given crop. Elimination of the need for temporal analysis would also permit statements of crop condition to be made on a more near real-time basis.

4.4.1.2 MSS7/MSS5 Ratio

The ratio of MSS7/MSS5 (RVI) has been shown to respond to leaf area index (Kanemasu, 1977) and to be relatively constant over many soil types (Richardson and Wiegand, 1977). This ratio was examined by Blad et al. (1977) who concluded that it could be used to assess moisture stress in corn. A transformation similar to this can also be calculated with Thematic Mapper data as TM4/TM3 (TMRVI).

The data sets used to study the TMRVI and RVI were the 1982 SAL data, the Stoner et al. (1980) bare soil data and the data set of Walburg et al. (1982). These data indicate that the RVI and TMRVI are essentially the same. R^2 for TMRVI versus LAI for the SAL data was 7% lower than for the RVI, but this was probably related to the relatively large number of data points in the TMRVI regression (1080), compared to the RVI (783 data points) (Table 4.5).

The major problem arising from the use of RVI or TMRVI concerns the high values of predicted LAI over bare soil. Note that both models predict mean LAI values over bare soils of between 0.7 and 1.0. It is clear that estimates of LAI of canopies with incomplete cover (below about LAI = 2.5) are strongly biased by these models. It is important to realize, however, that other reflectance bands exist and that the RVI or TMRVI transformations may not be the most effective in terms of estimating LAI.

4.4.2 Logarithmic Transformations

The nature of the intercorrelations among the reflectance data was first examined (Table 4.6). The correlation matrix shows that the three visible bands (TM1-TM3) are highly correlated with TM5 and TM7 (middle infrared). This suggests that predictive models will probably not be composed of all the TM bands.

One transformation form of interest is the ratio of two bands, i.e., A/B. Another form is known as a normalized difference (ND). An ND is calculated as:

$$ND = (A-B)/(A+B)$$

Some algebraic manipulation reveals the nature of this calculation:

Table 4.5 Linear regression results of (near-IR)/(visible) ratio with leaf area index. The ratio is calculated using MSS bands 7 and 5 and Thematic Mapper bands 4 and 3. Also given are means and standard deviations of predicted LAI over two bare soil data sets, the 1982 SAL corn data and the Walburg et al. (1980) data set.

INSTRUMENT	MSS (Exotech)	THEMATIC MAPPER (Barnes MMR)
R^2	0.79	0.72
Mean/std predicted LAI over bare soil at SAL--1982	0.7/0.07	1.0/0.2
Mean/std predicted LAI over 251 wet soils (Stoner et al., 1980)	0.8/0.13	1.0/0.05
Mean/std difference between measured and predicted LAI at SAL--1982	0.19/0.48	0.13/0.60 (Walburg et al. data)
Model Name	RVI	TMRVI

LAI = 0.183 + 0.32*(Band7/Band5)

LAI = 0.623 + 0.238*(TM4/TM3)

Table 4.6 Correlation matrix (r) for all the reflectance data collected over corn at SAL during 1982 by the Barnes 12-1000 radiometer.

	TM1	TM2	TM3	TM4	MMR5	TM5	TM7	Thermal
TM1	1.0	0.99	0.98	-0.60	0.61	0.96	0.97	0.54
TM2		1.00	0.99	-0.61	0.63	0.97	0.97	0.46
TM3			1.00	-0.68	0.57	0.96	0.96	0.32
TM4				1.00	0.08	-0.62	-0.67	-0.30
MMR5					1.00	0.69	0.59	0.15
TM5						1.00	0.99	0.62
TM7							1.00	0.67

$$(A-B)/(A+B) = A/(A+B) - B/(A+B)$$

but $A/(A+B) = (A+B-B)/(A+B) = 1-B/(A+B)$

thus, $(A-B)/(A+B) = 1-2B/(A+B) = 1-2/((A/B)+1)$

Hence, a normalized difference is a function of the ratio A/B. The difference between a ratio and an ND is their dynamic range. A ratio can range between ± infinity, while normalized differences range between ± 1. The result is a nonlinear relationship between the two transformations. The normalized difference approximates $\log_{10}(A/B)$ (Gardner et al., 1983).

Logarithmic transformations are useful for linearizing certain curve forms (Steel and Torrie, 1960) (Fig. 4.3). They may also result in more valid statistical tests, since assumptions concerning normality are often more appropriate on a logarithmically transformed scale than on the original (Steel and Torrie, 1980). Note that the relationship between LAI and reflectance in the individual wavebands (except TM4 and MMR5) corresponds to the curve form:

$$LAI = a + b \log (reflectance)$$

4.4.3 Transformations Based on Agronomic Theory

Agronomically the development of leaf area within a canopy can be described in terms of horizontal and vertical components. Total canopy leaf area is dependent on plant density and the surface area of individual leaves (horizontal components) and the number of layers of leaves produced (vertical component).

If reflectance data respond to leaf area then it should be possible to define reflectance terms that respond primarily to either vertical or horizontal LAI components. Reflectance in each waveband has already been interpreted with respect to horizontal and vertical phytomass components (Table 4.3). Conceptually, these 9 basic (3 vertical and 6 horizontal) terms

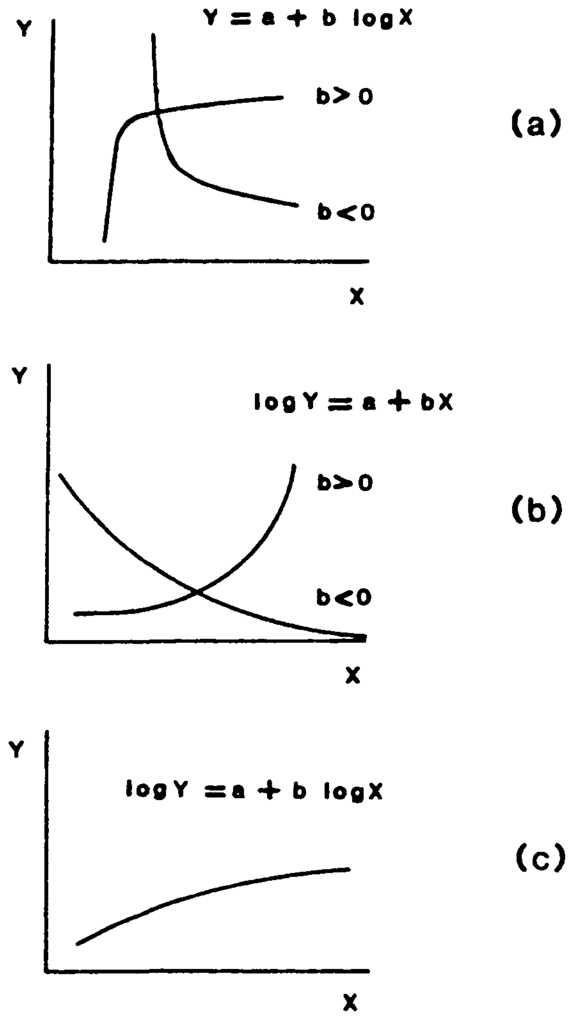


Fig. 4.3 Relationships between two variables, X and Y, for which logarithmic transformations are appropriate (Steel and Torrie, 1960).

normalize the vertical and horizontal reflectance components. Agronomically, there is an interaction between the horizontal and vertical LAI components. Hence, there should also be an interaction between horizontal reflectance and vertical reflectance terms. A total of 83 terms result from this theory (Table 4.7).

4.4.4 Bare Soil Response of 83 Reflectance Terms

The behavior of the 83 transformation terms over bare soil was next investigated (Table 4.8). Fifteen terms were identified which exhibit coefficients of variability of less than 20% for the 248 soils of the Stoner data set. Nine terms were identified which maximize the differences between these soils. Coefficients of variability ranged from 81.6 to 185.1 for these terms (Table 4.9). For comparison, CVs of the Landsat MSS transformations RVI and greenness were 19.1 and 64.7%, respectively, indicating that the RVI is more effective at minimizing soil background differences than the greenness index.

The terms that maximize differences between soils may be of interest in separate studies concerned with identifying soil characteristics via remote sensing. Since predictive models for estimating LAI may contain more than one term, it is not possible to state in advance which combination of terms may also minimize soil differences.

4.4.5 LAI Model Definitions/Responses

Consequently, stepwise regression techniques were used to define 170 LAI prediction models based on the 83 previously defined terms. R^2 values ranged from 0.03 to 0.83. It is of interest to note that not all possible models were calculated. To compute all possible models from 83 terms would have resulted in 2^{83} regressions. At best, only a small fraction of the theoretical maximum number of models is represented by these results. 130 models with R^2 values in excess of 0.81 were identified (Table 4.10)

4.4.6 Model Selection Criteria

Table 4.7 Definitions of the spectral terms used in developing prediction equations for leaf area index.

Term	Definition
TM1	(0.45-0.52 μm)
TM2	(0.52-0.60 μm)
TM3	(0.63-0.69 μm)
TM4	(0.76-0.90 μm)
TM5	(1.55-1.75 μm)
TM7	(2.08-2.35 μm)
MMR5	(1.15-1.30 μm)
LTM1	log(TM1)
LTM2	log(TM2)
LTM3	log(TM3)
LTM4	log(TM4)
LTM5	log(TM5)
LTM7	log(TM7)
LMMR5	log(MMR5)
T1	TM2/TM1
T2	TM3/TM1
T3	TM4/TM1
T4	TM5/TM1
T5	TM7/TM1
T6	TM3/TM2
T7	TM4/TM2
T8	TM5/TM2
T9	TM7/TM2
T10	TM4/TM3
T11	TM5/TM3
T12	TM7/TM3
T13	TM4/TM5
T14	TM7/TM4
T15	TM5/TM7
T16	TM1/MMR5
T17	TM2/MMR5
T18	TM3/MMR5
T19	TM4/MMR5
T20	MMR5/TM5
T21	MMR5/TM7
V1--T13	TM4/TM5
V2--T20	MMR5/TM5
V3--T19	TM4/MMR5
V4--1/V1	TM5/TM4
V5--1/V2	TM5/MMR5
V6--1/V3	MMR5/TM4

Table 4.7 (Con't)

Term	Definition
H1--1/T1	TM1/TM2
H2--1/T2	TM3/TM1
H3--1/T6	TM2/TM3
H4--1/T5	TM7/TM1
H5--1/T9	TM2/TM7
H6--1/T12	TM3/TM7
F1	V1*H1
F2	V1*H2
F3	V1*H3
F4	V1*H4
F5	V1*H5
F6	V1*H6
F7	V2*H1
F8	V2*H2
F9	V2*H3
F10	V2*H4
F11	V2*H5
F12	V2*H6
F13	V3*H1
F14	V3*H2
F15	V3*H3
F16	V3*H4
F17	V3*H5
F18	V3*H6
F19	V4*H1
F20	V4*H2
F21	V4*H3
F22	V4*H4
F23	V4*H5
F24	V4*H6
F25	V5*H1
F26	V5*H2
F27	V5*H3
F28	V5*H4
F29	V5*H5
F30	V5*H6
F31	V6*H1
F32	V6*H2
F33	V6*H3
F34	V6*H4
F35	V6*H5
F36	V6*H6

Table 4.8 Summary of the response of 83 transformation terms defined in Table 4.7 to reflectance data from bare soil at SAL and from the Stoner soil study. CV = coefficient of variation. An asterisk indicates terms which minimize or maximize differences between soils.

Term	Mean/cv SAL soil	Mean/cv Stoner soil	Term	Mean/cv SAL soil	Mean/cv Stoner soil
TM1	10.63/16.4	6.02/38.2	H2	0.63/12.7	0.74/41.2
TM2	13.21/16.0	6.21/47.6	*H3	0.78/ 7.1	0.72/12.7
TM3	17.08/16.5	8.91/48.4	H4	0.31/44.1	0.46/46.2
TM4	24.52/13.5	13.16/40.4	H5	0.39/32.3	0.47/53.4
MMR5	37.18/12.6	19.27/29.8	H6	0.49/18.0	0.67/48.7
TM5	40.90/15.1	19.14/24.5	F1	0.50/37.3	0.67/29.2
TM7	35.67/19.2	13.19/22.9	F2	0.40/66.4	0.48/33.4
*LTM1	2.35/ 7.5	1.74/18.9	F3	0.49/48.6	0.48/32.6
LTM2	2.57/ 6.9	1.73/26.2	*F4	0.21/157.3	0.35/164.3
LTM3	2.82/ 7.2	2.07/24.5	*F5	0.26/120.8	0.37/185.1
*LTM4	3.19/ 5.1	2.49/17.6	*F6	0.31/73.2	0.53/145.3
*LMMR5	3.60/ 4.9	2.91/11.1	F7	0.74/15.0	1.00/26.3
*LTM5	3.69/ 5.9	2.92/ 9.2	F8	0.58/30.9	0.75/33.9
*LTM7	3.54/ 8.5	2.55/ 9.0	*F9	0.72/21.3	0.71/13.1
T1	1.24/ 3.3	1.06/24.2	*F10	0.30/84.1	0.48/88.3
T2	1.61/ 6.7	1.53/33.0	*F11	0.36/62.9	0.50/102.5
T3	2.32/ 9.3	2.29/29.5	*F12	0.46/36.7	0.71/83.7
T4	3.87/11.9	3.45/28.5	F13	0.54/16.9	0.67/25.5
T5	3.35/14.8	2.39/28.1	F14	0.42/33.1	0.48/31.3
*T6	1.29/ 4.7	1.42/13.6	*F15	0.52/23.0	0.48/19.8
*T7	1.87/11.6	2.17/16.6	*F16	0.22/88.0	0.33/83.1
T8	3.10/10.4	3.51/37.0	*F17	0.26/66.0	0.34/95.8
T9	2.69/14.1	2.45/37.6	*F18	0.33/38.6	0.49/81.6
*T10	1.46/23.7	1.54/13.1	F19	1.34/10.5	1.71/62.8
T11	2.40/ 7.9	2.55/44.1	F20	1.04/ 8.0	1.29/75.3
T12	2.08/12.0	1.78/46.1	F21	1.29/ 8.6	1.20/47.0
T13	0.61/26.4	0.68/32.6	F22	0.50/ 8.9	0.70/36.0
T14	1.45/15.2	1.14/38.8	F23	0.63/ 6.1	0.68/17.7
*T15	1.17/14.2	1.45/ 9.9	*F24	0.81/ 6.3	0.96/14.9
T16	0.29/12.2	0.32/34.9	F25	0.88/ 6.1	1.05/41.1
T17	0.36/ 9.8	0.32/32.2	F26	0.68/ 5.8	0.77/52.3
T18	0.46/ 8.9	0.45/32.5	F27	0.85/ 4.0	0.74/24.3
T19	0.66/10.7	0.67/21.4	F28	0.34/22.0	0.46/32.9
*T20	0.92/ 9.6	1.00/12.5	F29	0.42/14.5	0.46/32.5
*T21	1.09/32.9	1.45/19.1	F30	0.53/ 8.8	0.65/32.8
V1	0.61/26.4	0.68/32.6	F31	1.22/ 5.6	1.63/51.0
*V2	0.92/ 9.6	1.00/12.5	F32	0.95/ 3.9	1.21/61.9
V3	0.66/10.7	0.67/21.3	F33	1.18/ 3.8	1.14/33.3
V4	1.67/11.1	1.62/35.0	F34	0.47/20.0	0.69/33.9
*V5	1.10/ 6.4	1.02/12.5	F35	0.58/14.2	0.68/27.5
V6	1.52/ 7.1	1.56/23.2	F36	0.74/ 8.7	0.97/26.3
H1	0.81/ 4.0	1.02/31.5			

Table 4.9 Summary of the reflectance terms which minimize and maximize differences between the 251 soils of the Stoner soil data.

Terms which minimize differences	Coefficient of variability for Stoner soil data	Terms which maximize difference	Coefficient of variability for Stoner soil data
LTM1	18.9	(TM4/TM5)*(TM7/TM1)	164.3
LTM4	17.6	(TM4/TM5)*(TM2/TM7)	185.1
LMMR5	11.1	(TM4/TM5)*(TM3/TM7)	145.3
LTM5	9.2	(MMR5/TM5)*(TM7/TM1)	88.3
LTM7	9.0	(MMR5/TM5)*(TM2/TM7)	102.5
TM3/TM2	13.6	(MMR5/TM5)*(TM3/TM7)	83.7
TM4/TM2	16.6	(TM4/MMR5)*(TM7/TM1)	83.1
TM4/TM3	13.1	(TM4/MMR5)*(TM2/TM7)	95.8
TM5/TM7	9.9	(TM4/MMR5)*(TM3/TM7)	81.6
MMR5/TM5	12.5		
MMR5/TM7	19.1		
(MMR5/TM5)*(TM2/TM3)	13.1		
(TM4/MMR5)*(TM2/TM3)	19.8		
(TM5/TM4)*(TM2/TM7)	17.7		
(TM5/TM4)*(TM3/TM7)	14.9		

Table 4.10 Summary of statistical tests to identify the best LAI predictive models for corn data from the Sandhills Agricultural Laboratory, to determine which models exhibit the least bias over bare soil and to test the behavior of these models over and independent LAI/reflectance data set. An asterisk indicates unbiased models.

Model Name	Terms in Model	R^2 (SAL corn data)	Mean/std predicted LAI over SAL soil	Mean/std predicted LAI over Stoner soils	Mean/std of difference between predicted and measured LAI (Walburg data)
M1	T12	0.03	2.7/0.2	2.9/0.6	0.05/1.3
M2	LMMR5	0.06	2.3/0.7	5.1/1.3	-0.08/1.3
M3	MMR5	0.08	2.2/0.6	4.6/0.7	-0.08/1.2
M4	T1	0.11	1.9/0.2	0.9/1.4	-1.6 /1.5
M5	T8	0.38	1.4/0.6	2.2/2.5	0.2 /1.2
M6	T4	0.54	0.5/0.7	-0.2/1.6	-1.4 /1.4
M7	T5	0.60	1.2/0.8	2.8/1.1	0.9 /0.9
M8	T9	0.60	0.8/0.8	1.3/1.9	0.1 /0.9
M9	TM4	0.62	1.1/0.6	-0.8/0.9	0.2 /0.9
M10	LTM4	0.63	1.1/0.6	-0.8/0.9	0.2 /0.9
M11	T11	0.67	1.1/0.9	-2.6/2.3	0.2 /0.9
M12	TM1	0.68	0.8/0.2	1.0/1.0	0.1 /0.9
M13	TM2	0.69	-0.3/0.9	2.0/1.1	0.2 /0.7
M14	T2	0.70	-0.1/0.9	2.7/1.2	-0.5 /0.9
M15	T10	0.72	1.0/0.1	1.0/0.05	0.1 /0.6
M16	TM3	0.72	-0.3/0.8	1.9/1.2	-0.2 /0.8
M17	TM5	0.72	-0.1/1.0	3.3/0.7	-0.2 /0.9
M18	TM7	0.73	-0.4/0.9	2.6/0.4	-0.1 /0.9
M19	LTM2	0.74	0.1/0.6	2.8/1.4	-0.1 /0.8
M20	LTM5	0.75	0.2/0.9	3.3/1.1	-0.2 /0.8
M21	T15	0.75	0.6/0.3	1.1/0.2	0.5/ 0.7
M22	LTM1	0.75	-0.1/0.5	1.8/1.0	-0.6 /0.9
M23	T7	0.75	0.7/0.1	0.9/0.1	0.9 /0.1

Difference = (measured LAI-predicted LAI)

Table 4.10 (Con't)

Model Name	Terms in Model	R^2 (SAL corn data)	Mean/std predicted LAI over SAL soil	Mean/std predicted LAI over Stoner soils	Mean/std of difference between predicted and measured LAI (Walburg data)
M24	T6	0.76	0.3/0.4	-0.5/1.1	-0.03/0.7
M25	T14	0.77	-0.5/0.7	0.5/1.4	-0.2 /0.8
M26	LTM7	0.78	0.2/0.6	2.1/0.5	0.1 /0.7
M27	T13	0.78	0.6/0.3	0.8/0.4	2.0 /1.8
M28	T3	0.78	0.6/0.1	0.6/0.2	-0.5 /0.8
M29	LTM3	0.79	0.1/0.4	1.7/1.1	-0.1 /0.7
M30	T4 T13	0.80	0.3/0.2	0.2/0.4	1.2 /1.5
M31	TM2 T13	0.80	0.2/0.4	1.3/0.3	1.4 /1.4
M32	MMR5 LTM3	0.80	0.2/0.2	0.8/0.9	-0.04/0.6
M33	LTM3 LMMR5	0.80	0.2/0.2	0.4/0.7	-0.03/0.6
M34	T2 T14	0.80	-0.2/0.6	0.7/0.7	0.3 /0.7
M35	LTM1 T13	0.80	0.2/0.3	1.1/0.4	1.0/ 1.2
M36	TM7 T7	0.81	0.01/0.5	1.6/0.2	0.01/0.6
M37	TM1 T13	0.81	0.1/0.4	1.1/0.4	1.3 /1.4
M38	LTM3 T14	0.81	-0.2/0.5	1.2/0.3	-0.1 /0.6
M39	TM7 T3	0.81	0.1/0.4	1.2/0.2	0.3 /0.7
M40	TM2 LTM4	0.81	-0.1/0.3	-0.3/0.8	-0.03/0.6
M41	TM3 T3	0.81	0.1/0.3	0.9/0.4	-0.4 /0.7
M42	LTM3 T13	0.81	0.3/0.3	1.2/0.5	0.9 /1.0
M43	TM4 LTM5	0.81	0.2/0.5	1.6/0.6	-0.1 /0.6
M44	TM5 LTM4	0.81	-0.04/0.5	0.4/0.9	-0.1 /0.6
M45	T13 T14	0.81	-0.02/0.5	0.5/0.9	1.0 /1.2
M46	TM3 T13	0.81	0.1/0.4	1.1/0.3	1.3 /1.3
M47	TM4 LTM3	0.81	0.2/0.3	0.9/0.6	0.01/0.6
M48	TM4 LTM2	0.81	0.1/0.2	1.1/0.6	0.02/0.6
M49	LTM4 LTM5	0.81	0.2/0.4	0.6/0.8	-0.1 /0.6
*M50	TM4 LTM1	0.81	0.0/0.2	0.5/0.5	-0.4 /0.6

Table 4.10 (Con't)

Model Name	Terms in Model	R^2 (SAL corn data)	Mean/std predicted LAI over SAL soil	Mean/std predicted LAI over Stoner soils	Mean/std of difference between predicted and measured LAI (Walburg data)
*M51	LTM3 LTM4	0.82	0.1/0.2	0.2/0.2	0.0/0.6
M52	T3 T14	0.82	-0.05/0.7	0.5/0.4	-0.4/0.7
M53	T10 T14	0.82	-0.1/0.5	0.5/0.9	-0.1/0.6
M54	LTM1 LTM4	0.82	-0.02/0.2	-0.3/0.8	-0.4/0.6
*M55	LTM2 LTM4	0.82	0.1/0.2	0.2/0.4	-0.01/0.6
M56	T7 T14	0.82	-0.1/0.4	0.5/0.8	-0.1/0.6
M57	MMR5 LTM4	0.82	0.03/0.5	-0.3/1.7	0.1/0.6
M58	LTM4 LMMR5	0.82	0.1/0.6	0.9/1.3	0.04/0.6
M59	MMR5 LTM4 T5	0.82	-0.02/0.4	-0.6/1.6	-0.1/0.6
M60	MMR5 LTM4 T9	0.82	0.04/0.5	-0.5/1.6	0.03/0.6
M61	TM2 LTM4 LMMR5	0.82	0.01/0.5	0.6/1.0	0.02/0.6
*M62	TM5 LTM2 LTM4	0.82	0.02/0.3	0.3/0.4	-0.04/0.6
*M63	LTM2 LTM4 LTM5	0.82	0.1/0.3	0.4/0.4	-0.04/0.6
M64	MMR5 LTM4 T12	0.82	0.01/0.4	-0.4/1.5	0.04/0.6
M65	LTM4 LMMR5 T11	0.82	0.11/0.5	0.9/1.0	0.1/0.6
M66	MMR5 LTM4 T11	0.82	0.1/0.4	-0.2/1.4	0.1/0.6
M67	LTM4 LMMR5 T9	0.82	0.1/0.6	0.7/1.2	0.03/0.6
M68	MMR5 LTM1 LTM4	0.82	0.02/0.3	-0.2/1.1	-0.2/0.6
M69	MMR5 LTM5 T12	0.82	0.1/0.4	1.2/0.9	-0.3/0.6
M70	MMR5 LTM3 LTM4	0.82	0.04/0.4	-0.04/0.9	0.04/0.6
M71	LTM4 LMMR5 T5	0.82	0.04/0.5	0.5/1.3	-0.1/0.6
M72	MMR5 LTM4 T4	0.82	-0.03/0.4	-0.5/1.4	0.1/0.6
M73	LTM3 LTM4 LMMR5	0.82	0.1/0.4	0.7/0.7	0.02/0.6
*M74	LTM4 LTM5 T8	0.82	0.1/0.3	0.5/0.4	-0.04/0.6
M75	LTM1 LTM4 LMMR5	0.82	0.03/0.4	0.4/0.8	-0.2/0.6
*M76	LTM5 LMMR5 T12	0.82	0.1/0.3	0.4/0.3	-0.3/0.6
M77	LTM4 LMMR5 T12	0.82	0.1/0.6	0.8/1.1	0.01/0.6
M78	T9 T13 T14	0.82	-0.1/0.4	0.4/0.6	0.02/0.6
M79	LTM4 LMMRR5 T4	0.82	0.02/0.4	0.5/1.0	-0.1/0.6
M80	T12 T13 T14	0.82	-0.1/0.4	0.3/0.5	1.1/1.2

Table 4.10 (Con't)

Model Name	Terms in Model	R^2 (SAL corn data)	Mean/std predicted LAI over SAL soil	Mean/std predicted LAI over Stoner soils	Mean/std of difference between predicted and measured LAI (Walburg data)
M81	MMR5 LTM4 T8	0.82	0.03/0.4	-0.3/1.3	0.1/0.6
M82	MMR5 LTM2 LTM4	0.82	0.05/0.3	0.9/0.9	0.02/0.6
M83	LTM2 LTM4 LMMR5	0.82	0.1/0.4	0.6/0.6	0.02/0.6
M84	LTM4 LMMR5 T8	0.82	0.1/0.5	0.7/0.9	0.1/0.6
M85	LTM4 LTM5 T5	0.83	0.02/0.3	-0.1/0.9	-0.4/0.6
*M86	LTM4 LTM5 T9	0.83	0.1/0.3	0.4/0.5	-0.2/0.5
*M87	LTM4 LTM5 T12	0.83	0.1/0.4	0.5/0.4	-0.2/0.5
*M88	LTM4 LTM5 T12 T15	0.83	0.1/0.4	0.5/0.5	0.2/0.5
M89	T3 T4 T5 T14	0.83	-0.2/0.4	0.1/1.2	-0.6/0.6
M90	LTM4 LTM5 T5 T12	0.83	0.1/0.3	0.3/0.6	-0.6/0.6
M91	LTM4 LTM5 T2 T12	0.83	0.3/0.3	0.5/0.5	-0.3/0.6
M92	LTM4 LTM5 T11 T15	0.83	0.04/0.4	0.6/0.7	-0.3/0.6
M93	MMR5 LTM5 LTM7 T11	0.83	0.2/0.6	1.7/1.3	-0.6/0.5
*M94	LTM4 LTM5 T6 T9	0.83	0.1/0.3	0.4/0.4	-0.2/0.5
*M95	LTM4 LTM5 T9 T11	0.83	0.1/0.3	0.5/0.4	-0.1/0.5
M96	LTM4 LTM5 T9 T14	0.83	0.03/0.3	0.3/0.6	-0.2/0.5
M97	LTM4 LTM5 T9 T13	0.83	0.1/0.3	0.4/0.6	-0.5/0.6
M98	LTM4 LTM5 T5 T10	0.83	0.1/0.3	0.05/0.8	-0.4/0.6
M99	LTM2 LTM4 LTM5 LTM7	0.83	0.1/0.3	0.4/0.7	-0.3/0.5
M100	TM4 LTM4 LTM5 T12	0.83	0.1/0.4	-0.05/0.7	-0.3/0.5
M101	T3 T4 T9 T14	0.83	-0.2/0.5	0.8/0.7	-0.1/0.5
M102	LTM4 LTM5 T6 T12	0.83	0.1/0.3	0.6/0.6	-0.1/0.5
*M103	LTM4 LTM5 T9 T12	0.83	0.1/0.3	0.5/0.5	-0.2/0.5
M104	LTM3 LTM4 LTM5 T12	0.83	0.1/0.4	0.6/0.7	-0.3/0.5
M105	TM4 LTM4 LTM5 T9	0.83	0.1/0.3	-0.3/0.9	-0.2/0.5
M106	T10 T11 T12 T14	0.83	0.1/0.3	-0.3/1.0	-0.4/0.5

Table 4.10 (Con't)

Model Name	Terms in Model	R^2 (SAL corn data)	Mean/std predicted LAI over SAL soil	Mean/std predicted LAI over Stoner soils	Mean/std of difference between predicted and measured LAI (Walburg data)
M107	LTM5 LMMR5 T10 T15	0.83	0.1/0.4	0.6/0.6	-0.6/0.6
M108	LTM4 LTM5 LTM7 T12	0.83	0.1/0.4	0.5/0.7	-0.3/0.5
M109	LTM4 LTM5 LTM7 T8	0.83	0.1/0.4	0.5/0.7	-0.3/0.5
M110	TM5 TM7 T10 T14	0.83	0.03/0.5	0.1/1.5	-0.2/0.6
M111	LTM4 LTM5 LTM7 T10	0.83	0.2/0.5	0.7/1.2	-0.4/0.6
M112	T7 T8 T9 T14	0.83	-0.2/0.5	0.1/1.3	-0.3/0.6
M113	LTM3 LTM4 LTM5 LTM7	0.83	0.1/0.4	0.5/0.7	-0.3/0.5
M114	LTM5 LTM7 LMMR5 T11	0.83	0.2/0.3	0.4/0.6	-0.6/0.6
M115	LTM4 LTM5 T10 T15	0.83	0.1/0.5	0.7/1.0	-0.4/0.6
M116	LTM4 LTM5 LTM7 T11	0.83	0.1/0.5	0.6/0.9	-0.3/0.5
VP1	V1	0.78	0.6/0.3	0.8/0.4	0.001/0.6
VP2	V2	0.79	0.4/0.3	0.7/0.4	-0.2/0.6
VP3	V5	0.80	-0.01/0.5	0.5/0.8	-0.2/0.6
VP4	V4	0.80	-0.2/0.6	-0.1/1.8	-0.2/0.6
VP5	V3	0.80	0.4/0.5	0.5/0.9	0.1/0.6
VP6	V6	0.82	-0.2/0.6	-0.3/2.0	-0.01/0.6
VF1	V5 F35	0.82	-0.1/0.3	0.2/0.8	-0.3/0.6
VF2	V5 F30	0.82	-0.1/0.3	-0.1/0.5	-0.3/0.6
VF3	V6 F35	0.82	-0.1/0.5	-0.4/2.0	-0.04/0.6
VF4	V6 F28	0.82	-0.1/0.4	-0.6/1.8	-0.2/0.6
VF5	V5 F13	0.82	0.2/0.5	1.0/0.7	-0.2/0.6
VF6	V5 F23	0.82	-0.1/0.3	0.1/0.7	-0.3/0.6
VF7	V3 F28	0.82	0.1/0.1	-0.5/1.1	-0.3/0.6
VF8	V6 F14	0.82	0.1/0.6	0.02/1.6	0.1/0.6
VF9	V2 F34	0.82	0.1/0.2	-0.7/1.3	0.6/0.6
VF10	V2 F30	0.82	0.2/0.2	-0.1/0.7	-0.3/0.6
VF11	V6 F30	0.82	-0.1/0.5	-0.5/1.4	-0.1/0.6

Table 4.10 (Con't)

Model Name	Terms in Model	R^2 (SAL corn data)	Mean/std predicted LAI over SAL soil	Mean/std predicted LAI over Stoner soils	Mean/std of difference between predicted and measured LAI (Walburg data)
VF12	V4 F7	0.82	0.02/0.6	0.6/1.1	0.1/0.6
VF13	V6 F1	0.82	0.1/0.6	0.1/1.6	0.1/0.6
*VF14	V3 F24	0.82	0.1/0.4	-0.2/0.5	-0.02/0.6
VF15	V6 F13	0.82	0.1/0.6	0.2/1.7	0.2/0.6
VF16	F13 F25	0.82	0.1/0.5	-0.1/1.6	0.1/0.6
VF17	V6 F23	0.82	0.1/0.5	-0.4/1.7	-0.1/0.6
VF18	V6 F2	0.82	0.1/0.6	-0.02/1.6	0.1/0.6
VF19	V5 F36	0.82	-0.1/0.3	-0.1/0.4	-0.3/0.6
VF20	V6 F8	0.82	0.1/0.5	0.1/1.5	-0.2/0.6
VF21	V6 F7	0.82	0.7/0.5	0.8/1.3	-0.2/0.6
VF22	V6 F29	0.82	-0.1/0.5	-0.4/1.8	-0.1/0.6
VF23	V2 F23	0.82	-0.5/0.2	-0.6/0.7	0.1/0.6
VF24	V4 F1	0.82	0.02/0.5	0.4/1.2	0.1/0.6
*VF25	V1 F24	0.82	0.1/0.3	-0.3/0.4	-0.1/0.5
VF26	V2 F22	0.82	-0.02/0.2	-0.9/1.6	-0.5/0.6
VF27	V3 F22	0.82	0.04/0.2	-0.8/1.6	-0.2/0.6
VF28	V1 F22	0.82	0.04/0.2	-1.1/1.7	-0.4/0.6
VF29	V4 F8	0.82	0.03/0.5	0.3/1.0	0.1/0.6
VF30	V4 F14	0.82	-0.03/0.6	0.2/1.1	0.2/0.6
VF31	V4 F2	0.82	0.02/0.5	0.3/1.2	0.02/0.6
*VF32	V2 F24	0.82	0.1/0.3	-0.2/0.3	-0.2/0.6
VF33	V4 F13	0.82	0.01/0.7	0.6/1.3	0.3/0.6
FF1	F1 F19	0.82	-0.01/0.5	-0.7/2.5	-0.03/0.6
FF2	F8 F19	0.82	-0.01/0.5	-0.7/2.3	-0.04/0.6
FF3	F14 F19	0.82	-0.04/0.5	-0.8/2.5	0.01/0.6
FF4	F2 F19	0.82	-0.02/0.5	-0.9/2.6	-0.1/0.6

Table 4.10 (Con't)

Model Name	Terms in Model	R^2 (SAL corn data)	Mean/std predicted LAI over SAL soil	Mean/std predicted LAI over Stoner soils	Mean/std of difference between predicted and measured LAI (Walburg data)
FF5	F13 F31	0.82	0.1/0.6	-1.0/3.0	0.1/0.6
FF6	F13 F19	0.82	-0.04/0.7	-0.4/2.5	0.2/0.7
VH1	V6 H6	0.82	-0.04/0.5	-0.4/1.8	-0.04/0.6
VH2	V6 H2	0.82	0.1/0.6	0.1/1.5	0.1/0.6
VH3	V6 H1	0.82	0.1/0.7	0.4/1.7	0.2/0.6
VH4	V4 H2	0.82	-0.04/0.6	0.4/1.0	0.1/0.6
VH5	V4 H1	0.82	-0.1/0.8	1.4/1.6	1.0/0.7
HF1	H1 F19	0.82	-0.2/0.8	-0.1/2.8	0.4/0.8
HF2	H2 F20	0.82	0.05/0.5	-0.5/2.8	0.1/0.6
HF3	H2 F21	0.82	0.2/0.6	1.0/1.3	0.3/0.6
HF4	H2 F31	0.82	-1.9/1.2	-3.8/3.6	-0.8/1.2

The final selection of useful LAI models was based on three criteria: 1) R^2 values from the original regression; b) predicted LAI over a wide range of bare soils (Stoner soil data) and c) verification over an independent LAI/reflectance data set (Walburg data).

The results of applying these criteria show that 69 models predict LAI values to within 0.1 ± 0.6 for the Walburg data. Performance of two of these models is illustrated in Fig. 4.4. The majority of these models exhibited a significant bias over the Stoner soil data, however (Table 4.10). Only 16 models had predicted LAI values over the Stoner soil data of less than 0.5 . These 16 models are suitable for inclusion in future remote sensing studies over corn. Their behavior over other crops should also be investigated.

The selection of the appropriate model from the 16 could be based on the desired application. For example, Model M51 contains TM3, which is sensitive to chlorophyll. This model would be appropriate in studies relating to stress factors that cause plant yellowing, such as nitrogen stress or severe moisture stress. Model M55, however, does not contain a band that is sensitive to chlorophyll. This model might be used to assess LAI without regard to the effects of nitrogen stress. Model M86 contains the moisture absorption bands TM5 and TM7. Thus, this model may be useful for assessing the relative effects of moisture stress.

It should be emphasized that many effective transformations of Thematic Mapper data exist. The development or selection of a particular one depends on research objectives. For example, transformations may be developed which serve to act as crop discriminators. Blad et al. (1982) reported that the ratio TM7/TM2 effectively separated corn from soybeans. Transformations may be developed which respond primarily to the problems caused by disease. It is clear that the potential exists for developing a myriad of models, with many

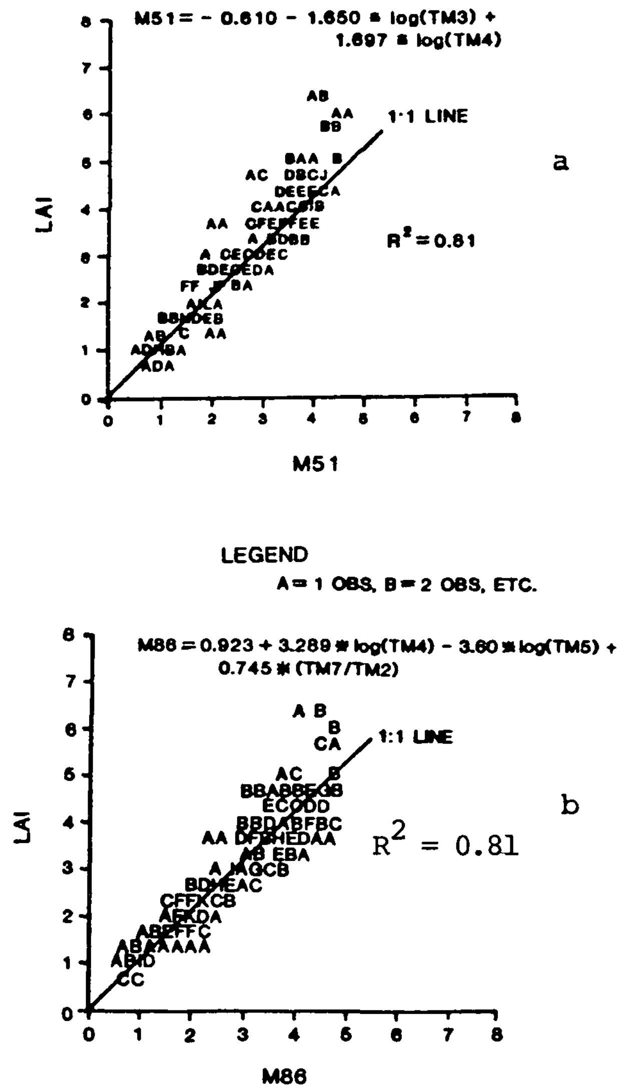


Fig. 4.4 Relationship between measured and predicted LAI for the data of Walburg et al. (1982) using two prediction models developed at SAL in 1982.

purposes. Since Model M86 is an appropriate moisture stress transformation that exhibits no bias over the soil at SAL, it is selected to predict LAI where needed in the remainder of this study. It is recognized that other models are more generally applicable than this model, however.

4.5 Soybean Data--Seasonal Trends and Correlations

The seasonal trends of soybean canopy reflectances were similar to those of the corn and will not be presented here. The correlation matrices of the reflectance and agronomic data were also similar (Tables 4.11-4.13). The comments made concerning the interdependency of the various reflectance and agronomic paramters in corn also apply to the soybeans.

One significant difference was apparent in the analysis of variance of the agronomic components, however. Leaf area index in corn was shown to be the only significant agronomic factor in explaining canopy reflectance. The situation in soybeans is more complex. The wet stem weight accounts for at least 2% of the variance in all wavebands (Table 4.14). This result is not unexpected since soybean canopy geometry is different from that of corn. Corn stalks are vertical and have relatively small diameters. From the vertical direction, they will be only a small fraction of the total area viewed by a radiometer. Soybean stems branch significantly in the horizontal direction, resulting in a much larger percentage of the radiometer view area being filled with branch structures.

4.5.1 Effect of Pubescence on Soybean Canopy Reflectance

The analysis of pubescence effects on soybean canopy reflectance is not yet complete. Preliminary analysis indicates results that are only in partial agreement with individual leaf spectra measurements (Gausman and Cardenas, 1973a) (Table 4.15).

Gausman and Cardenas (1973a) showed that leaves with dense pubescence

Table 4.11 Correlation matrix (r) for all reflectance and thermal data acquired by the Barnes 12-1000 over soybeans at SAL during 1982.

	TM1	TM2	TM3	TM4	MMR5	TM5	TM7	TEMP
TM1	1.000	0.989	0.980	-0.680	-0.009	0.968	0.977	0.806
TM2		1.000	0.983	-0.696	-0.023	0.953	0.964	0.742
TM3			1.000	-0.772	-0.104	0.948	0.971	0.761
TM4				1.000	0.681	-0.606	-0.733	-0.683
MMR5					1.000	0.126	-0.070	-0.318
TM5						1.000	0.977	0.793
TM7							1.000	0.866
TEMP								1.000

Table 4.12 Correlation matrix for all soybean agronomic data collected at SAL during 1982.

	LAI	Wet Leaf Weight	Wet Stem Weight	Total Wet Phytomass	Dry Leaf Weight	Dry Stem Weight	Total Dry Phytomass	Leaf Water Content	Stem Water Content	Canopy Water Content
LAI	1.000	0.956	0.968	0.973	0.970	0.551	0.704	0.329	-0.020	0.200
Wet leaf weight		1.000	0.951	0.982	0.958	0.009	0.286	0.341	-0.032	0.259
Wet stem weight			1.000	0.992	0.957	0.983	0.979	0.194	0.017	0.249
Total wet phytomass = wet (leaf+stem) weight				1.000	0.967	0.980	0.982	0.217	-0.003	0.245
Dry leaf weight					1.000	0.574	0.731	0.334	-0.083	0.122
Dry stalk weight						1.000	0.979	-0.890	-0.082	0.163
Total dry phytomass = dry (leaf+stem) weight							1.000	-0.755	-0.083	0.135
Leaf water content = (wet leaf)-(dry leaf) weight								1.000	0.538	0.885
Stem H_2O = (wet stem)-(dry stem) weight									1.000	0.818
Canopy water content = (total wet phytomass)-(total dry phytomass)										1.000

Table 4.13 Correlation matrix between all reflectance and thermal data from the Barnes 12-1000 and all soybean agronomic data from SAL in 1982.

	LAI	Wet Leaf	Wet Stalk	Wet BIO	Dry Leaf	Dry Stalk	Dry BIO	Leaf H_2O	Stalk H_2O	Total H_2O
TM1	-0.797	-0.755	-0.764	-0.781	-0.790	-0.634	-0.711	0.029	-0.090	-0.245
TM2	-0.803	-0.746	-0.751	-0.769	-0.800	-0.580	-0.670	0.015	-0.092	-0.248
TM3	-0.845	-0.823	-0.800	-0.817	-0.836	-0.612	-0.705	-0.103	-0.082	-0.236
TM4	0.878	0.851	0.864	0.860	0.854	0.604	0.703	0.205	-0.002	0.108
MMR5	0.474	0.237	0.290	0.270	0.443	0.296	0.350	0.005	-0.099	-0.110
TM5	-0.728	-0.719	-0.715	-0.734	-0.733	-0.627	-0.692	0.001	-0.065	-0.202
TM7	-0.813	-0.784	-0.793	-0.809	-0.808	-0.672	-0.747	0.019	-0.041	-0.178
TEMP	-0.634	-0.420	-0.511	-0.500	-0.627	-0.674	-0.704	0.167	0.064	0.043

Table 4.14 Percent variation for the components of the model (SAS notation): reflectance = LAI wetleaf wetstem dryleaf drystem, for all the soybean reflectance and agronomic data collected at SAL in 1982 (n = 627). Type I Sum of Squares (SS) indicates the percent of variability in reflectance explained by a particular term after adjusting for the effects of the previous terms. Percent variation by components = Type I SS/Total SS.

Waveband (μm)	R^2	Percent Variation by Components				
		LAI	Wetleaf	Wetstem	Dryleaf	Drystem
0.45-0.52	0.66	0.63	0.00	0.02	0.00	0.00
0.52-0.60	0.64	0.60	0.00	0.02	0.00	0.00
0.63-0.69	0.72	0.69	0.00	0.02	0.00	0.00
0.76-0.90	0.78	0.75	0.01	0.02	0.00	0.00
1.15-1.30	0.22	0.10	0.01	0.08	0.03	0.00
1.55-1.75	0.60	0.55	0.00	0.04	0.00	0.00
2.08-2.35	0.70	0.67	0.00	0.02	0.00	0.00

Table 4.15 Mean seasonal percent difference in reflectance between normal, sparse and dense pubescent soybeans (Harosoy cv.) at SAL in 1982. Comparisons were made between plots in C area receiving the same irrigation level.

Wavelength (μm)	Percent Difference in Reflectance		
	Dense-Normal	Dense-Sparse	Normal-Sparse
0.45-0.52	0.11 ***	-0.02 NS	-0.14 ***
0.52-0.60	0.10 *	-0.07 NS	-0.17 ***
0.63-0.69	0.02 NS	-0.34 ***	-0.36 ***
0.76-0.90	0.72 ***	1.43 ***	0.7 **
1.15-1.30	0.45 ***	0.51 **	0.06 NS
1.55-1.75	0.09 NS	-0.47 ***	-0.56 ***
10.4-12.5	-0.03 **	-0.76 ***	-0.47 **
2.08-2.35	-0.08 NS	-0.81 ***	-0.73 ***
TOTAL	1.38%	0.31%	-1.26%

* - differences significant at $\alpha = 0.10$
** - differences significant at $\alpha = 0.05$
*** - differences significant at $\alpha = 0.01$
NS - not significant
N - 169 for all calculations

reflect less energy in the visible wavelengths than leaves of plants with either glabrous or normal pubescence. Our data show that the canopy of the soybean isoline with dense pubescence tended to reflect more visible light than did the normal pubescent isoline but less than the sparse (glabrous) canopy. On a seasonal basis, the differences were small. The canopy with sparse pubescence reflected more visible energy than the normal. Similar relationships also were found for reflectance in the middle infrared bands. Hence, the visible canopy reflectance and leaf spectra trends are in general agreement.

Gausman and Cardenas (1973a) showed that in the near IR the normal and glabrous pubescent leaves had similar reflectances but the dense had about 1.5% less reflectance. Our results show the opposite effect. The dense pubescence canopies reflected an average 1.43% more than the sparse and 0.73% more than the normal pubescent canopies. The normal pubescent canopy reflected 0.7% more than the sparse. The difference between these two trends, if real, may be related to the transmittance properties of the leaves. If the dense pubescence leaves have a higher transmissivity, then multiple reflectance effects could cause higher canopy reflectances, even though individual leaf reflectances are lower. Further analysis and research in this area is planned.

4.5.2 Effect of Pubescence on Soybean Canopy Energy Balance

Table 4.15 shows that the dense pubescent canopy reflected an average of 1.38% more energy and had canopy temperatures an average 0.3 C lower than the normal pubescent canopy. This is in accordance with energy balance expectations.

The situation is less clear in the comparisons involving the canopy with sparse pubescence, however. The dense reflected only 0.31% more energy than the sparse, yet was an average of 0.76 C cooler. This may imply that the dense canopy was reflecting more energy than the sparse in wavebands that were not measured. It may also imply that convective cooling is more efficient for dense versus sparse pubescence. This conclusion agrees with a theoretical analysis of convective heat loss by pubescence. Convective heat transfer is increased in direct proportion to the relative density of leaf pubescence (Wolpert, 1962).

The normal pubescence canopy reflected 1.26% less energy than the sparse and was 0.47 C cooler, showing a disagreement with energy balance expectations. We conclude that the energy balance effect of pubescence is complex and involves both radiation and convective effects. Hence, analysis of the energy balance of soybean canopies differing in pubescence will not be complete until convective heat transfer rates of leaves and canopies differing in pubescence are established.

4.5.3 Influence of Soybean Pubescence Density on Plant Water Relations Under Dryland and Well-Water Conditions

The effect of drought stress on various plant physiological functions has been widely studied. Water stress develops when there is inadequate soil water to meet evaporative demands. When this occurs soil and plant water potentials decline (Slatyer, 1969). The physiological responses to reduced plant water potentials are numerous and have various levels of sensitivity (Hsaio, 1973). Generally, as plant water potentials decline, stomatal resistance increases (Boyer, 1970), transpiration declines (Mederski et al., 1973) and leaf and canopy temperatures increase (Stevenson and Shaw, 1971; Bartholic et al., 1972; Jung and Scott, 1980). Pressure and osmomotic potentials are also affected (Howell, 1979).

Research on the effects of soybean pubescence density on various physiological parameters in conjunction with water stress is incomplete. Ghorashy et al. (1971) found that dense pubescence caused no statistically significant change in single-leaf carbon exchange rates at identical leaf water potentials in the Clark cultivar. Nielsen et al. (1983) and Baldocchi et al. (1983) showed that dense pubescence in the Harosoy cultivar increased shortwave radiation reflectivity and decreased evapotranspiration. Garay and Wilhelm (1983) reported that dense pubescent Harosoy soybeans exhibited increased root density. This resulted in a greater soil moisture extraction capability.

These findings suggest that dense pubescence on soybean plants may significantly improve their ability to withstand severe drought. Indeed, water relations of a shrub native to the American Southwest Desert were shown to be improved by increased pubescence (Ehleringer and Bjorkman, 1976; Ehleringer and Mooney, 1978). If this hypothesis is true, soybean production could be expanded into drought-prone areas, such as western Nebraska. Consequently, an experiment was designed to investigate the interaction between soybean pubescence density and physiological indicators of drought stress, such as leaflet and canopy temperatures, stomatal resistance, transpiration and leaf water, osmotic and pressure potentials.

4.5.3.1 Drought Stress

Water stress was manifested in nearly every variable measured throughout the entire season. Data from the normal pubescent isoline are indicative of the observed effects. The interaction of pubescence density with water stress is discussed in a subsequent section. Analyses of variance on the pooled mid-day values showed that stomatal resistances, along with leaflet and canopy temperatures, were significantly increased ($P > 0.10$) while transpiration, leaf and osmotic potentials significantly declined due to drought stress

(Figs. 4.5-4.10). The average differences for the normal isoline were: 78 s m^{-1}, 1.7 C, 2.9 C, 143 mg m^{-2} s^{-1}, 0.2 MPa and 0.3 MPa for stomatal resistance, leaflet temperature, canopy temperature, transpiration, leaf water potential and osmotic potential, respectively. No statistically significant change due to water stress was observed for the pressure potential, although the trend was lower for pressure potential in the dryland treatment (Fig. 4.11). This suggests that osmotic potentials adjusted to lower drought-induced plant water potential, which caused no change in the pressure potential.

Diurnal data from 21 July are representative of the typical daily curves of the measured parameters. Total leaf water potentials of leaves from the dryland plot appeared to be slightly decreased at the predawn 0400 solar hour, compared to leaves under well-watered conditions (Fig. 4.12). The difference in potential at this time was about 0.2 MPa and remained so for most of the day. Water potential differences increased to about 0.3 MPa at midafternoon but declined to 0.2 MPa near sunset. Osmotic potential followed the same course but was more strongly affected by water stress (Fig. 4.13). The largest difference between the dryland and well-watered plants was observed about midmorning and was about 0.35 MPa. Pressure potential, though not affected significantly throughout the season, did exhibit a response to water stress on 21 July (Fig. 4.14). Negative pressure potentials resulted from dilution of osmotic potentials by apoplastic water. Absolute differences, however, showed that osmotic adjustment resulted in higher pressure potentials in the dryland plot.

Stomatal resistance and transpiration were strongly affected by water stress on 21 July (Figs. 4.15 and 4.16). Stomatal resistance differences due to stress were observed beginning at 0800 hours and continued through the day.

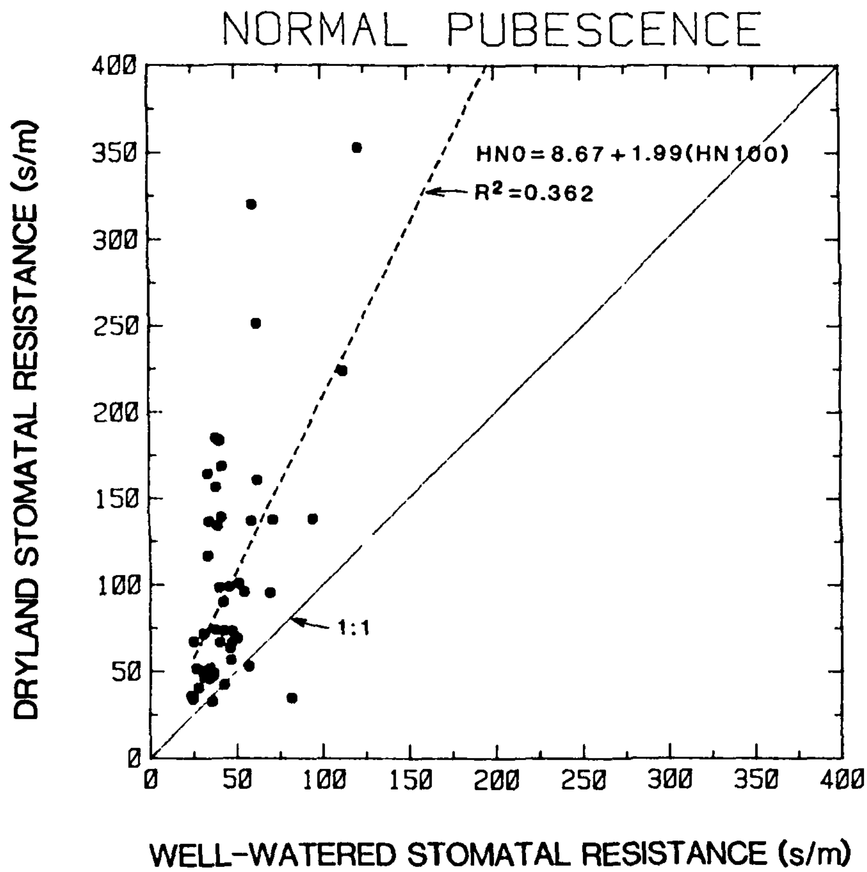


Fig. 4.5 Stomatal resistance of single sunlit leaves from the normal pubescent isoline at midday over the growing season under dryland and well-watered conditions.

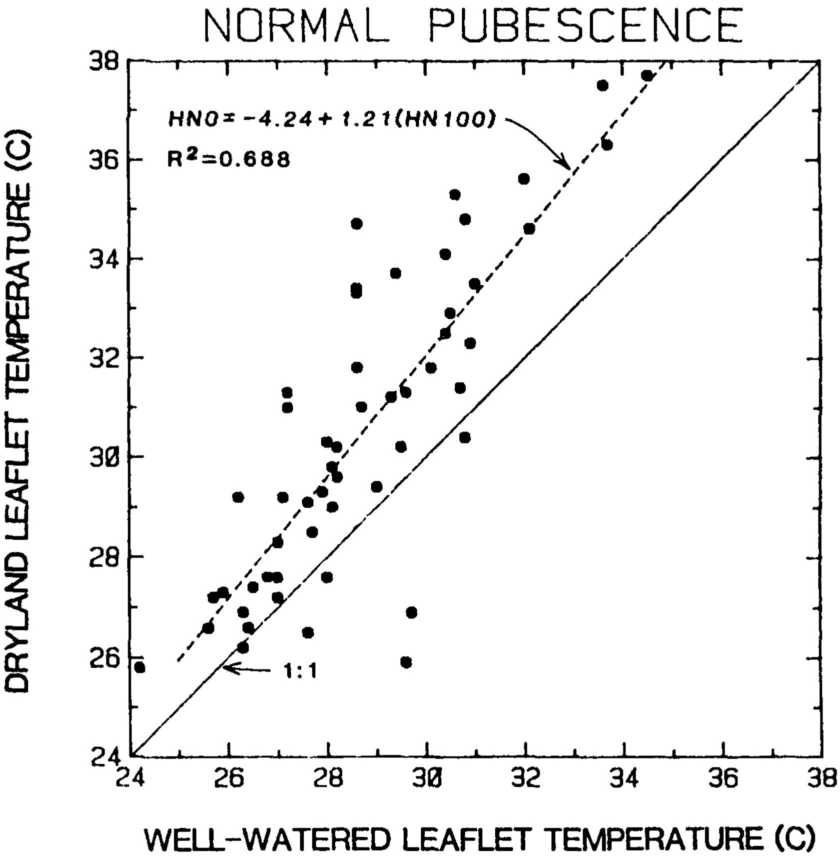


Fig. 4.6 Temperature of single sunlit leaves from the normal pubescent isoline at midday over the growing season under dryland and well-watered conditions.

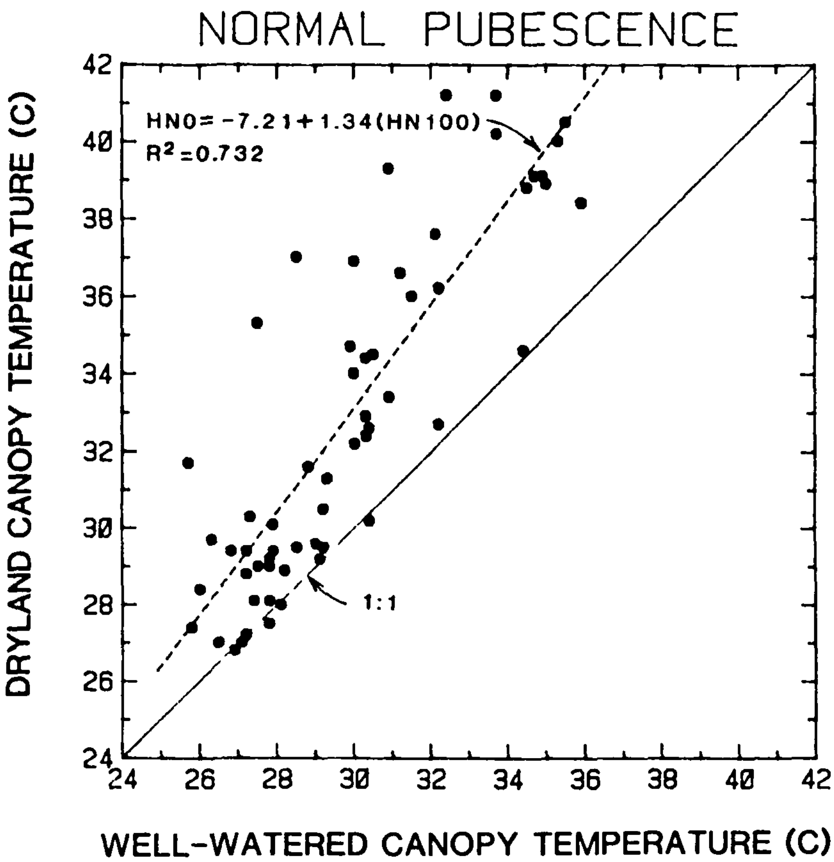


Fig. 4.7 Canopy temperature of the normal pubescent isoline at midday over the growing season under dryland and well-watered conditions.

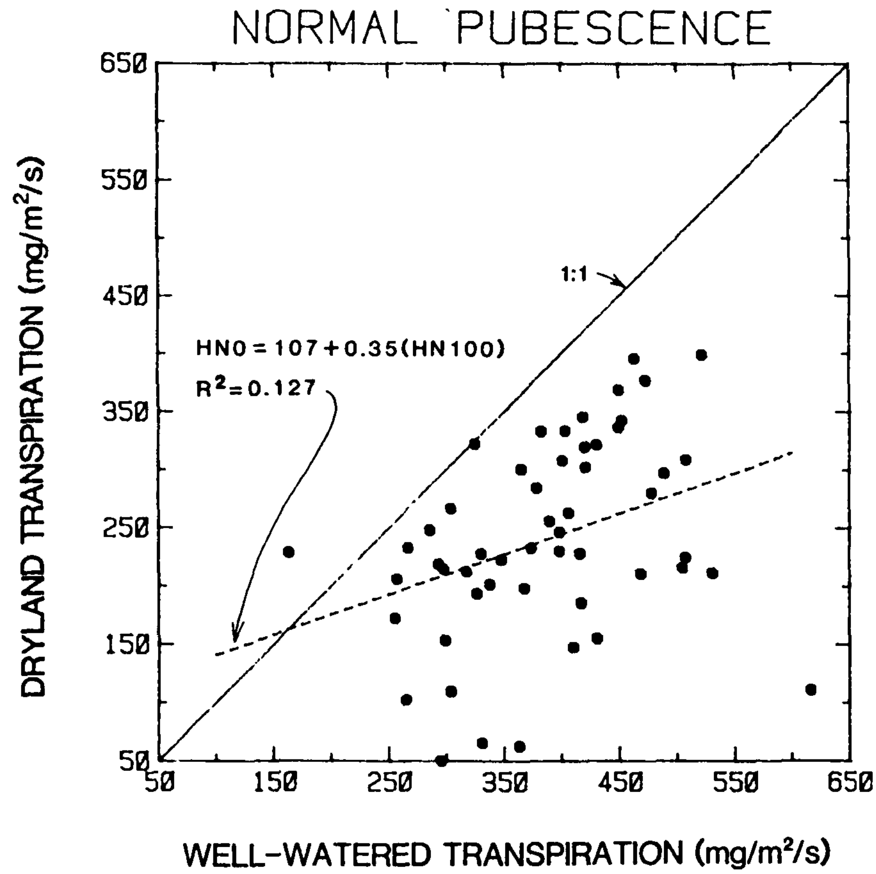


Fig. 4.8 Transpiration rate of single sunlit leaves from the normal pubescent isoline at midday over the growing season under dryland and well-watered conditions.

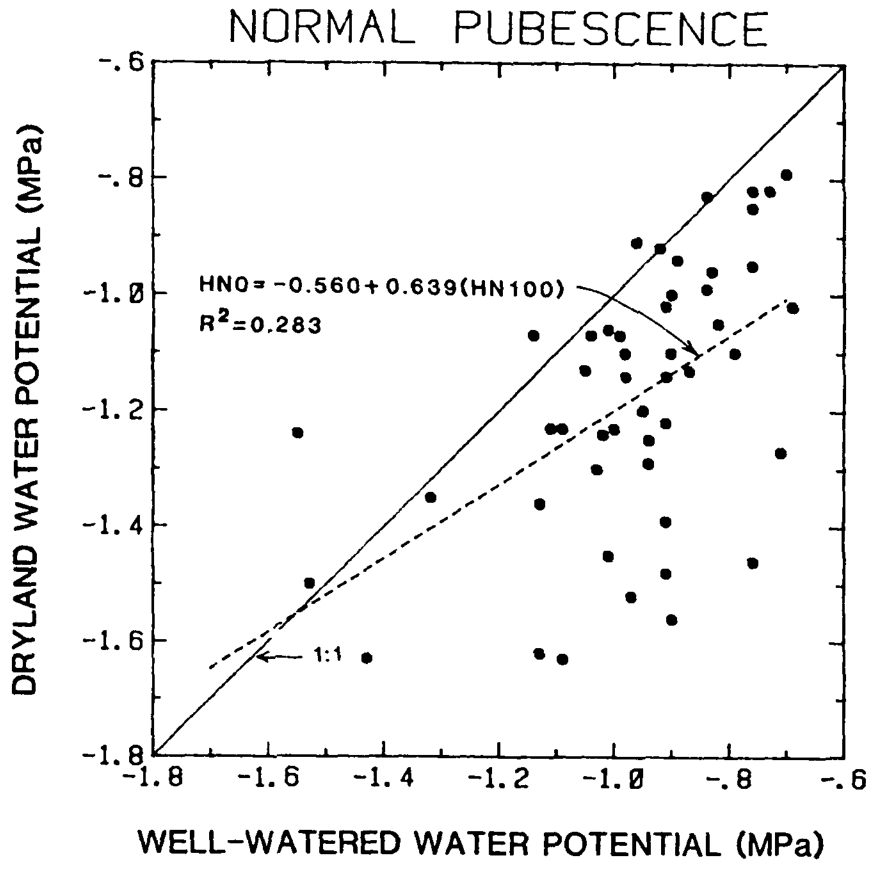


Fig. 4.9 Total leaf water potential of single sunlit leaves from the normal pubescent isoline at midday over the growing season under dryland and well-watered conditions.

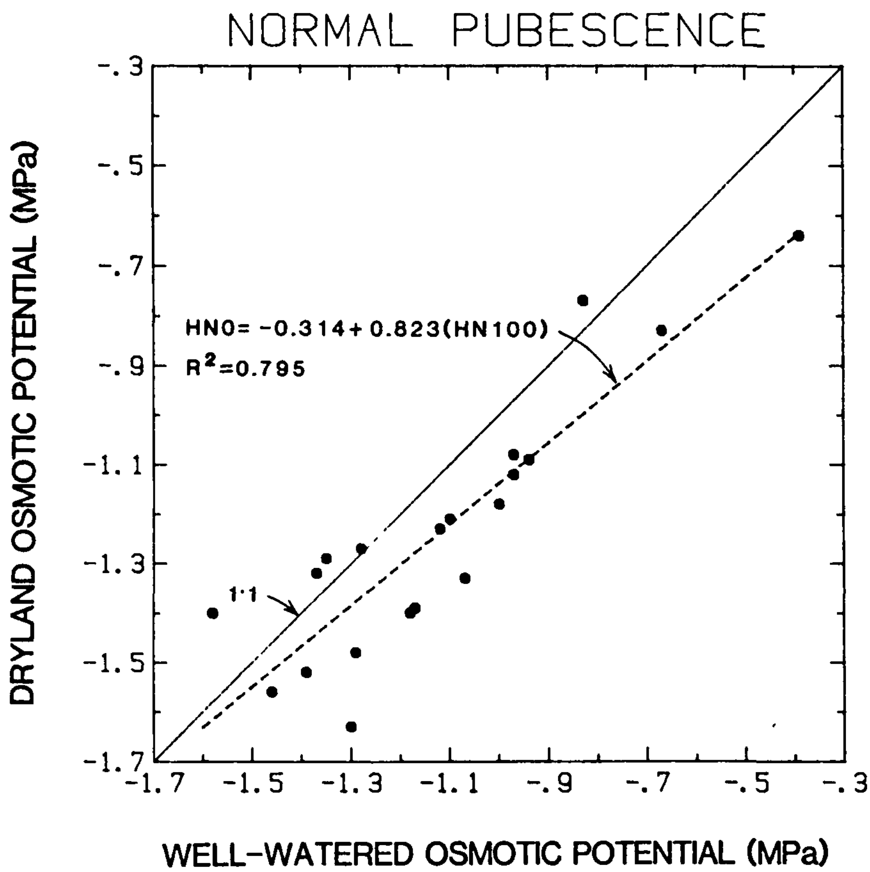


Fig. 4.10 Osmotic potential of single sunlit leaves from the normal pubescent isoline at midday over the growing season under dryland and well-watered conditions.

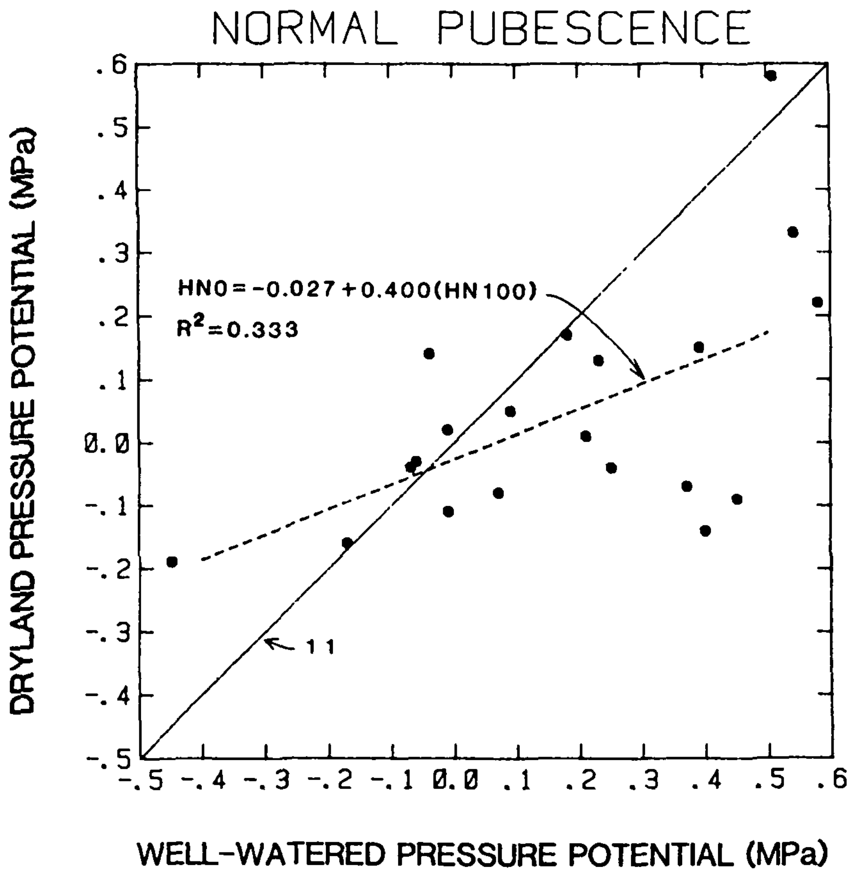


Fig. 4.11 Pressure potential of single sunlit leaves from the normal pubescent isoline at midday over the growing season under dryland and well-watered conditions.

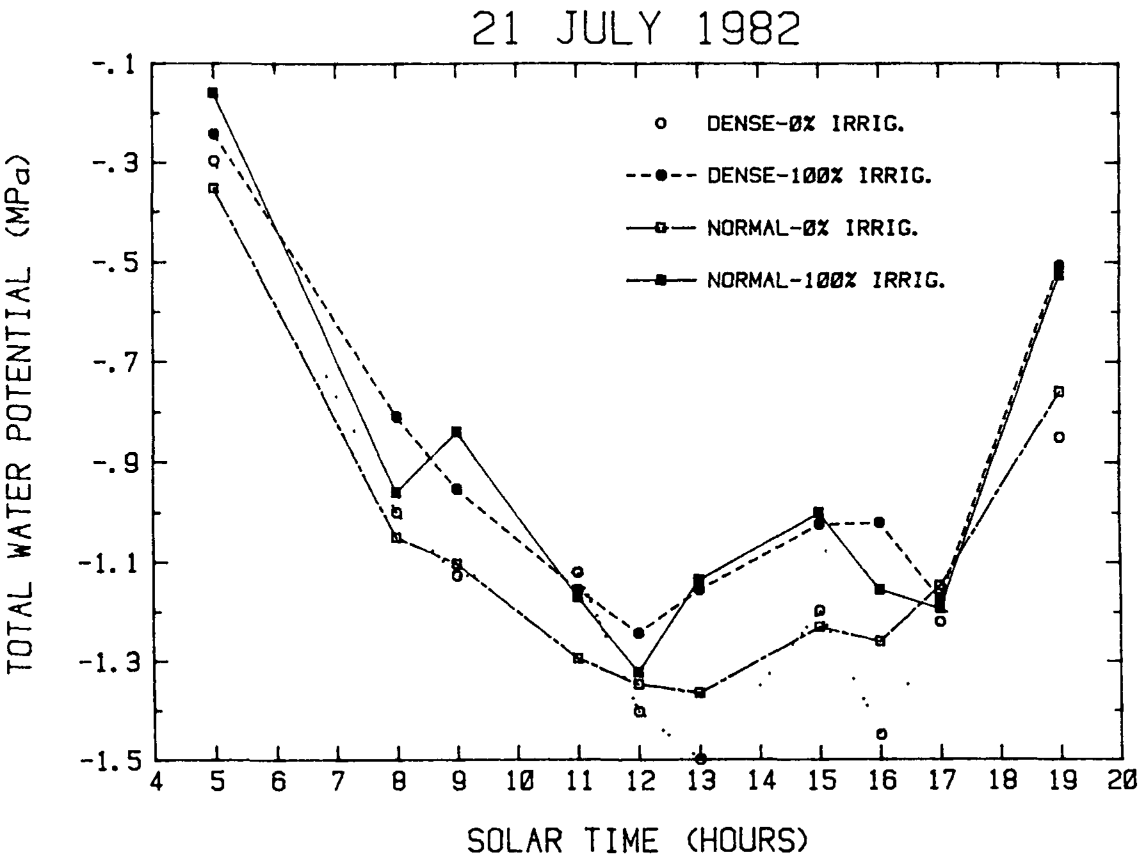


Fig. 4.12 Total leaf water potential of the dense and normal pubescent isolines on 21 July in the dryland and well-watered plots.

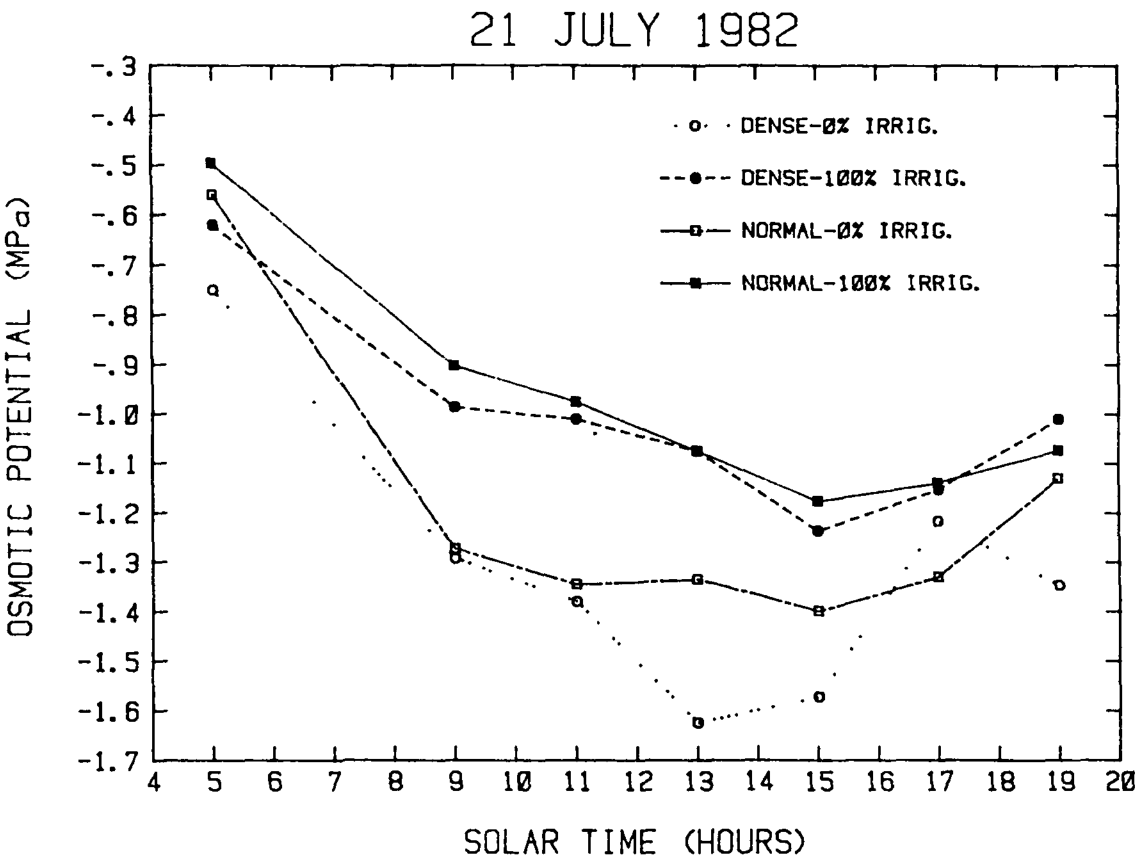


Fig. 4.13 Osmotic potential of the dense and normal pubescent isolines on 21 July in the dryland and well-watered plots.

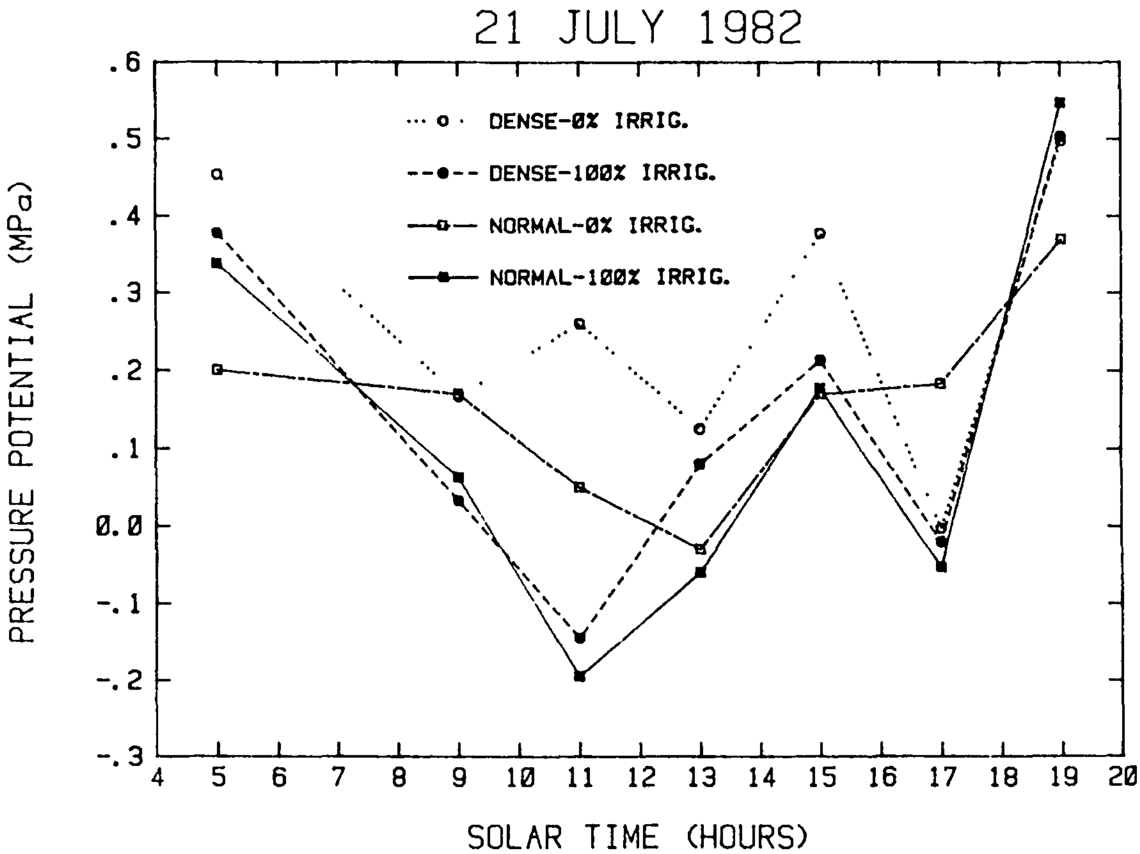


Fig. 4.14 Pressure potential of the dense and normal pubescent isolines on 21 July in the dryland and well-watered plots.

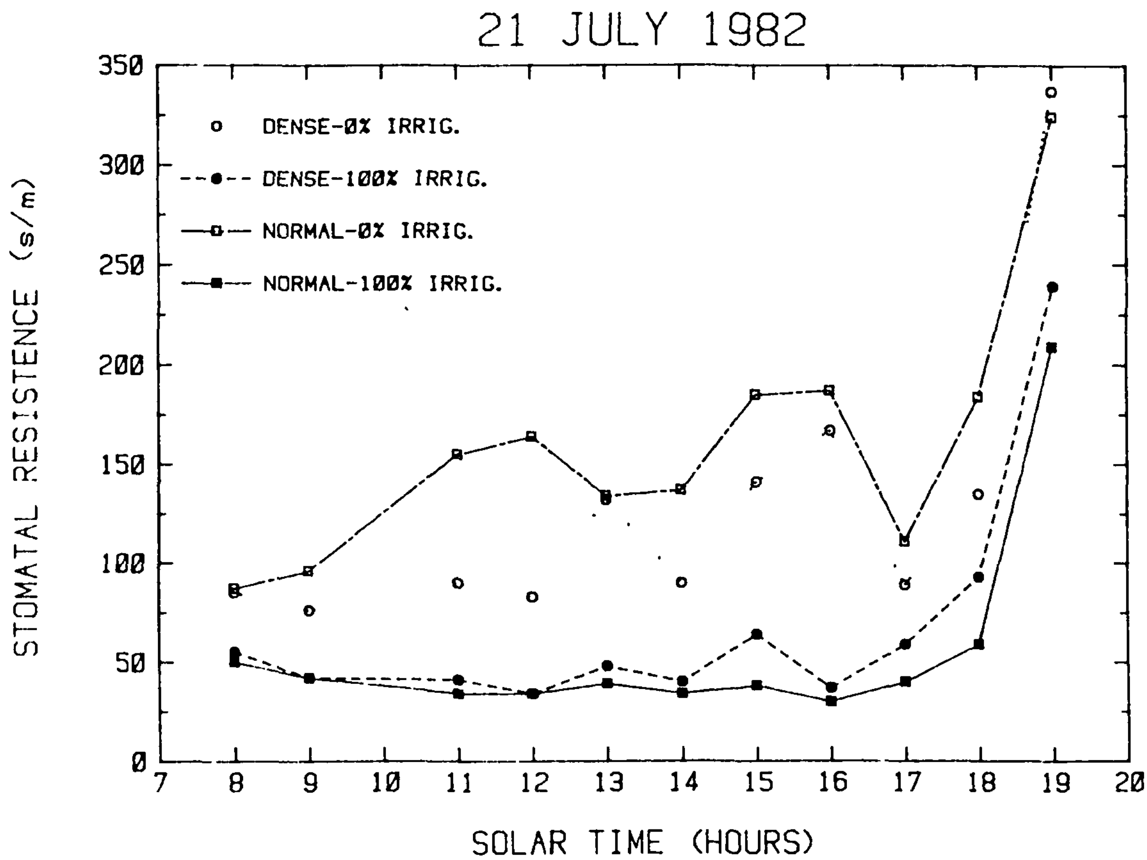


Fig. 4.15 Stomatal resistance of the dense and normal pubescent isolines on 21 July in the dryland and well-watered plots.

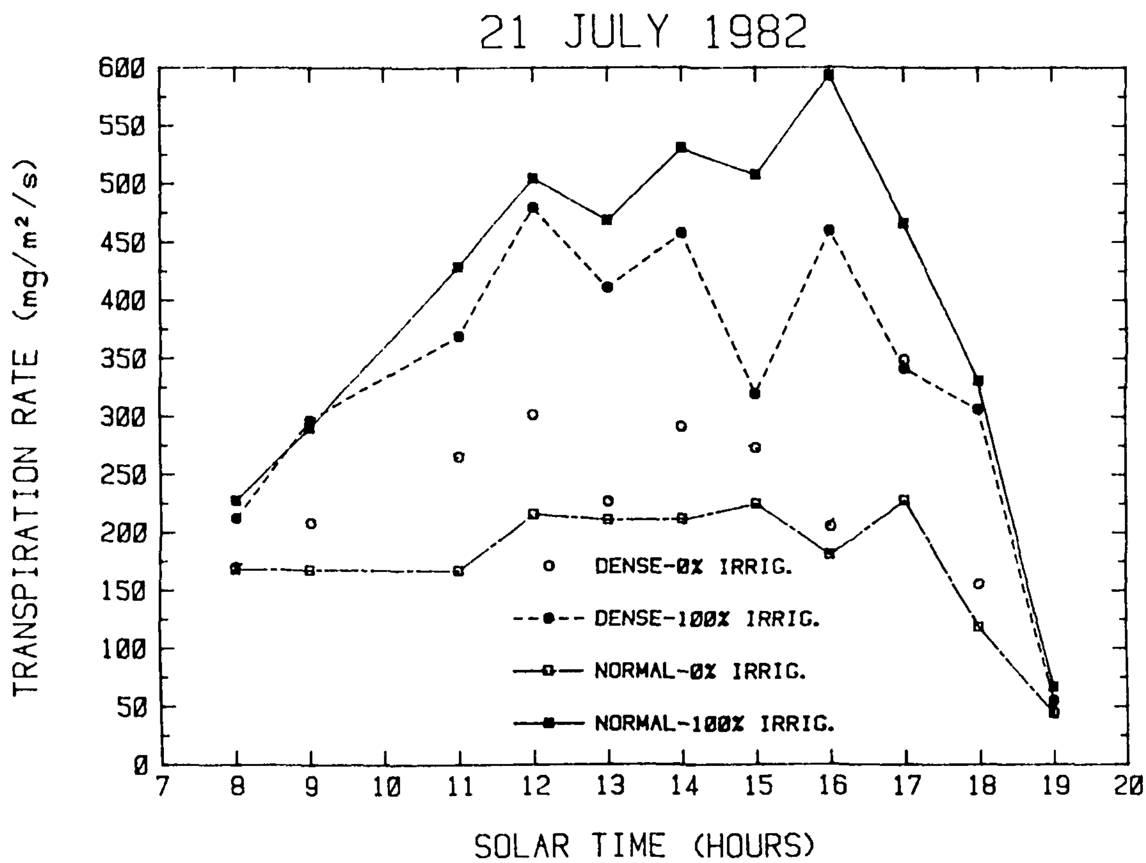


Fig. 4.16 Transpiration rates of the dense and normal pubescent isolines on 21 July in the dryland and well-watered plots.

The dramatic increase in stomatal resistance and decrease in transpiration at 1800 and 1900 hours was due to the low amount of solar radiation near sunset. Stomatal resistance differences due to water stress were observed to be about 150 s m^{-1} during the midafternoon. At the same time transpiration was decreased about 325 mg m^{-2} s^{-1}.

As a result of the reduction in transpiration of the water-stressed plants on 21 July, leaflet and canopy temperatures increased (Figs. 4.17 and 4.18). Large differences at 0800 suggest that water stress was severe. Canopy temperature differences increased from about 1.5 C at 0800 to about 5.0 C at 1300. Leaflet temperature differences for the same time period were 3.0 and 5.0 C.

4.5.3.2 Pubescence Density

Pubescence density was an important factor in the water relations observed during the study. Seasonal averages of transpiration, leaflet and canopy temperatures were all significantly ($P \geqslant 0.10$) reduced because of increased pubescence density when grown under well-watered conditions. The average differences for these three variables were, respectively, 60 mg m^{-2} s^{-1}, 0.3 C and 0.2 C (Figs. 4.19-4.21). Stomatal resistance and total leaf water, osmotic and pressure potentials were not significantly affected. The trend, however, was toward increased stomatal resistances and osmotic potentials and decreased pressure potentials (Figs. 4.22-4.24). There was no effect of pubescence density on total leaf water potential (Fig. 4.25).

Diurnal patterns, exemplified by data from 21 July (Figs. 4.12-4.18), followed the seasonal trends observed for pubescence density under wellwatered conditions. The effects due to increased pubescence were much smaller than the effects caused by drought stress. As such, the effects due to pubescence generally did not become apparent until about midafternoon. On 21 July, dense

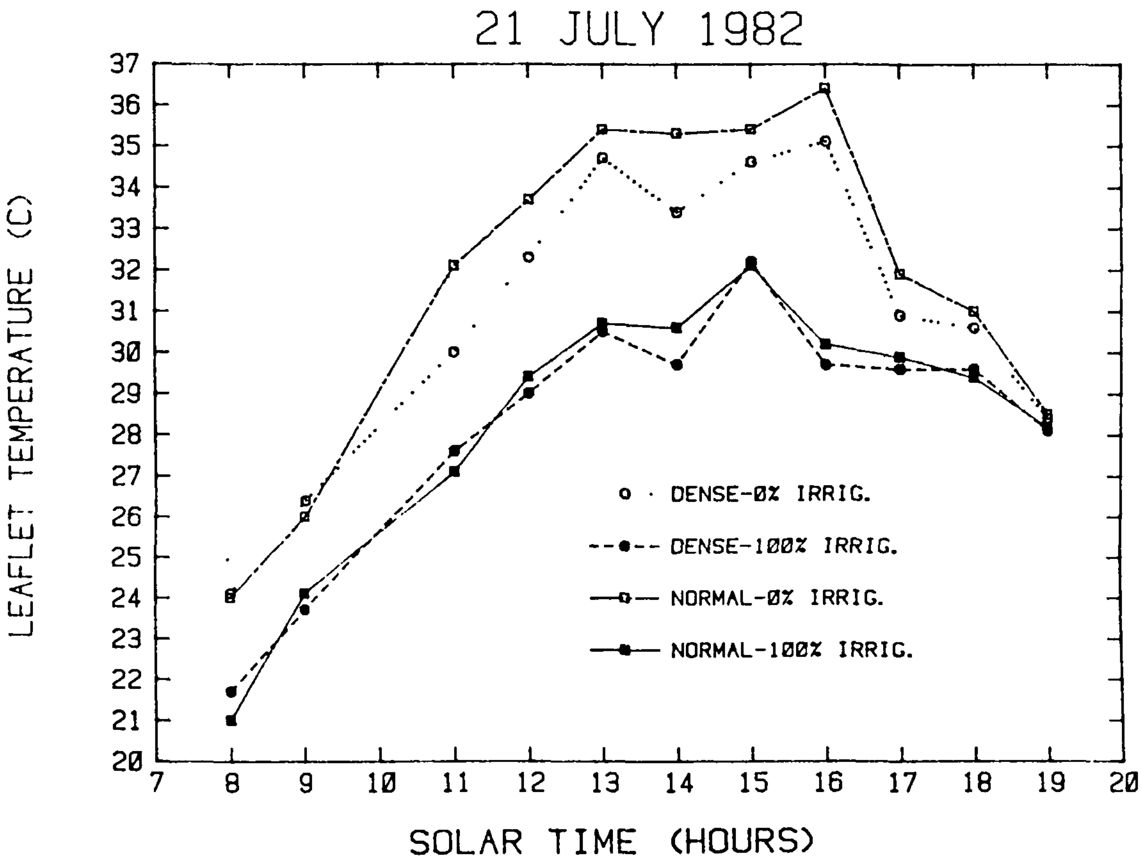


Fig. 4.17 Leaflet temperature of the dense and normal pubescent isolines on 21 July in the dryland and well-watered plots.

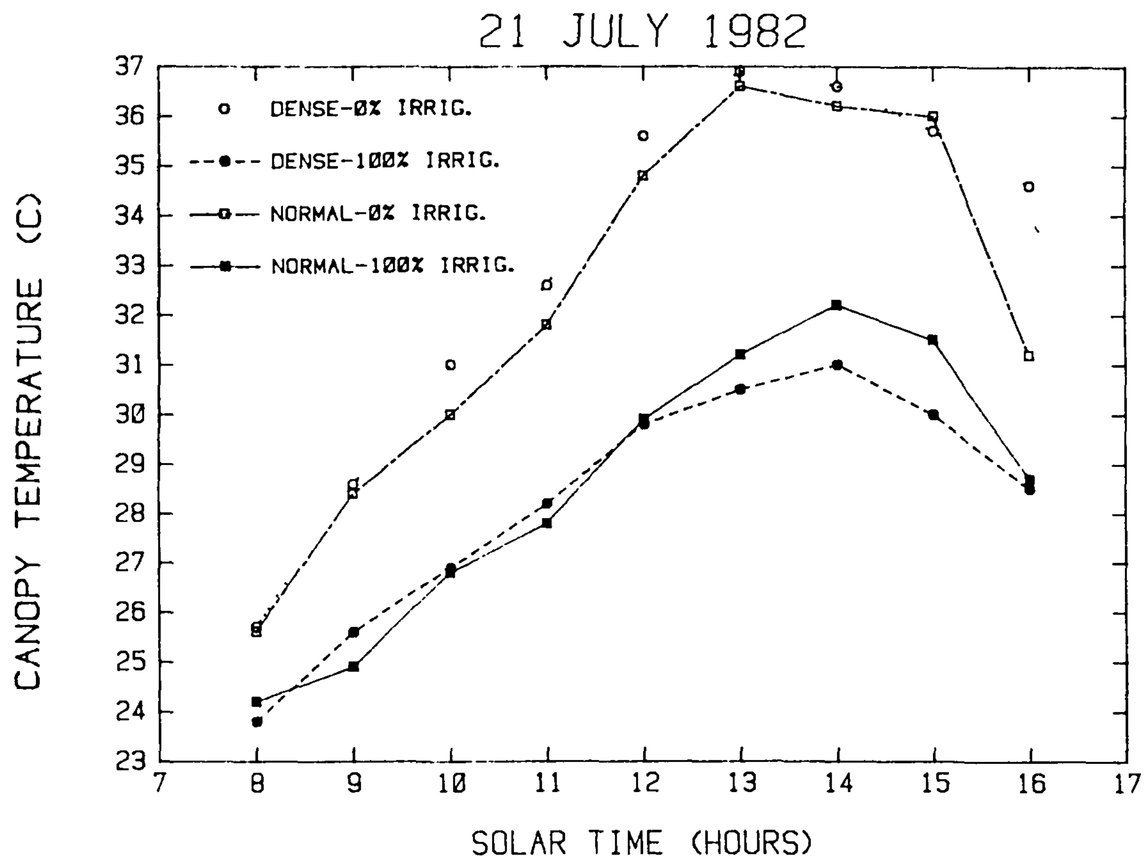


Fig. 4.18 Canopy temperature of the dense and normal pubescent isolines on 21 July in the dryland and well-watered plots.

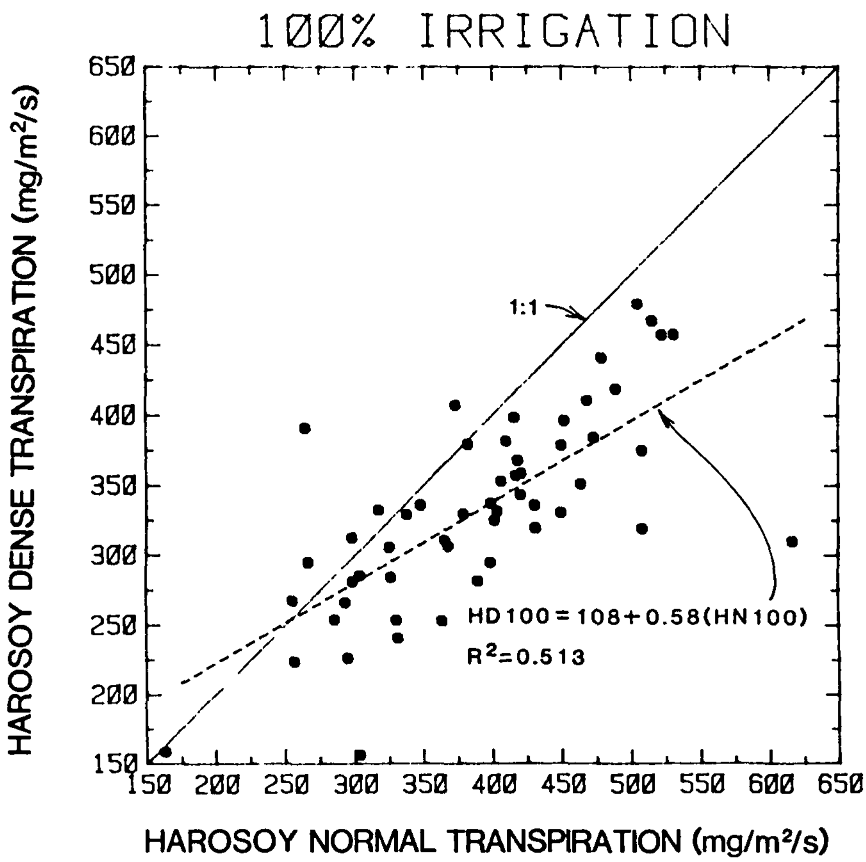


Fig. 4.19 Transpiration rate of dense and normal pubescent leaves at midday under well-watered conditions for the growing season.

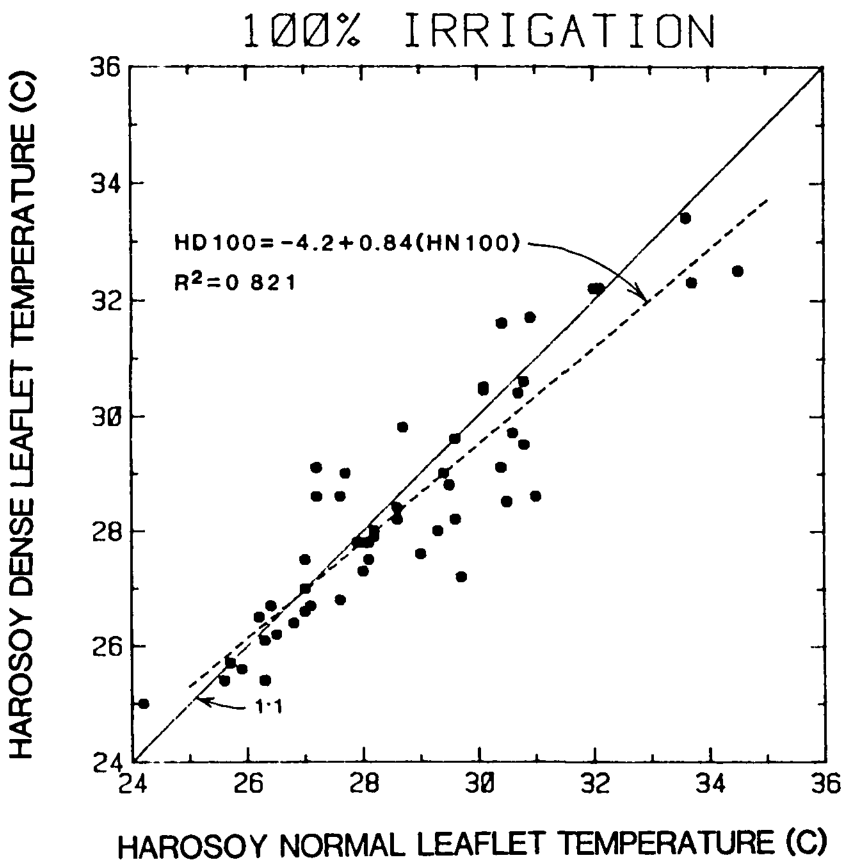


Fig. 4.20 Leaflet temperature of dense and normal pubescent leaves at midday under well-watered conditions for the growing season.

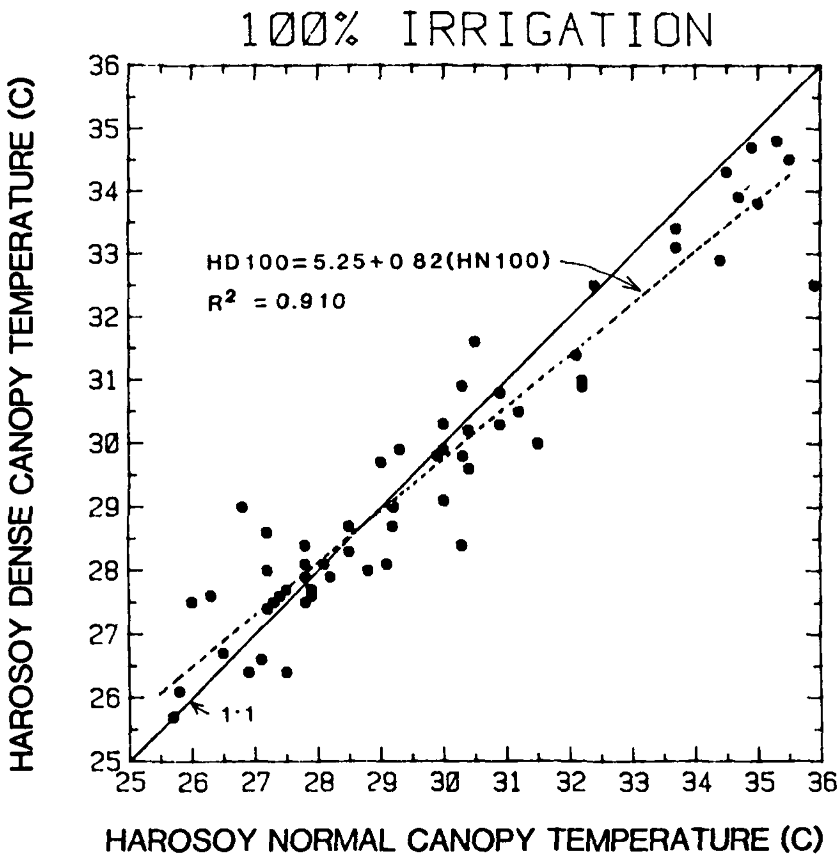


Fig. 4.21 Canopy temperature of dense and normal pubescent leaves at midday under well-watered conditions for the growing season.

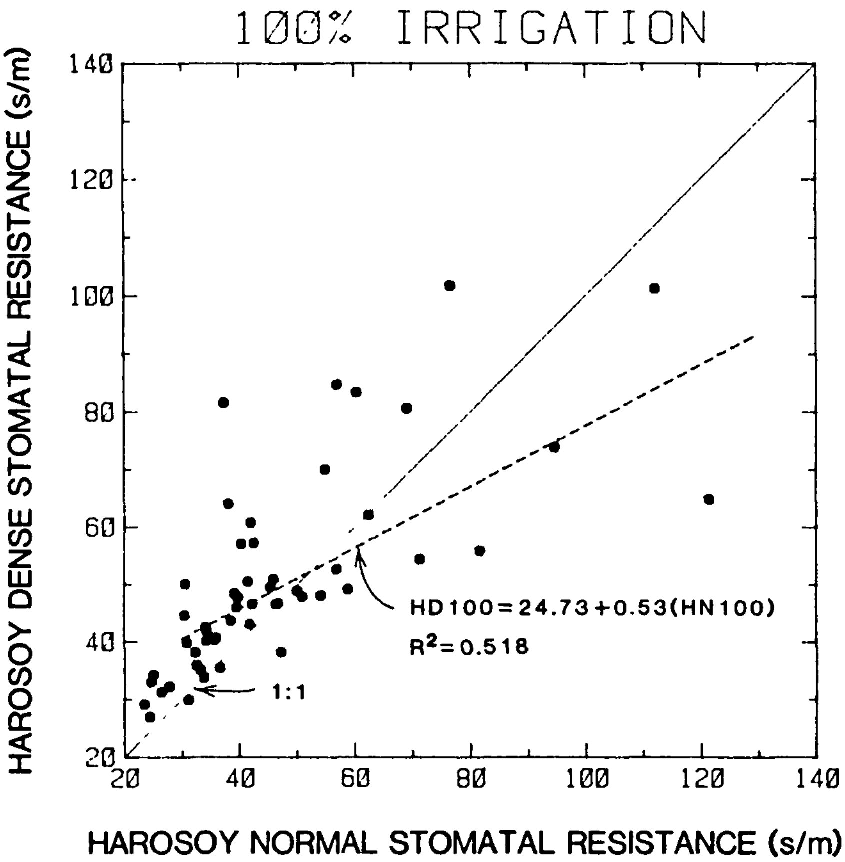


Fig. 4.22 Stomatal resistance of dense and normal pubescent leaves at midday under well-watered conditions for the growing season.

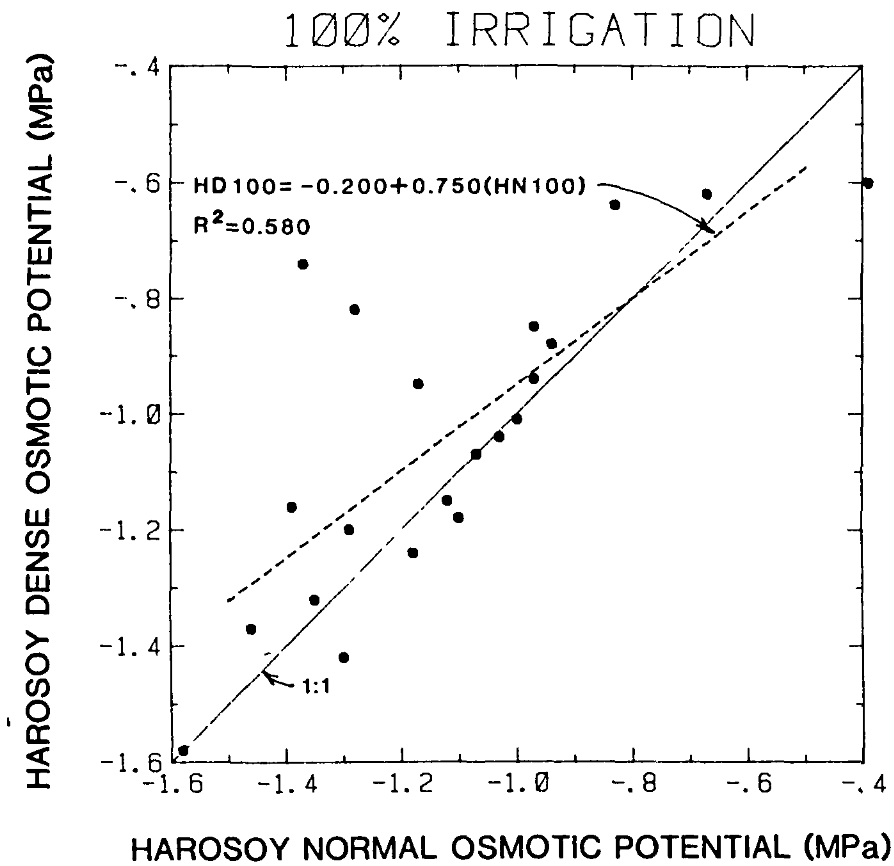


Fig. 4.23 Osmotic potential of dense and normal pubescent leaves at midday under well-watered conditions for the growing season.

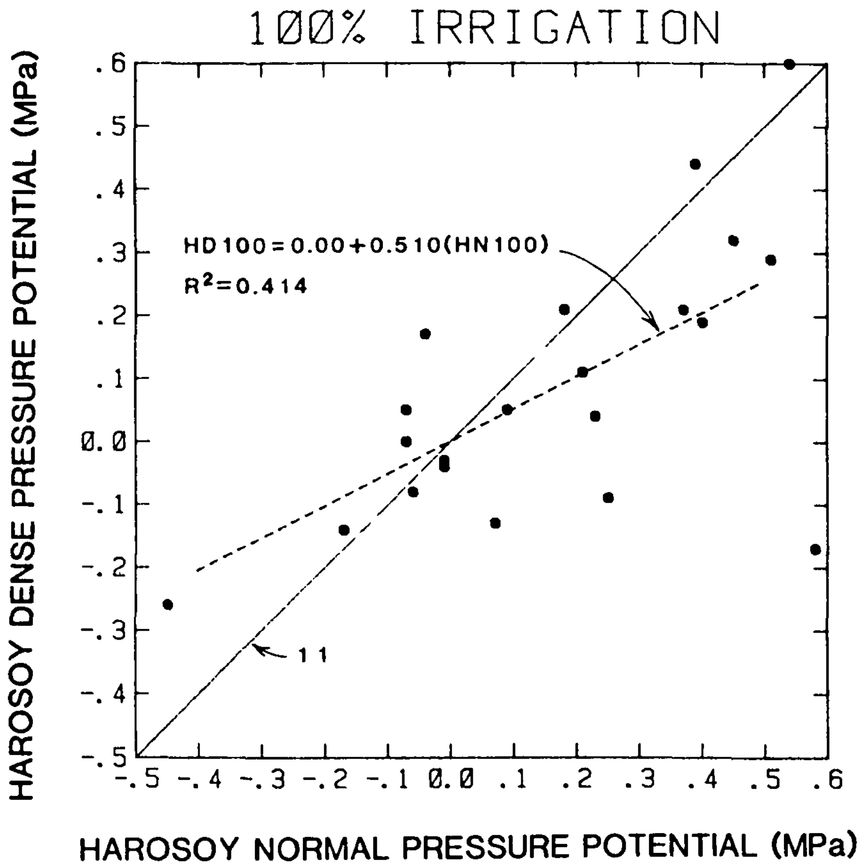


Fig. 4.24 Pressure potential of dense and normal pubescent leaves at midday under well-watered conditions for the growing season.

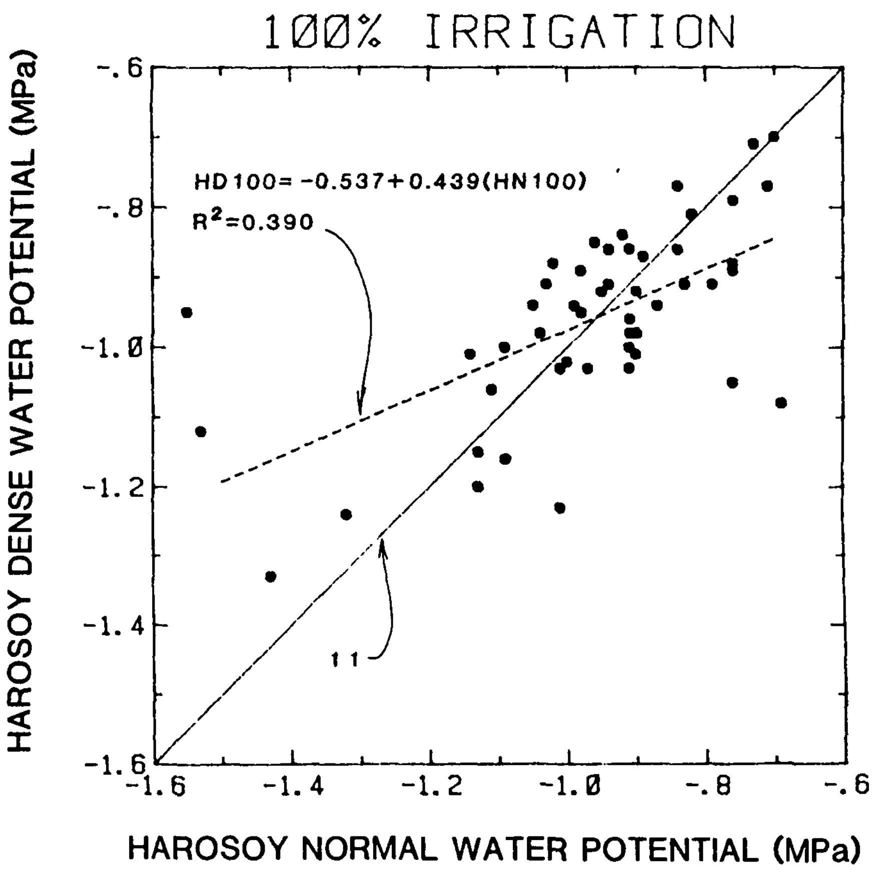


Fig. 4.25 Total leaf water potential of dense and normal pubescent leaves at midday under well-watered conditions for the growing season.

pubescence under well-watered conditions reduced canopy and leaflet temperatures at midafternoon by about 1.2 and 0.5 C, respectively. Transpiration was also decreased by about 50 to 75 mg m^{-2} s^{-1} and stomatal resistance increased by about 15 s m^{-1} at midday due to increased pubescence. No consistent differences were observed in the potential measurements at midday on 21 July.

The combined results of canopy and leaflet temperature measurements together with observations of stomatal resistance and transpiration for the season illustrated the effect of increased pubescence on the microclimate in the well-watered plots. Dense pubescence consistently decreased transpiration, but this did not result in increased canopy or leaflet temperatures. Instead, canopy and leaflet temperatures declined, suggesting that some mechanism other than transpirational cooling was responsible for cooler canopy temperatures. From this it can be inferred that increased sensible heat flux and/or albedo in the dense pubescent isoline were the primary mechanisms for decreasing canopy and leaflet temperatures under well-watered conditions (see Baldocchi et al., 1983; Nielsen et al., 1983).

Pubescence density affected water relations of the water stressed crop. Analyses of variance showed that drought stress interacted with pubescence density to cause a different response depending on the severity of the stress. Data from 21 July were indicative of this phenomenon. Total leaf water potential on this day (Fig. 4.12) showed large differences between well-watered and dryland plots. indicating severe stress. Data scatter within the dryland plots was too large to determine whether a significant difference in potentials existed because of pubescence density. However, pubescence density effects were observed on all other variables under dryland conditions. Osmotic potential (Fig. 4.13), stomatal resistance (Fig. 4.15) and leaflet temperature were all decreased in the dense pubescent isoline by about 0.2 MPa, 40 s m^{-1}, and 1.0 C, respectively. Pressure potential, transpiration rate and canopy temperature showed increases of 0.15 MPa, 50 mg m^{-2} s^{-1} and 0.5 C, respectively.

The increase in canopy temperature due to pubescence measured by the IRT on 21 July was in direct contrast to the decrease in leaf temperature measured by thermocouple in the dryland plots. These conflicting patterns may have resulted from canopy geometry differences. The dense isoline exhibited a more open canopy than the normal isoline when grown under water-stressed conditions until about 1 August. Thus, the dense isoline exposed more bare soil to the view of the IRT. After the canopy cover became more complete, canopy temperature patterns agreed with leaflet temperature patterns.

Data from 1 September contrasted with data from 21 July. Little stress was visible on this day. Under these conditions, canopy and leaflet temperatures, stomatal resistance and transpiration trends of the dryland plants were identical to the trends observed under well-watered conditions (Fig. 4.26).

4.5.4 Estimating LAI Over Soybeans Using Corn LAI Models

Models M1-M116 were applied to the soybean data collected at SAL. The results show that predicted LAI values from 17 models were not significantly different from measured values. LAI ranged from 0 to 7.2. Only six of these models were among the 16 corn LAI models shown to be applicable over a wide range of soils (Table 4.16). These six models are thus applicable to corn and soybeans. Additional testing of these models is encouraged to determine whether general use should be recommended. Model 95 appears to be the most accurate of these six models.

4.5.5 Interpretation of LAI Models

The agronomic interpretations of the six LAI models in Table (4.17) are virtually identical. Conceptually, they reduce to the following equation:

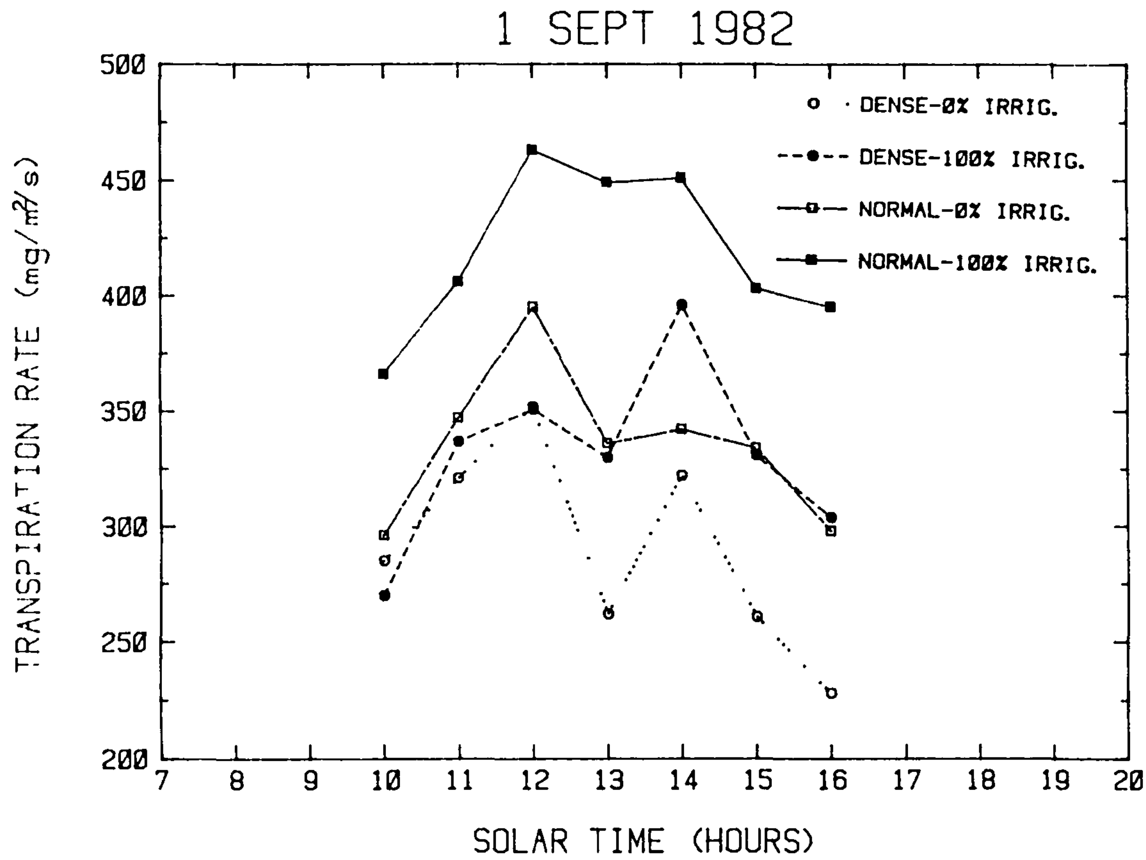


Fig. 4.26 Transpiration rates of the dense and normal pubescent isolines on 1 September in the dryland and well-watered plots.

Table 4.16 t-test results indicating the corn LAI models which are also applicable to soybeans. The t-test was performed on the difference between measured and predicted LAI values. 892 data points were used in the test. An asterisk indicates models which had low values of predicted LAI over the Stoner soil data.

Model	Mean Difference (measured-predicted LAI)	t value	Probability t is greater
M29	0.04	1.59	0.11
M56	0.03	1.36	0.17
*M62	0.01	0.53	0.60
*M74	0.03	1.21	0.23
M85	-0.02	-0.87	0.39
*M87	-0.04	-1.57	0.12
*M94	-0.01	-0.42	0.68
*M95	-0.001	-0.06	0.95
M96	0.03	1.43	0.15
M100	0.03	1.39	0.16
M101	0.03	1.18	0.24
*M103	-0.009	-0.40	0.69
M108	-0.03	-1.19	0.24
M109	0.02	0.75	0.45
M111	-0.02	-0.94	0.35
M112	0.004	0.16	0.89
M113	0.008	0.34	0.73

Table 4.17 Regression statistics for the six LAI models which are applicable to corn and soybeans and which predict low LAI values over a wide range of soils.

(Dependent variable = LAI) (N = 1218 for all regressions)

Variable	Parameter Estimate	R^2	Standard error of estimate of LAI	Mean/cv of Individual terms over Stoner soils
Model M62				
Intercept	-2.537	0.82	0.39	--
TM5	-0.0364			19.1/24.5
log(TM2)	-1.520			1.7/26.2
log(TM4)	2.492			2.5/17.6
Model M74				
Intercept	0.478	0.82	0.38	--
log(TM4)	2.426			2.5/17.6
log(TM5)	-2.513			2.9/ 9.2
TM5/TM2	0.392			3.5/37.0
Model M87				
Intercept	2.200	0.83	0.38	--
log(TM4)	2.492			2.5/17.6
log(TM5)	-3.029			2.9/ 9.2
TM7/TM3	0.540			1.78/46.1
Model M94				
Intercept	1.921	0.83	0.38	--
log(TM4)	2.952			2.5/17.6
log(TM5)	-3.350			2.9/ 9.2
TM3/TM2	-0.576			1.4/13.6
TM7/TM2	0.704			2.5/37.6
Model M95				
Intercept	1.085	0.83	0.38	--
log(TM4)	2.980			2.5/17.6
log(TM5)	-3.327			2.9/ 9.2
TM7/TM2	0.623			2.5/37.6
TM5/TM3	0.0648			2.55/44.1
Model M103				
Intercept	1.465	0.83	0.38	--
log(TM4)	2.921			2.5/17.6
log(TM5)	-3.347			2.9/ 9.2
TM7/TM2	0.399			2.5/37.6
TM7/TM3	0.291			1.78/46.1

LAI = (LAI response term) + (soil background correction term)

The LAI response term is similar for five of the models:

$$\text{LAI response} = \log\ (\text{TM4}/\text{TM5})^{x}$$

where x is between 0.83 and 0.97. Conceptually, the ratio TM4/TM5 and TM4/TM2 are (vertical LAI/horizontal LAI). Interestingly, the middle infrared band TM5 is statistically favored over the visible bands for representing horizontal LAI. This is probably due to the greater dynamic range of TM5 compared to TM1-TM3 (Fig. 4.1). TM4 and TM5 were also shown to be the two most important bands for estimating LAI in wheat (Ahlrichs and Bauer, 1982).

The soil background correction terms have similar interpretations in all six models. The correction term of model M62 is composed of a single band, where models M94, M95 and M103 have correction terms composed of two two-band ratios. Models M74 and M87 each have correction terms composed of a single two-band ratio. Model M87 will be discussed since the bands composing the LAI response term and soil correction term are all different. The discussion can be easily extended to all the models, however.

The ratio TM7/TM3 (horizontal LAI/horizontal LAI) is, in essence, an indication of the relative amount of exposed soil. For a given soil, this ratio should remain relatively constant whether the soil is wet or dry. It can now be seen why the ratio TM4/TM5 is superior to the ratio TM4/TM3 or TM4/TM2 for estimating LAI and why the ratio TM7/TM3 is a soil background correction term. Most soils reflect more energy in the 1.55-1.75 µm range than in the 0.76-0.90 µm range (Stoner and Baumgardner, 1982). Thus, the ratio TM4/TM5 will be less than 1.0 over most soils (Fig. 4.5). As a canopy develops, TM4 continuously increases, and TM5 asymptotically decreases to a relatively constant low value. The result is a ratio that becomes greater than 1.0 over vegetation. In contrast, the ratio of TM4/TM2 or TM4/TM3 will always be greater than 1.0 over soils. Therefore, the ratio TM4/TM5 is more sensitive to the presence of vegetation. When the ratio is less than 1.0, vegetation must be sparse or nonexistant.

Similarly, the ratio TM7/TM3 is also a good indicator of the presence of soil. This ratio will generally be much greater than 1.0 over bare soil (Stoner and Baumgardner, 1982) but will become approximately 1.0 over a fully developed canopy (Fig. 4.27). The behavior of model M87 is, therefore, consistent with agronomic and reflectance theory. Similar rationale applies to the interpretation of the other models.

4.6 Grain Yield/LAI Relationships

Linear relationships between maximum LAI and grain yield have been reported for LAI values less than 2.6. Between LAI values of 2.6 and 3.4, grain yield is linearly related to leaf area duration (LAI_{max} x number of days to maturity). Leaf area duration (LAD) can also be calculated as an integral, where LAD = $\int$ LAI dt. The limits of this integral can be across an entire season or over the grain formation period (Waldren, 1983). These relationships are variety dependent.

No significant relationship existed between maximum LAI and grain yield for the two corn hybrids (Fig. 4.28). Note that LAI values were generally in excess of the optimum range 2.6-3.4 (Waldren, 1983).

Reflectance estimates of LAI, using Model M86, when examined by grain-yield class, are instructive (Fig. 4.29). Note that plots which had high LAI values also tended to have high yields and that plots with low LAI values tended to have low yields. It is clear, however, that LAI data, even if integrated over the whole season, can only separate areas of relatively high and relatively low yields. A basic problem is that the effects of moisture

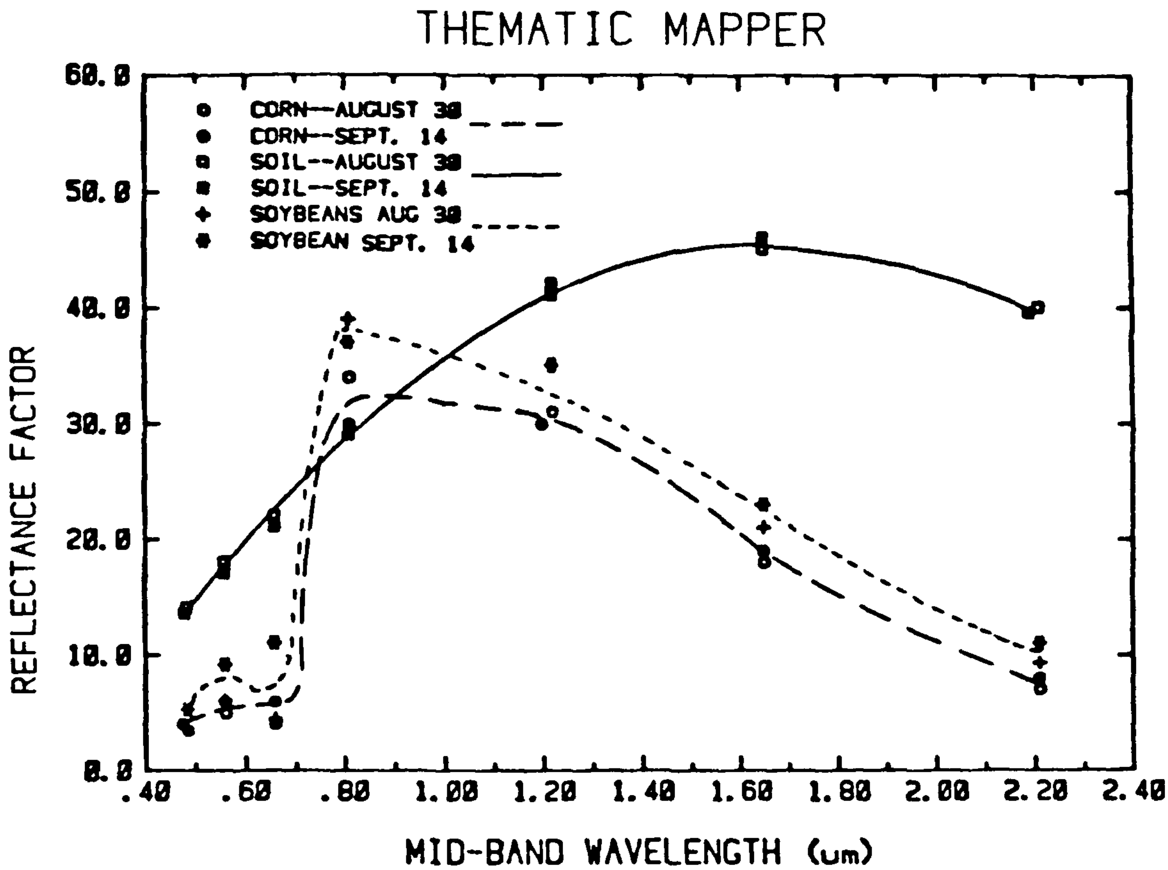


Fig. 4.27 Non-stressed corn, soybean and bare soil reflectances, as seen in the Thematic Mapper wavebands at SAL on two dates in 1981 (Blad et al., 1982a).

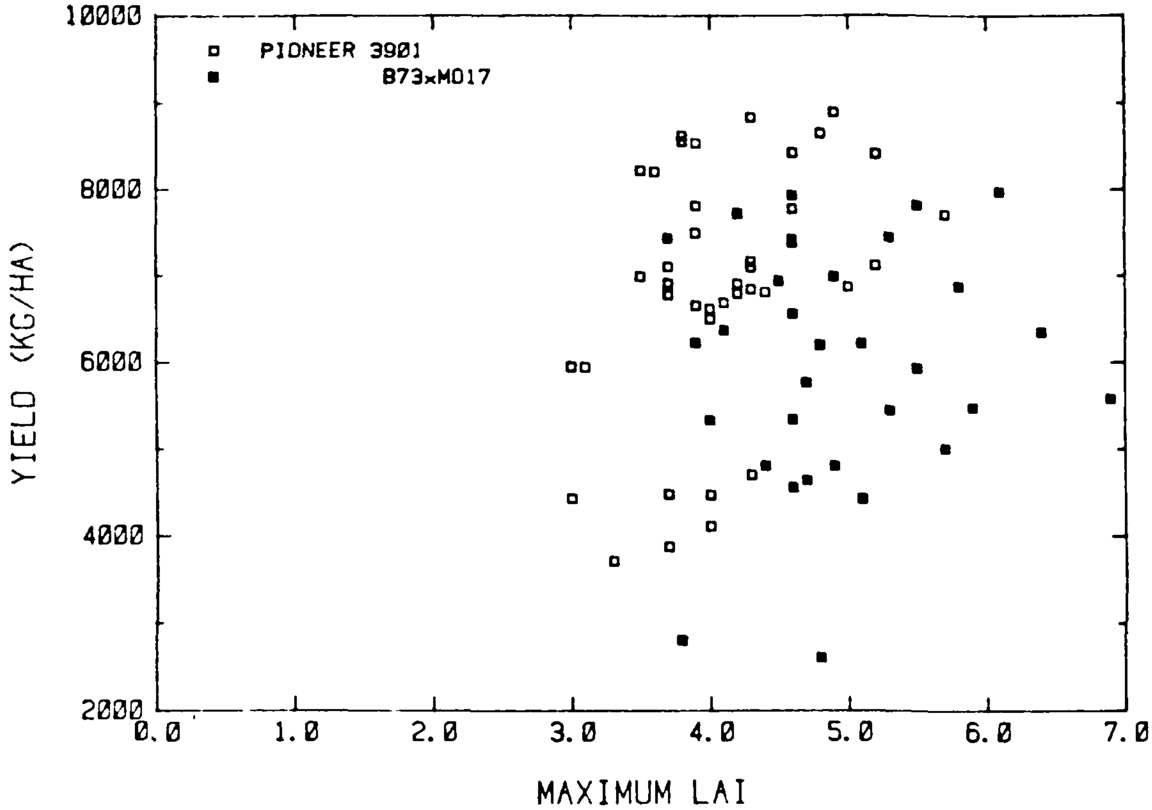


Fig. 4.28 Relationship between yield and maximum leaf area (LAI) for two corn hybrids grown at SAL in 1982.

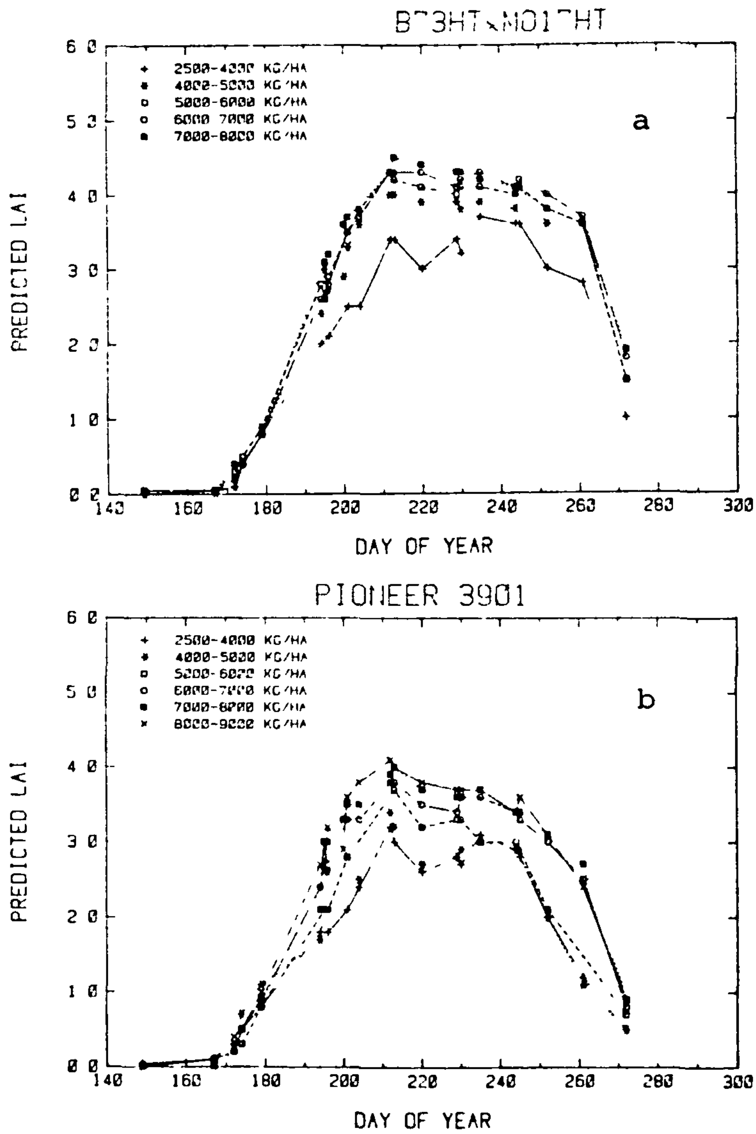


Fig. 4.29 Predicted LAI using spectral model M86 for two corn hybrids and 6 grain yield classes at SAL in 1982.

stress have not been included in this type of assessment. Canopies with similar seasonal LAI patterns can have greatly different yields.

It is important also to realize the hybrid differences that exist. LAI differences between the hybrids are pronounced at any given grain-yield level (Fig. 4.30). These differences are much greater than the differences that exist between grain-yield classes within a given hybrid. Two conclusions results from these findings: a) absolute grain yields cannot be accurately detected remotely without a prior knowledge of the yield potential of hybrids in a given area; b) the effects of moisture stress must be included in any grain-yield assessment technique.

One question that may be asked is whether the variability of reflectance measurements has any relationship to moisture stress. This question was investigated, but no consistent patterns emerged which can be used to estimate stress severity. Coefficients of varability were similar for all yield classes and both varieties on all sampling dates. CVs followed the expected seasonal trend: high CVs early in the season, low CVs at midseason and an increase in CVs at maturity (Fig. 4.31).

4.6.1 Remote Estimates of Active Moisture Stress

Many physiological processes are affected by plant water deficits (Hsaio, 1973). Four plant responses affected by water stress which may be detected remotely are:

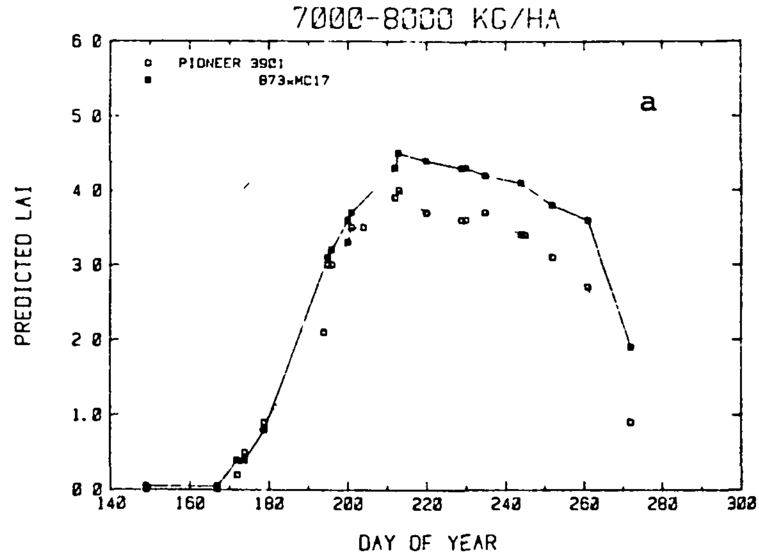
a. Leaf elongation rates--LAI estimates.

b. Senescence rates--leaf area duration.

c. Stomatal conductance--canopy temperature--canopy ET rates.

d. Canopy geometry changes (leaf curling, wilting) in effective LAI seen remotely.

Moisture stress during the pollination period results in a disturbance in



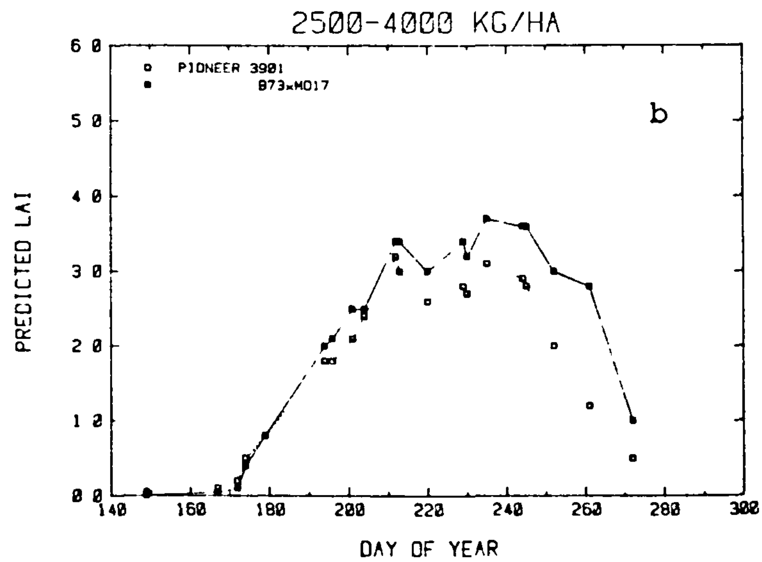


Fig. 4.30 Predicted leaf area for two corn hybrids and two yield classes at SAL in 1982.

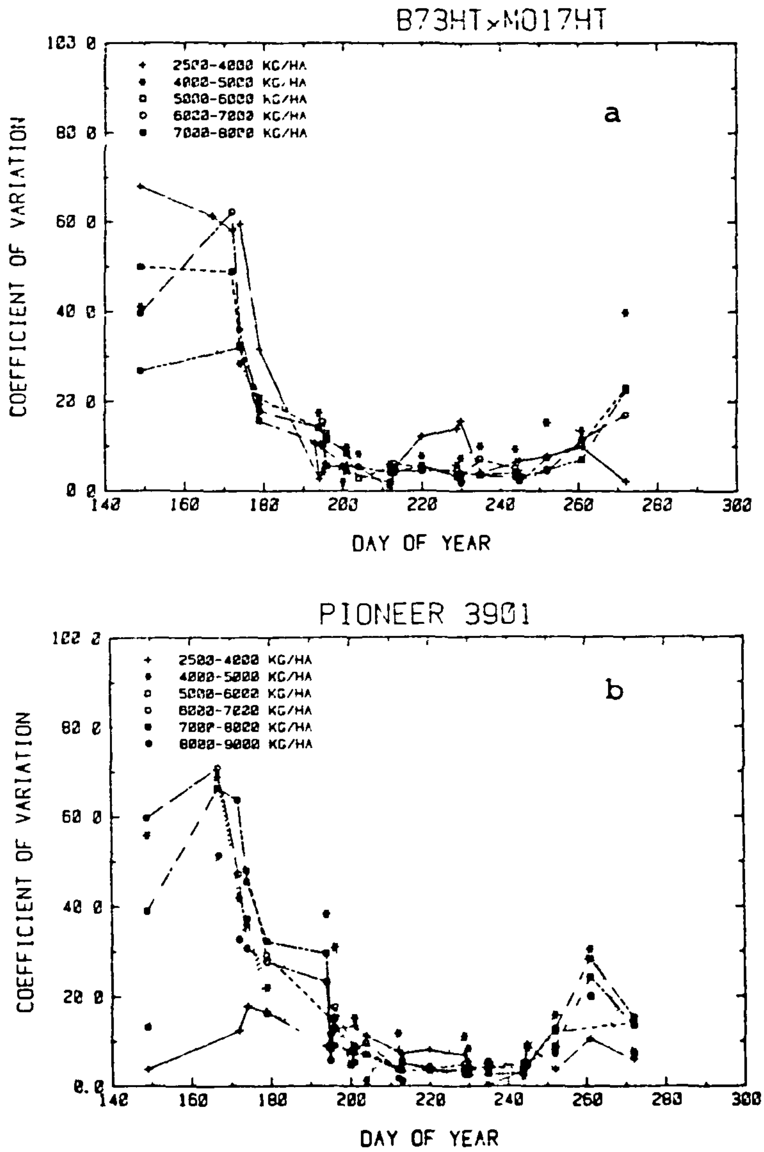


Fig. 4.31 Coefficient of variation for predicted leaf area for two corn hybrids and six grain yield classes at SAL in 1982.

the synchronization between tasseling and pollen shedding. The pollination period of corn is critical to the production of grain. The result is an increase in the number of barren plants (Waldren, 1983). Thus, a relatively short period of moisture stress (when compared to the life cycle of the plant) can produce large reductions in grain yield. Such a stress event will generally have little impact on LAI or senescence rates. The occurrence of moisture stress during this critical growth period can be detected remotely, however, since midday canopy temperatures will be elevated relative to non-stressed canopies.

Data from previous experiments indicate the importance of canopy temperature measurements in estimating grain-yield reductions caused by moisture stress (Fig. 4.32). The basic limitation in canopy temperature methods of estimating grain yields is the requirement of obtaining frequent (daily or several times per week) midday temperatures. Thus, it is highly desirable to develop a procedure for combining reflectance estimates of LAI with canopy temperature data. The requirement that data be obtained at midday (1300-1500 solar time) cannot be avoided since canopy moisture stress is maximal during this time period. Severe moisture stress, however, may be detectable by 1000-1100 (Blad et al., 1980).

Jackson (1982) proposed the use of a stress-degree day that can be used to mix thermal and spectral data. The stress-degree day is defined as:

$$SDD = \frac{(T_c - T_a) - (T_c - T_a)_{min}}{(T_c - T_a)_{max} - (T_c - T_a)_{min}} \tag{4.1}$$

The quantity (T_c-T_a) was shown to be a function of the vapor pressure deficit. Note that T_a appears in all terms in the SDD. One of the difficulties in using the SDD is deciding which air temperatures to use. Air temperatures

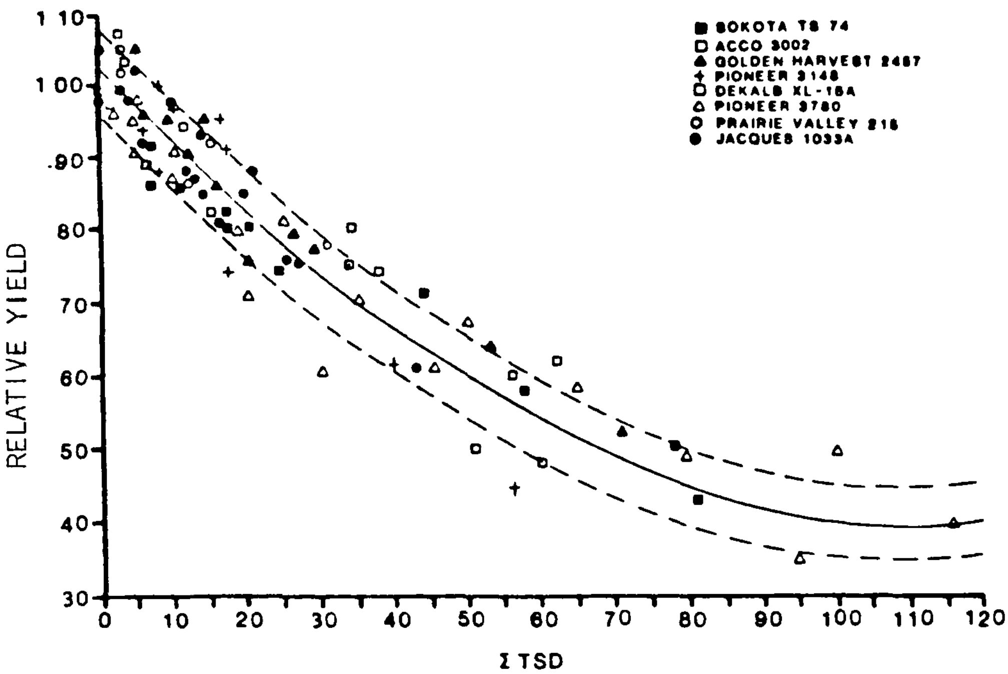


Fig. 4.32 Relationship between relative grain yield and the temperature stress day (TSD) for 8 varieties of corn grown at SAL in 1979 (Blad et al., 1980).

over stressed and nonstressed canopies will be different (Gardner et al., 1981). In addition to this difficulty T_a is not readily available from remotely sensed data. Consequently, a modified form of the SDD is proposed:

$$MSDD = 1 - (T_c - T_{c,min})/(T_{c,max} - T_{c,min}) \tag{4.2}$$

The term $T_{c,max}$ is the maximum canopy temperature that the canopy is capable of achieving. For the sake of discussion, the value of 40 C is selected. $T_{c,min}$ is the minimum canopy temperature achieved by a nonstressed canopy under a given set of environmental conditions. $T_{c,min}$ is measureable remotely. $T_{c,min}$ is taken as the canopy temperature of an area known (or assumed) to be nonstressed. Hence, all other canopies are referenced to a nonstressed area.

The next step is to combine the MSDD with reflectance data. Note that the MSDD ranges from 1 to 0 as the canopy becomes more severely stressed. Also, remember that LAI measurements can be similar for canopies experiencing different degrees of stress. One approach to mixing thermal and spectral data is, therefore, to calculate the interaction between relative LAI and MSDD, defined as a yield reduction factor (YRF):

$$YRF = ([LAI^*/LAI_{max})MSDD] \tag{4.3}$$

During most of the season, reflectance data were collected before the critical 1300-1500 (solar time) stress period. On 18 August, however, data were collected during this time interval. The LAI duration values were not calculated since the relative values of LAI between grain-yield classes remained approximately constant throughout the season (Fig. 4.29). Hence, the relationship between YRF obtained on 18 August and grain yield represents the seasonal trend.

As noted earlier, the grain yields versus LAI relationship is dependent on hybrid (Fig. 4.33a). In order to normalize this relationship it is necessary to calculate relative LAI (the ratio of LAI to LAI_{max} for a given variety). This results in similar curves for both hybrids (Fig. 4.33b). Further improvement can be achieved by also calculating relative grain yield (the ratio of grain yield to maximum yield for a given hybrid) (Fig. 4.34a). Note that both hybrids have the same basic relationship between relative LAI and relative grain yield, except at very low values of relative grain yield (less than 30%). Results suggest that B73xMo17 is more sensitive to severe water stress than is Pioneer 3901.

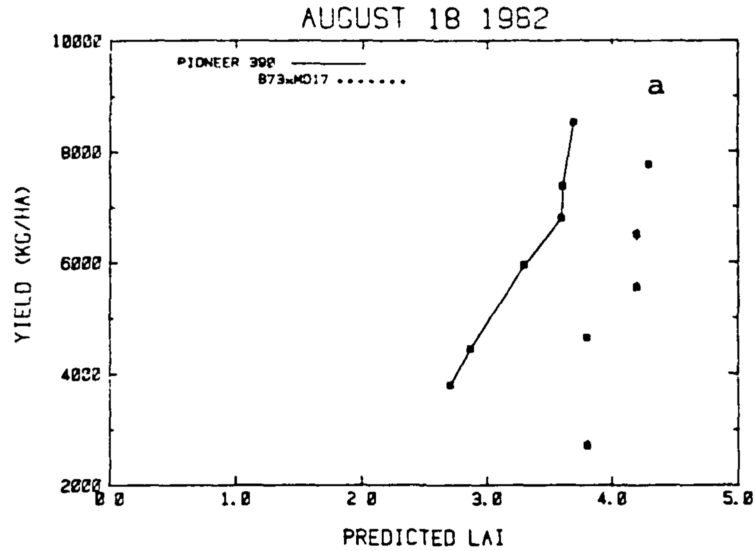
These results are still not satisfactory, however, since a wide range of relative yields occur at similar relative LAI values. When the YRF is used a slightly curvilinear relationship with relative grain yield results (Fig. 4.34b). Note the increased dynamic range of the relationship. It is clear that when canopy temperatures are included in grain-yield estimation, improved accuracy results. Thus YRF is more suitable for estimating grain yields than the procedures used in Figs. 4.33-4.34a.

4.7 Varietal Differences in Phytomass

B73xMo17 was vegetatively more productive than Pioneer 3901, with higher leaf area (Fig. 4.35), greater wet and dry leaf weights (Fig. 4.36) and greater wet stalk weights (Fig. 4.37). Interestingly, there was no significant difference in the dry stalk weights of the two varieties (Fig. 4.37b).

4.7.1 Leaf Area Index Relationships

In Section 4.2 it was shown that LAI is the basic canopy characteristic that is detectable with remote sensing techniques. Hence, the relationship between LAI and other agronomic parameters is of great interest. If varietal differences are present in a given relationship, the probability of developing



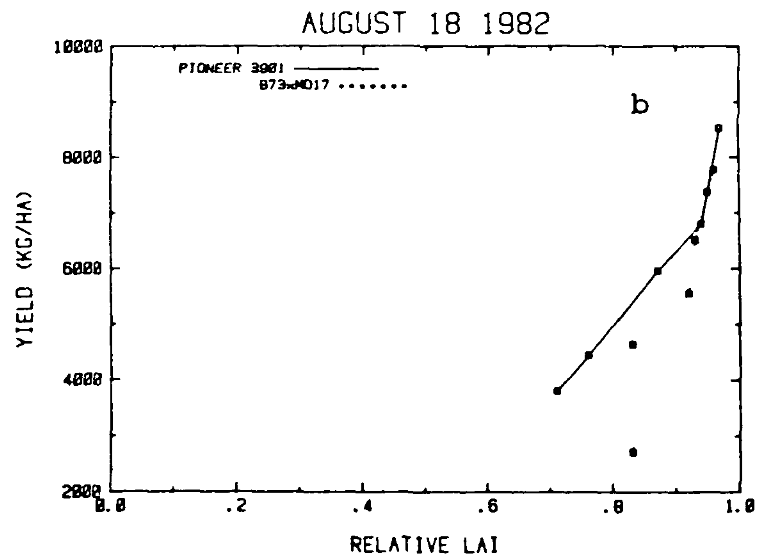


Fig. 4.33 Relationship between grain yield and a) predicted LAI and b) relative LAI estimates using reflectance model M86 for reflectance data from August 18, 1982.

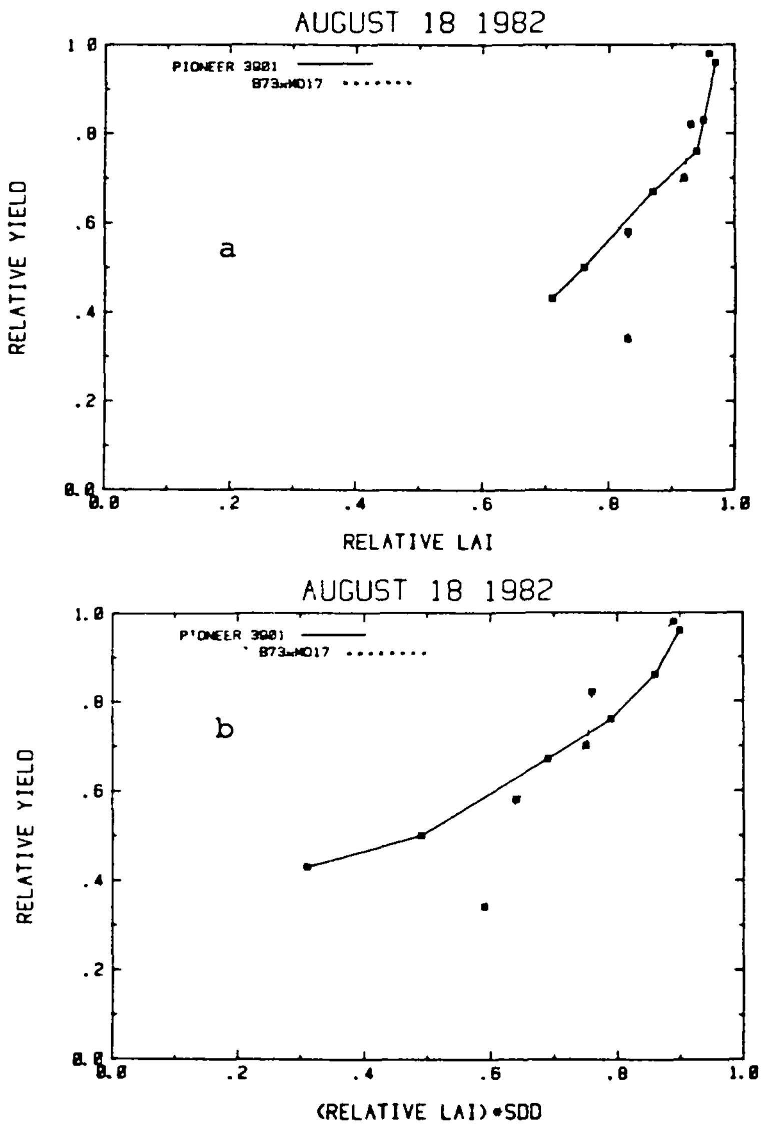


Fig. 4.34 Relative yield versus a) relative LAI and b) YRF where YRF is defined in the text.

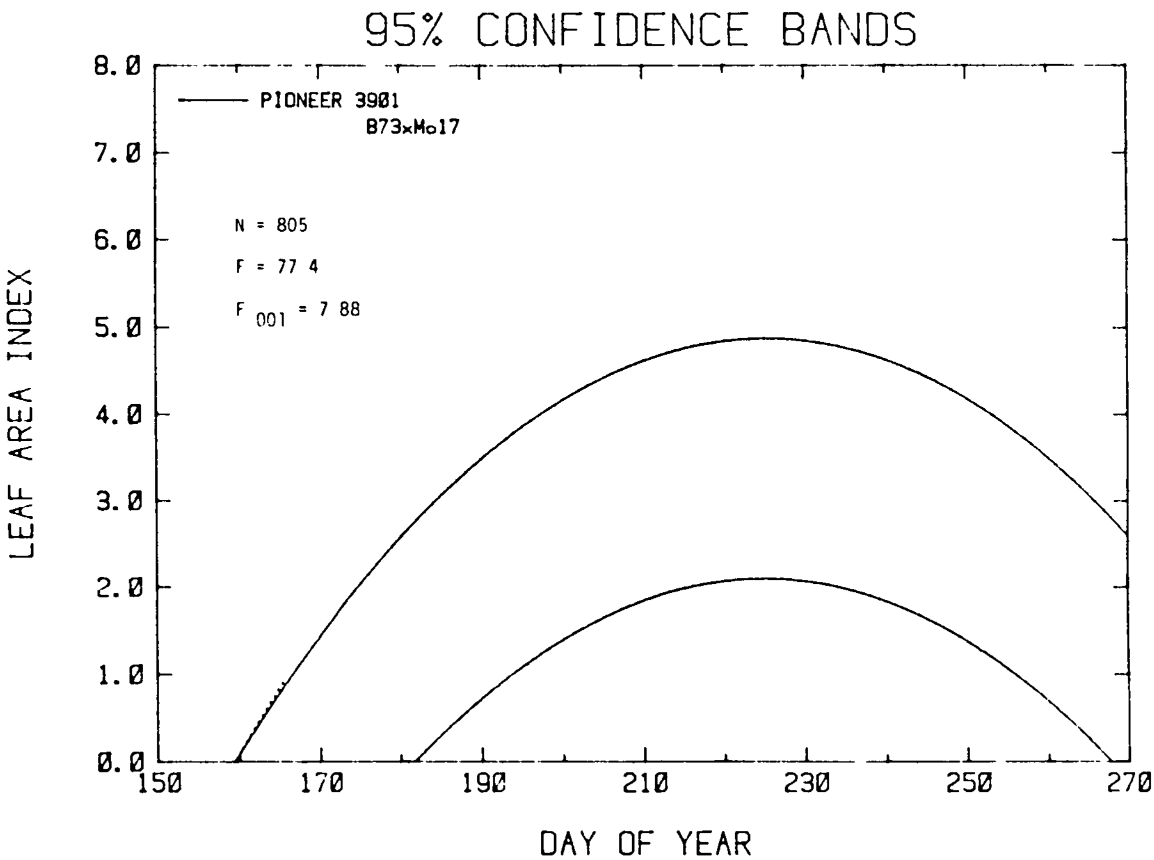


Fig. 4.35 Relationship between leaf area index and time for two corn hybrids grown at SAL in 1982. Lines represent the 95% confidence bands (region where at least 95% of the data points are located).

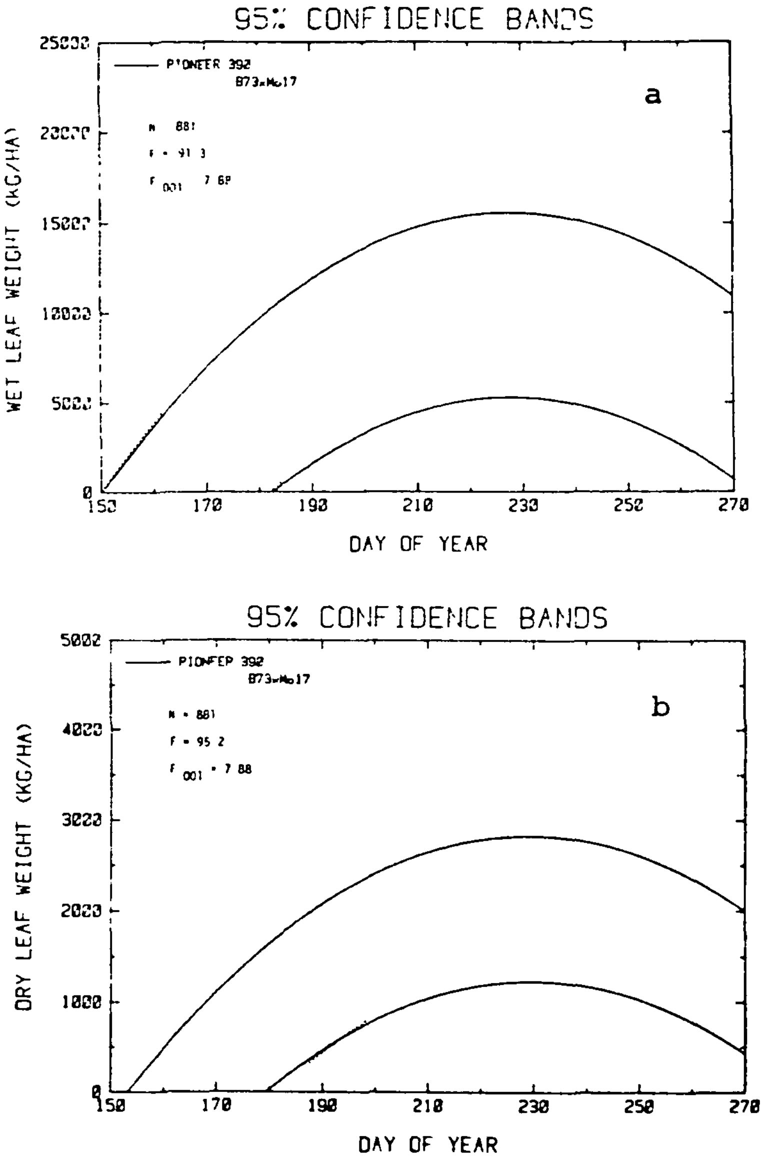
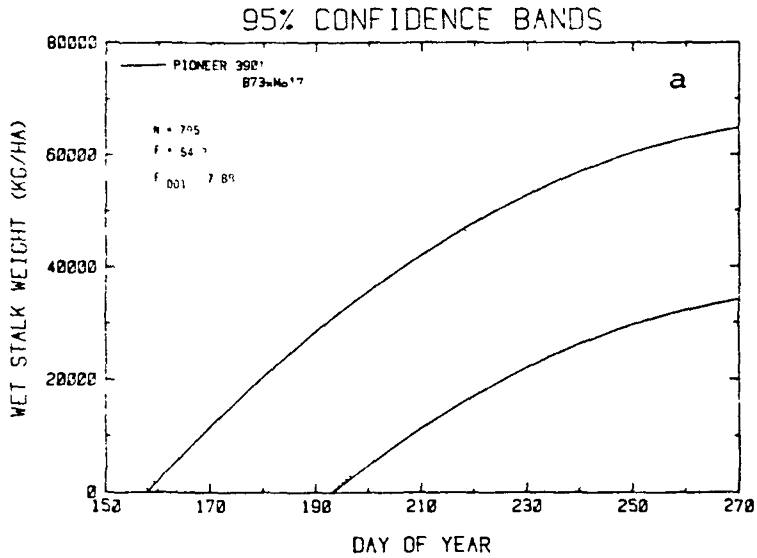


Fig. 4.36 As in Fig. 4.35 for a) wet leaf weight and b) dry leaf weight.



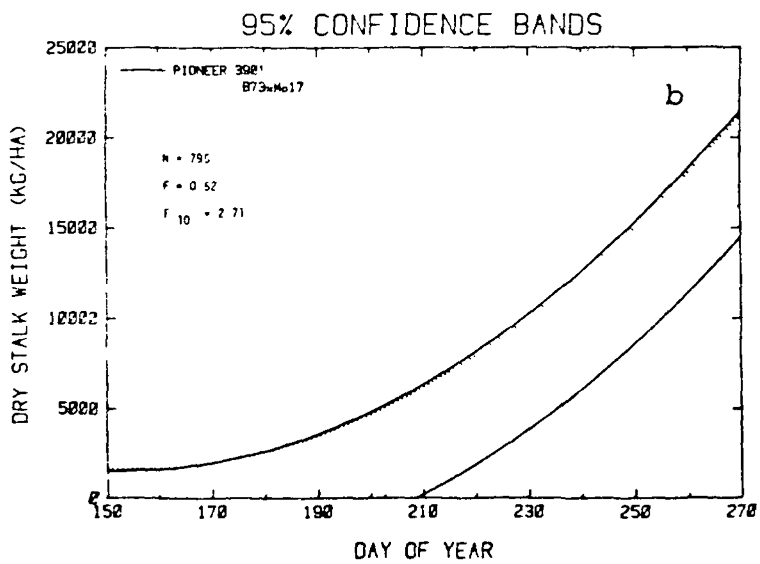


Fig. 4.37 As in Fig. 4.35 for a) wet stalk weight and b) dry stalk weight.

general prediction equations is low.

The relationship between LAI and wet and dry leaf weights was not significantly different for the two hybrids (Fig. 4.38). However, the relationships between LAI and wet and dry stalk weights were different for each hybrid (Fig. 4.39). As expected from considerations of canopy geometry, leaf parameters (LAI and weight) are estimatable with current remote sensing techniques, but developing stalk mass is not.

4.7.2 Effect of Moisture Stress on Agronomic Relationships

The effect of moisture stress on vegetative growth and grain yields depends on the severity of stress and on the stage of growth at which stress occurs (Somerhalder, 1962; Sionit and Kramer, 1977). The plant parts most affected by moisture stress will be the ones that are actively growing during the stress period (Slatyer, 1973). Thus, an understanding of the physiological and morphological development of corn, in relationship to moisture stress, is essential to interpreting the results of moisture stress.

The tasseling/silking stage of corn is the most sensitive to moisture stress in terms of grain-yield reductions (Robins and Domingo, 1953; Denmead and Shaw, 1960; Stewart et al., 1975; Musick and Dusek, 1980; Herrero and Johnson, 1981). The relative sensitivity of the vegetative growth and grain-fill periods appears to depend on the specific stress patterns, however. Stewart et al. (1975) indicated the vegetative growth period was more sensitive than the grain-fill period. Stewart et al. (1977) concluded that the vegetative and grain-fill periods were about equally sensitive to moisture stress. Musick and Dusek (1980) concluded that the grain-fill period was more sensitive to stress than the vegetative period.

The inconsistency of field experiments in determining the relative sensitivity of the vegetative grain-filling periods to moisture stress suggests

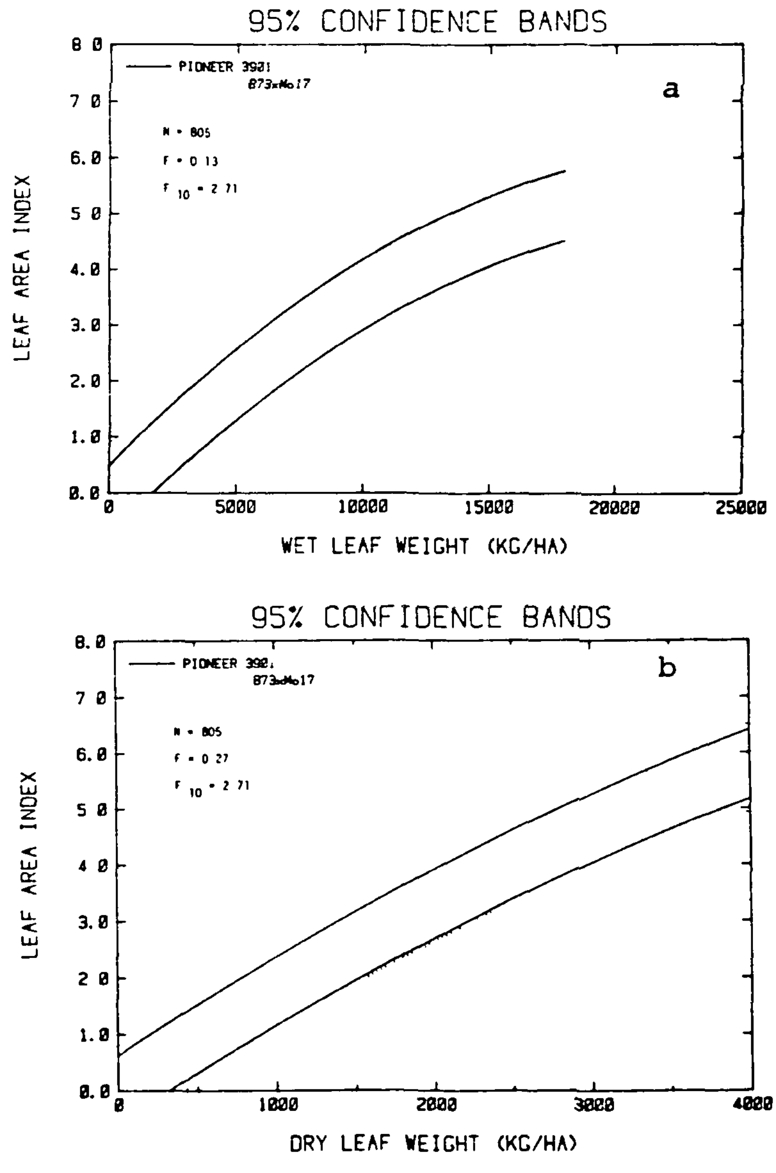


Fig. 4.38 Relationship between leaf area index and a) wet leaf weight and b) dry leaf weight for two corn hybrids grown at SAL in 1982.

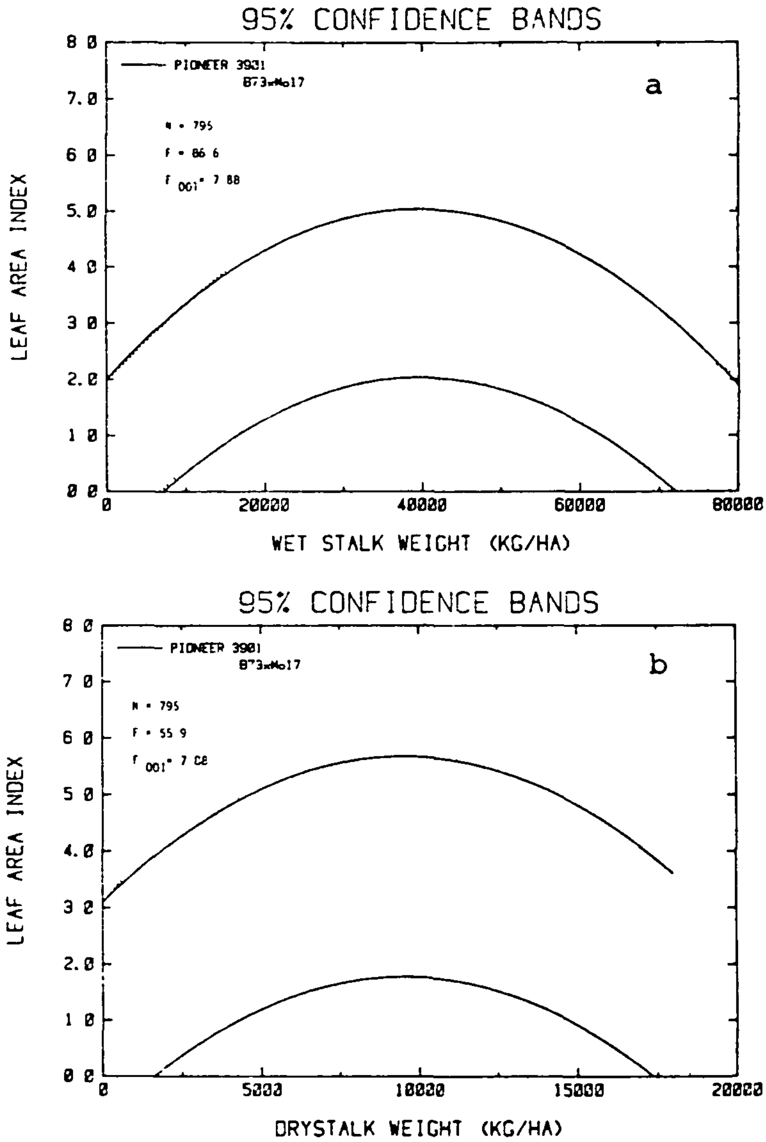


Fig. 4.39 Relationship between leaf area index and a) wet stalk weight and b) dry stalk weight for two corn hybrids grown at SAL in 1982.

that a more detailed description of the timing of stress is needed. The classification of corn development into three stages (vegetative, pollination, grain-fill) is an oversimplification in terms of grain-yield/stress relationships (Table 4.18). Moisture stress can directly affect reproductive plant parts as early as growth stage 2.5 (half-way through the "vegetative growth" period) (Hanway, 1971).

Thus, the occurrence of stress should be described as having occurred, for example, between growth stages 3.5 and 5.0. It is clearly possible for plants to experience sufficient stress that significantly reduces vegetative development without affecting grain yields. This situation could occur if stress was severe before growth stage 3.0, but removed thereafter. Significant grain-yield reductions could be expected if stress was severe between stages 3.0 and 5.0, however. This suggests that moisture stress experiments should be conducted with the objective of inducing stress during specific growth stages. For example, what would be the effect on grain yield if stress was severe during stages 3.0 and 7.0, but removed during the other growth stages? Inducement of stress during specific growth stages is difficult to achieve in field experiments, however. The vagaries of the weather may rapidly alter any preplanned stress treatment. Also, moisture stress does not develop instantaneously upon the withholding of irrigation. Hence, several growth stages will probably be included in any stress period. It is important to realize, however, that plant responses to moisture stress are strongly dependent on the severity of stress occurring at specific growth stages. For this reason, it will be difficult to reproduce specific results from year to year.

4.7.3 Vegetative Growth/Yield Relationship

The relationship between maximum vegetative height and grain yield was

Table 4.18 Sensitivity of corn plant parts to moisture stress as a function of phenological growth stage (Hanway, 1971).

Stage	Description	Moisture Stress Sensitivity
0.5	two leaves fully emerged	---
1.0	four leaves fully emerged, tassel initiation all leaves and ear shoots have been initiated	Vegetative development/height
1.5	six leaves fully emerged; nodal roots now form the major part of the root system. Internodes begin elongating	Vegetative development/height
2.0	eight leaves fully emerged, period of rapid leaf formation. Internode elongation continuing. Tassel beginning to develop.	Vegetative development/height
2.5	Tenth leaf fully emerged; rapid growth of the tassel is initiated; ear shoots begin developing.	Growth and development of the ears. Vegetative height
3.0	Twelfth leaf fully emerged; leaf enlargement is complete. Stalk and tassel are growing rapidly.	Potential size of the ear; potential height of the plant
3.5	Fourteenth leaf fully emerged, stalk is elongating rapidly. Tassel is near full size. Silks are developing.	the number of ovules which develop silks, i.e., the potential number of kernels on the ear.
4.0	Sixteenth leaf fully emerged; tip of tassel emerges from whort; silks are elongating rapidly.	Stress will delay silking more than tassel emergence and pollen shedding.
5.0	The leaves and tassel have been fully emerged for 2-3 days. Pollen begins shedding.	Number of ovules that will be fertilized is determined. Moisture stress may result in poor pollination and seed set.
6.0	Cob, husks and shank are fully developed. Grain is at blister stage.	Number of unfilled kernels.

Table 4.18 (con't)

Stage	Description	Moisture Stress Sensitivity
7.0	Dough stage. Kernels are growing rapidly.	Number of unfilled kernels.
8.0	Embryo growth is rapid. Rapid increase in grain weight.	Number of unfilled kernels.
9.0	All kernels fully dented. Embryo is morphologically mature. Dry matter accumulation in the kernels begins decreasing.	----
10.0	Dry matter accumulation has ceased. Grain continues to dry. Physiological maturity.	----

similar for both hybrids. Taller plants tended to have higher grain yields (Fig. 4.40). This relationship was more significant for Pioneer 3901 than for B73xMo17. Care must be taken in interpreting these results, however.

Vegetative height is determined by the pattern of moisture stress between stages 0 and 5.0, but grain yield is also strongly correlated with canopy ET during the grain-fill period (Mauer, 1981). The short plants in this study transpired less water between stages 5.0 and 10.0, thus reducing potential grain yield. Hence, the high correlation between vegetative height and grain yield for Pioneer 3901 (Fig. 4.40) is indicative of the relationship between yield and transpiration during the grain-fill period (Fig. 4.41) rather than the effects of moisture stress during vegetative growth.

The pattern of soil moisture differences in Pioneer 3901 did not become consistent with the grain-yield patterns until after growth stage 5 (Fig. 4.42). The soil moisture patterns in B73xMo17 were consistent with grain-yield trends by growth stage 3.0. The growth stage at which yield reductions occurred may be implied from these data. Note that the only major soil moisture differences to occur between the two highest yielding classes (yield classes 7000-8000 and 8000-9000 kg/ha) of Pioneer 3901 occurred between growth stages 4.0 and 6.0. The plots with the lowest yield (yield class 1500-4000 and 4000-5000 kg/ha) had significant soil moisture differences only between stages 3.0 and 4.0. This corresponds to the period of time when the tassel is growing and the silks are developing inside the plant.

The importance of stress during the vegetative period on grain yield was evident in B73xMo17. Grain-yield potentials appear to have been determined between stages 3.0 and 7.0. Note that the major soil moisture differences between plots with 1500-4000 kg/ha and 4000-5000 kg/ha occurrred between stages 3.0 and 4.0.

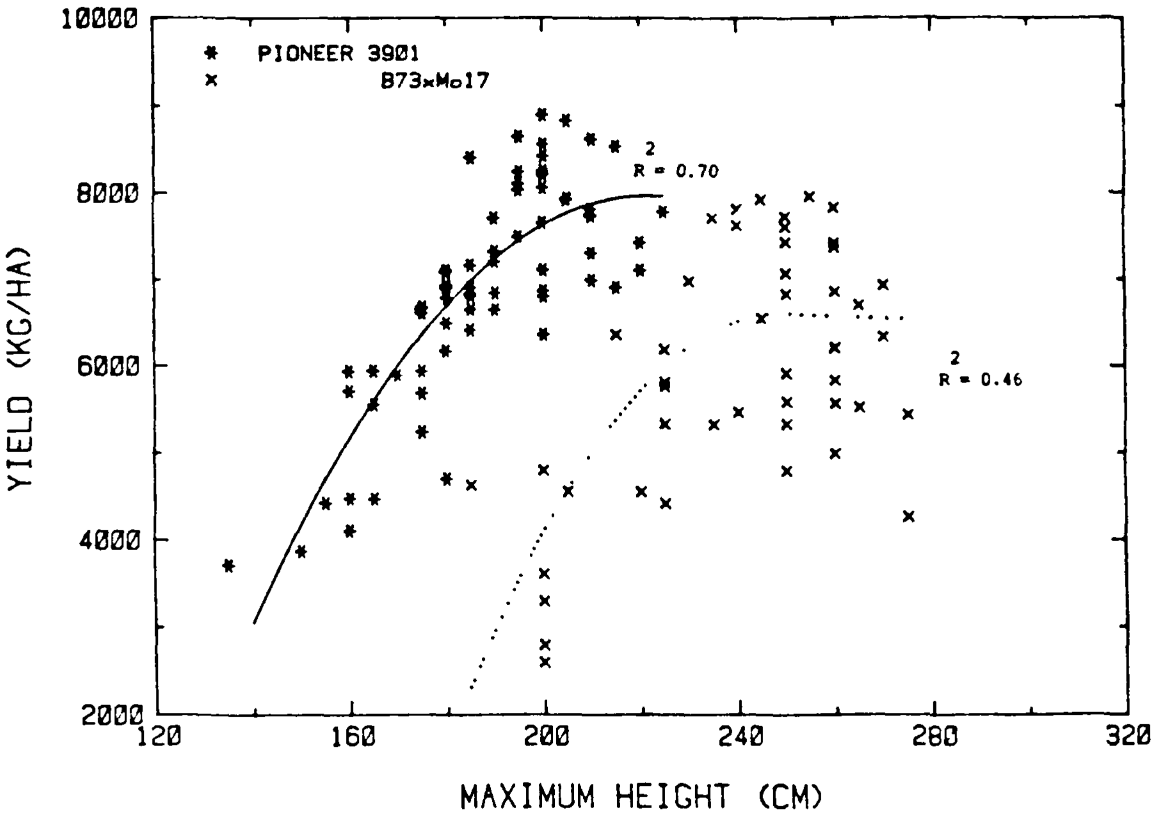


Fig. 4.40 Relationship between grain yield and maximum canopy height for two corn hybrids grown at SAL in 1982.

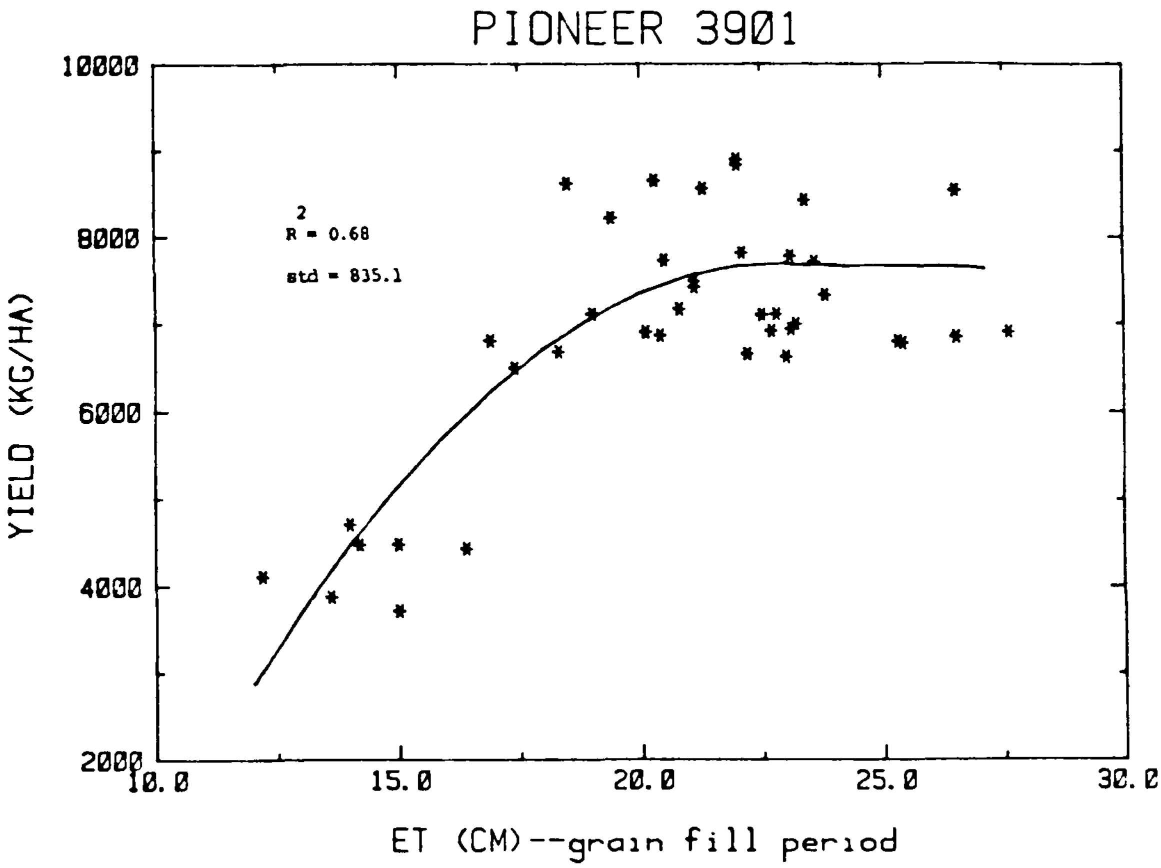


Fig. 4.41 Relationship between grain yield and evapotranspiration (ET) during the grain-fill period for Pioneer 3901 at SAL in 1982.

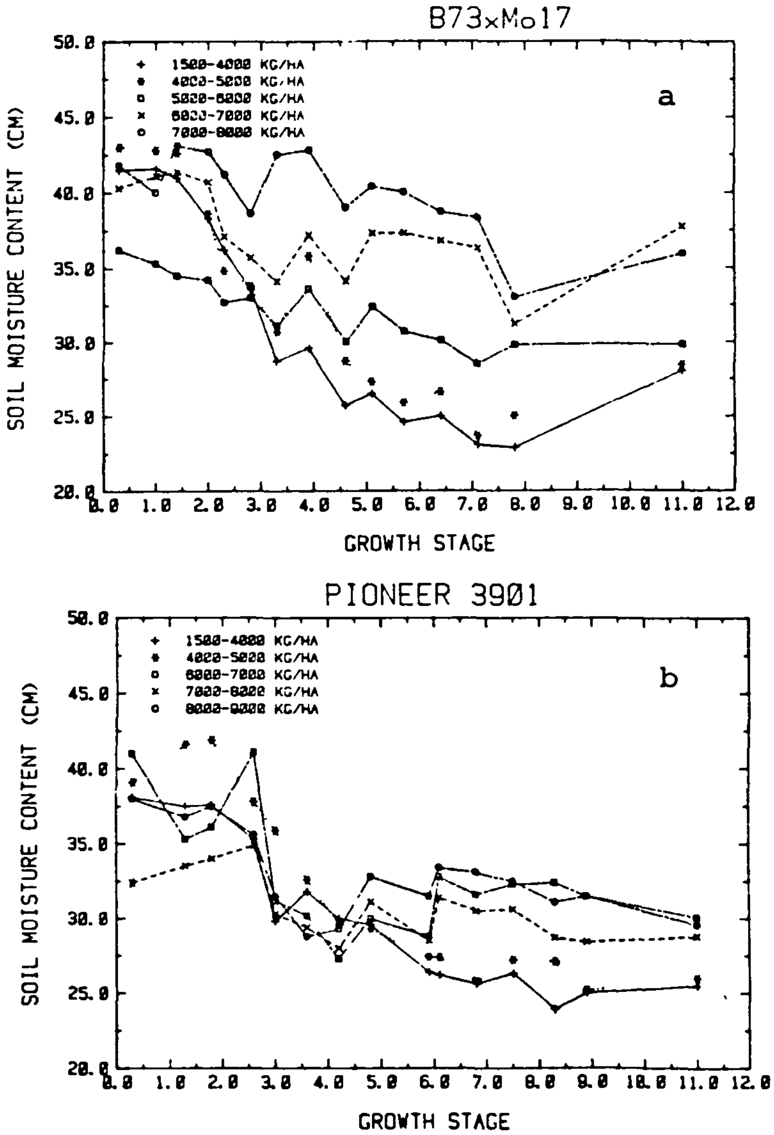


Fig. 4.42 Soil moisture content versus phenological growth stage for two hybrids of corn in 5 grain-yield classes at SAL in 1982.

These results support the general statement that the pollination period (stages 5.0-6.0) is the most important in terms of grain yield. They do, however, show that care must be taken in assuming that moisture stress before tasseling will not significantly affect grain yield. This appears to be true for moderate stress, but not for severe stress. Varietal sensitivities to moisture stress are also an important factor in determining the effect of vegetative stress on grain yields.

4.7.4. Effect of Moisture Stress on Phytomass Components

The seasonal relationship between leaf area and phytomass development and grain-yield class was similar for all components. Plots with high LAI and high phytomass tended to have high yields, while plots with low phytomass tended to have low yields. Plots with similar phytomass differed by as much as 1000-2000 kg/ha at all yield levels (Figs. 4.43-4.47). These results are further indication of the complex interaction between stress during the vegetative and grain-fill periods.

4.7.5 Phenology Relationships

There was a distinct difference in the phenological development of the two corn hybrids (Fig. 4.48). This difference resulted from a slower rate of development in the B73xMO17 hybrid between emergence and growth stage 2.0. Pioneer 3901 matured approximately 15 days before B73xMo17.

Phenology data from plots 13 (B73xMo17) and 18 (Pioneer 3901) were examined to determine the effects of moisture stress on phenological development. Height differences of 75 cm between fully irrigated and dryland plants were present on each plot.

Quadratic equations were fit to the seasonal phenology data as a function of variety and water treatment. R^2 values for all regressions were at least 0.97. No significant differences were detected between fully irrigated and

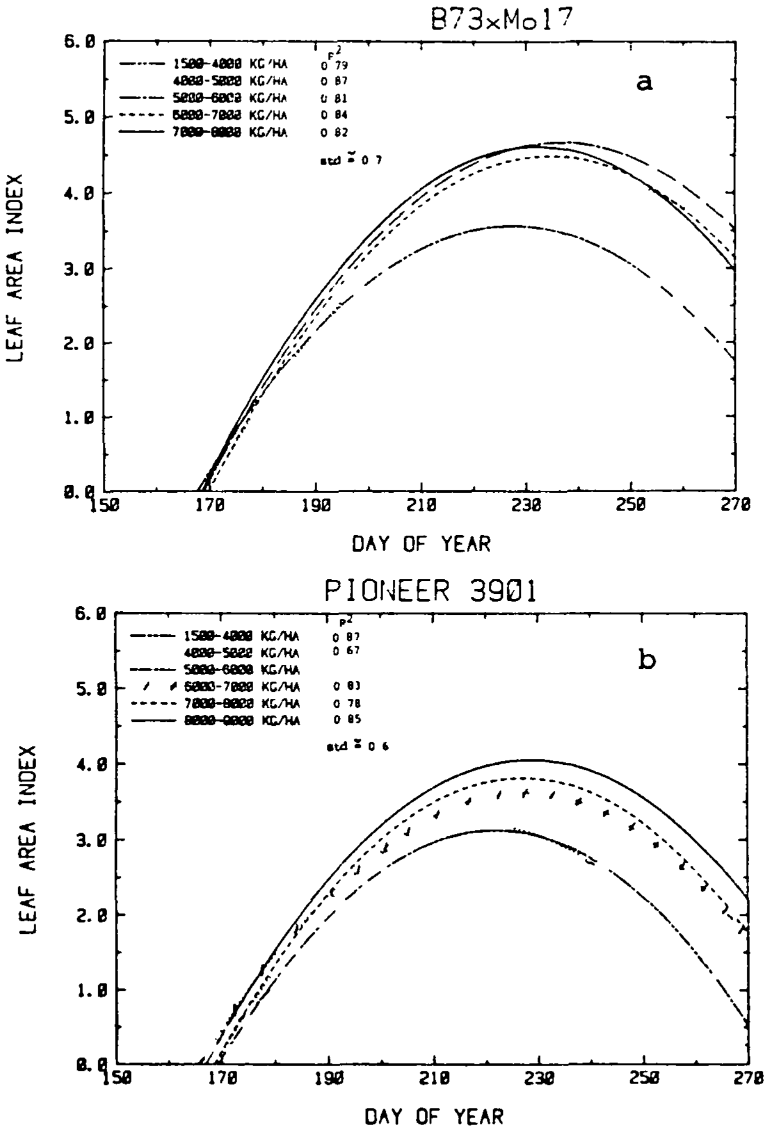


Fig. 4.43 Measured leaf area index trends for two corn hybrids and six grain yield classes at SAL in 1982.

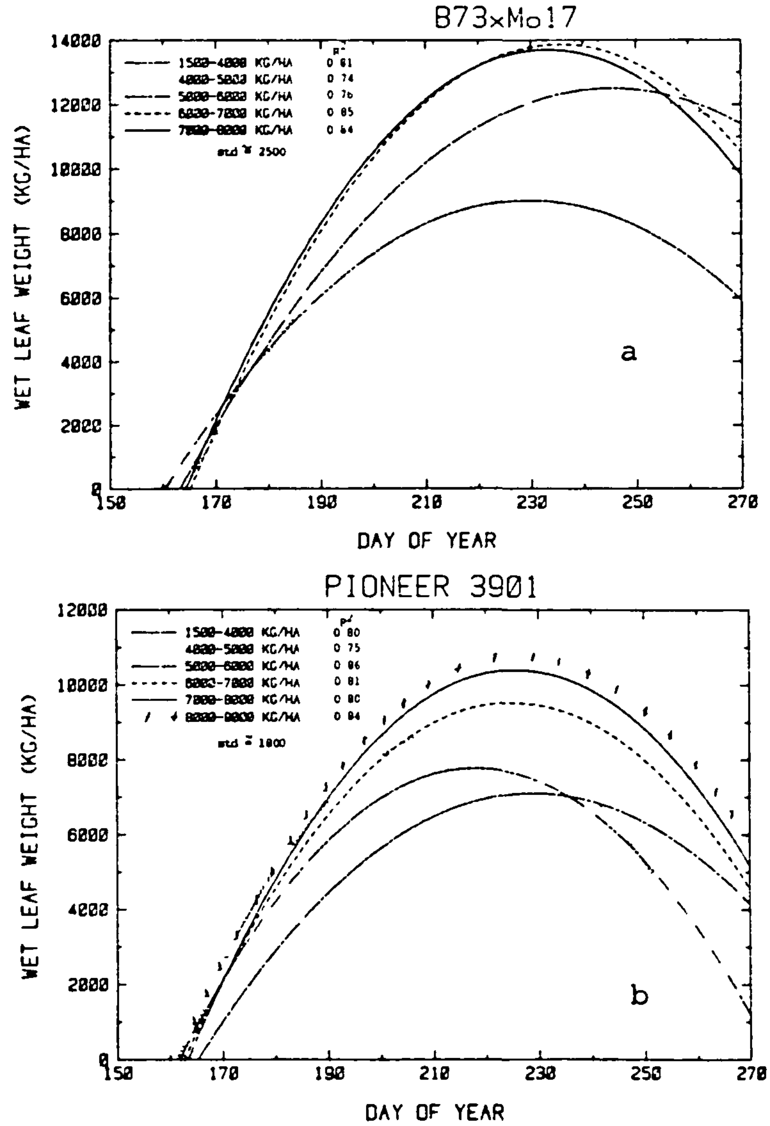


Fig. 4.44 As in Fig. 4.43 for leaf weight.

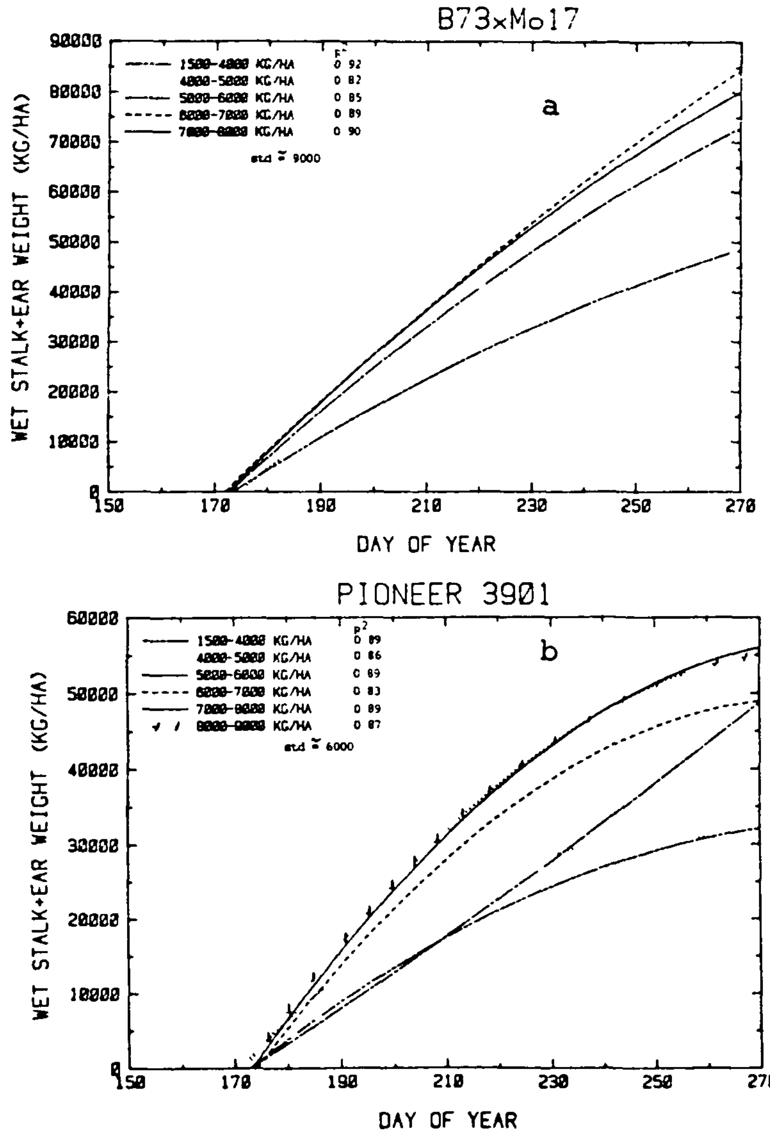


Fig. 4.45 As in Fig. 4.43 for wet stalk plus ear weight.

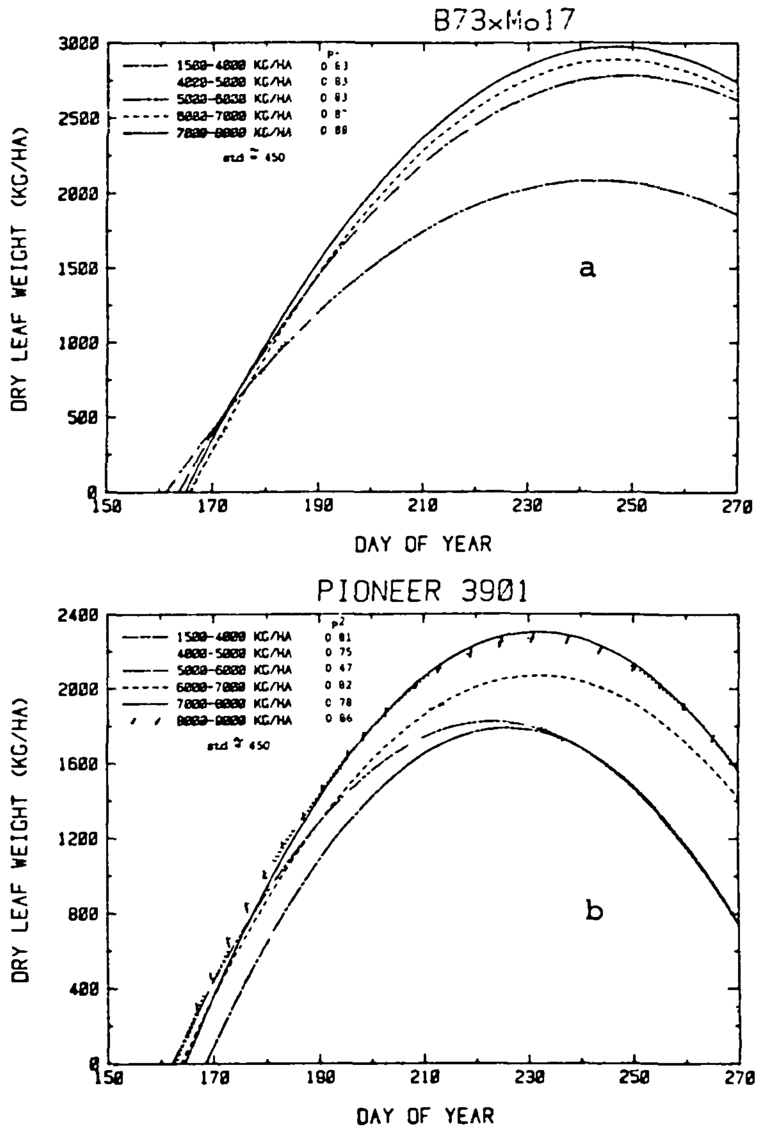


Fig. 4.46 As in Fig. 4.43 for dry leaf weight.

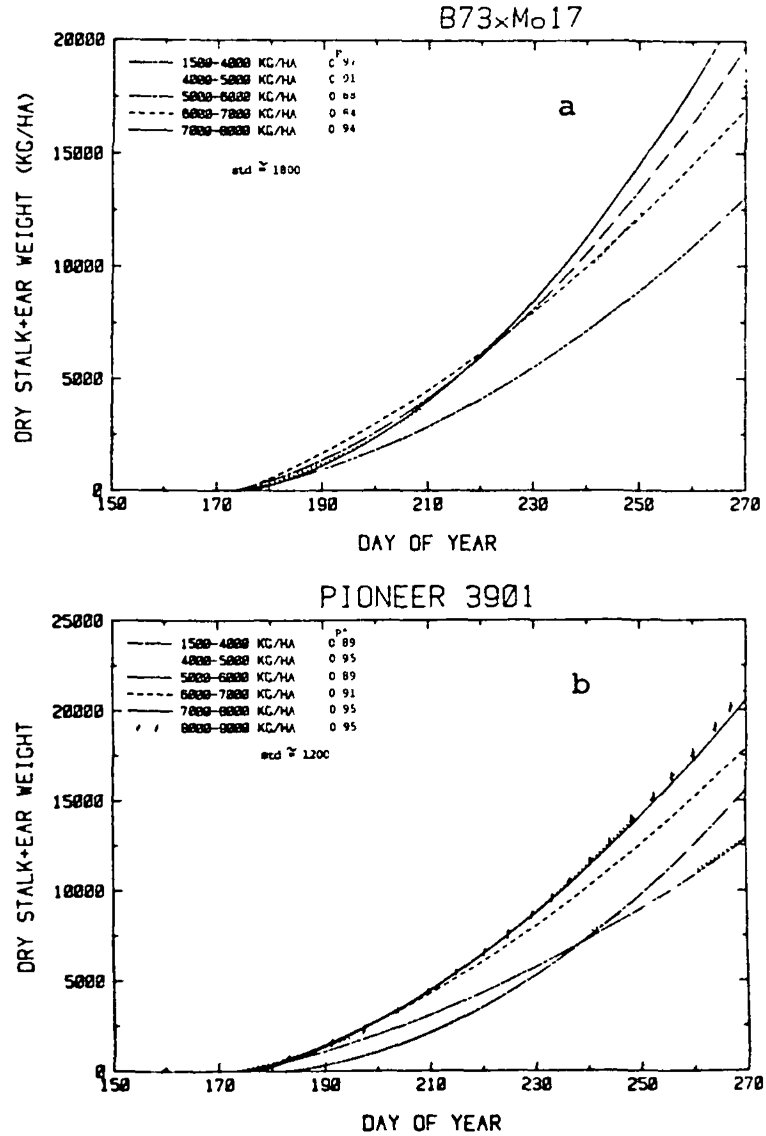


Fig. 4.47 As in Fig. 4.43 for dry stalk plus ear weight.

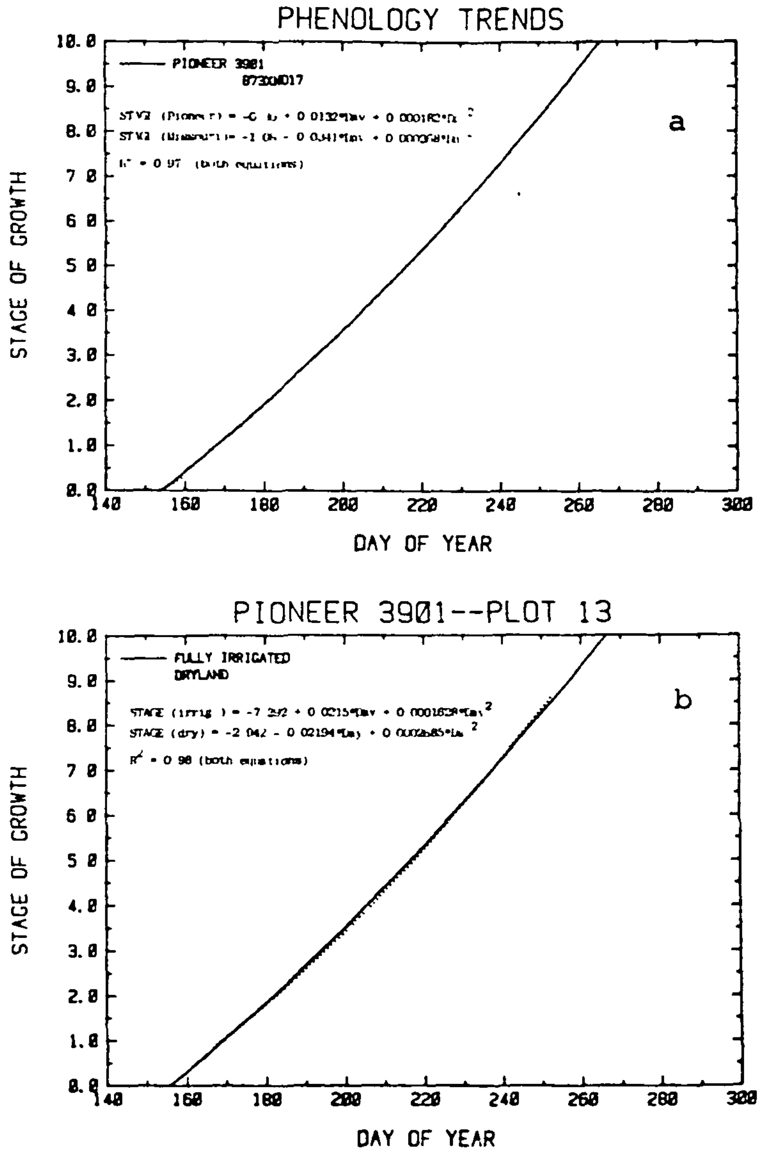


Fig. 4.48 Phenological trends for two varieties of corn a) variety means, b) irrigated versus dryland for Pioneer 3901.

dryland B73xMo17 or between fully irrigated and partially irrigated Pioneer 3901 plants.

There was, however, a statistical difference (alpha = 0.01) between the fully irrigated and dryland plants of Pioneer 3901. These data show that moisture stressed plants developed at essentially the same rate as fully irrigated plants until growth stage 9.0. At this point, plants subjected to moisture stress matured faster than irrigated plants. This trend is predictable since physiological maturity cannot occur until the plants have dried sufficiently. These results agree with previous research on corn at SAL (Gardner, 1979).

4.7.6 Remote Estimations of Phenology

4.7.6.1 Verification of Badhwar and Henderson's Corn Phenology Model

Phenological growth stages cannot be detected directly with remote sensing techniques. Badhwar and Henderson (1981) showed that growth stage could be estimated with canopy reflectance data, however. They concluded that corn is not detectable with reflectance data until Hanway stage 1.0.

Although stated in terms of the greenness transformation, Badhwar and Henderson's (1981) model is based on the assumption that LAI and greenness are highly correlated:

$$\text{stage of growth} = 1.0 + 10^* \frac{\int_{t_e}^{t_1} \text{Greenness } (t)dt}{\int_{t_s}^{t_e} \text{Greenness } (t)\, dt} \tag{4.4}$$

where t_1 is the date for which the growth stage is to be estimated, t_e is the date of spectral emergence and t_s is the date of canopy senescence. In terms of remotely estimated LAI, their model becomes:

$$\text{stage of growth} = 1.0 + 10^* \frac{\int_{t_e}^{t_1} (\text{estimated LAI})\, dt}{\int_{t_e}^{t_s} (\text{estimated LAI})\, dt} \tag{4.5}$$

This model is essentially a normalized leaf area duration curve.

Daily mean values of estimated LAI (using reflectance Model M86) for both hybrids were used to evaluate equation (4.5). t_e was estimated as day 165 for both hybrids (Fig. 4.49) corresponding to stages 0.8 and 0.6 for Pioneer 3901 and B73xMo17, respectively. The assumption that corn cannot be detected until stage 1.0 is acceptable. t_s was taken as day 285 for Pioneer 3901 and 300 for B73xMo17. These dates are approximately 20 days beyond the occurrence of grain maturity (stage 10.0). This is agronomically consistent since complete canopy senescence does not occur until the matured grain/canopy is sufficiently dried or until the canopy is killed by a frost. For this reason, Badhwar and Henderson (1981) have defined growth stage 11.0 as complete canopy senescence.

Growth stage prediction patterns are similar to those reported by Badhwar and Henderson (1981) (Fig. 4.50). The best agreement occurred before growth stage 6.0. Errors after stage 6.0 systematically increase and then decrease. The largest absolute error was 0.7, at growth stage 8.0. Errors before growth stage 6.0 were less than 0.2.

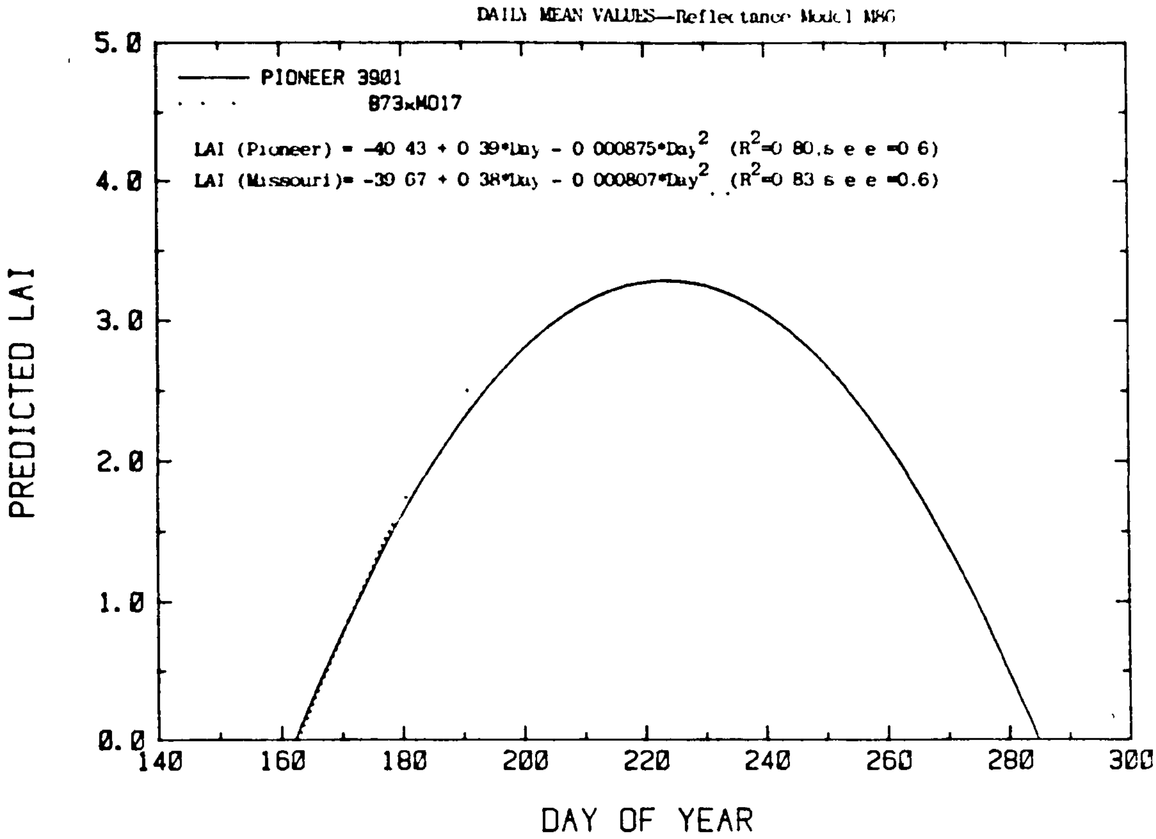


Fig. 4.49 Predicted LAI trends based on estimated values of LAI from canopy reflectance data using LAI model M86.

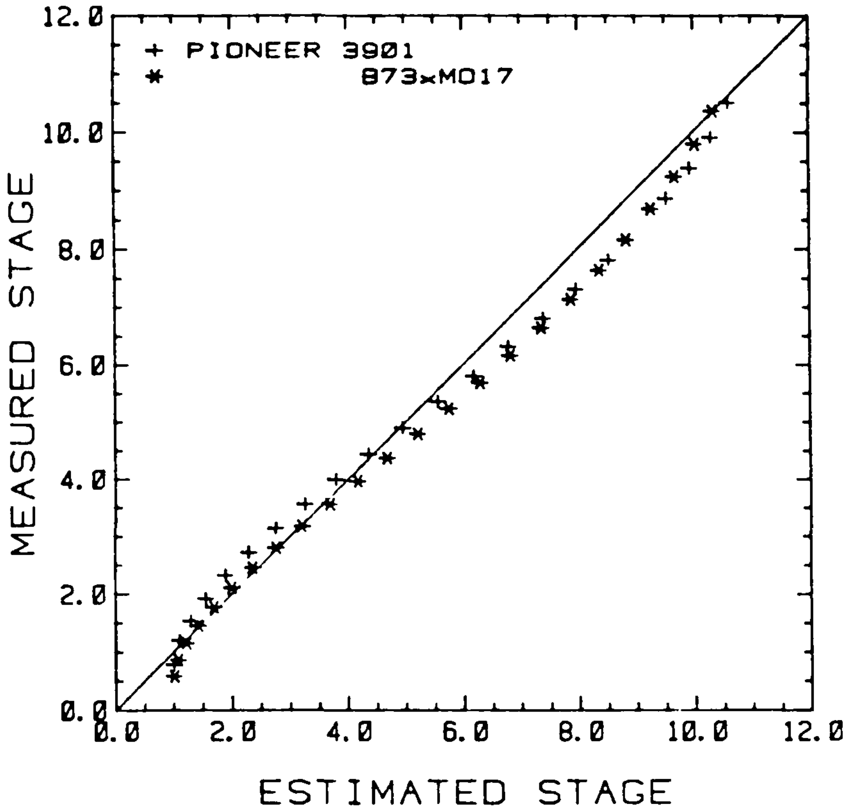


Fig. 4.50 Predicted versus measured phenolgoical stage for two hybrids of corn using the model of Badhwar and Henderson (1981).

The systematic errors produced after stage 6.0 are predictable. Before the beginning of the grain-fill period, LAI is a direct indicator of phenological stage since phenology is measured as a function of the number of emerged leaves. After tasseling, phenology is measured in terms of the development of grain within the ear. Although leaf area does begin to decline at this time, a significant amount of green leaf area may be present when physiological maturity (stage 10.0) is reached. Thus, equation 2 can be expected to systematically overestimate growth stage between stages 6.0 and 10.0. Further investigation is encouraged to determine methods of removing this systematic error.

4.7.7 Seasonal Relationship Between Canopy Temperature Reflectance and Phenology

Before growth stage 3.3 (in corn), there was a positive linear relationship between canopy temperature and reflectance in all wavebands, except the 0.76-0.90 (TM4) and 1.15-1.30 μm (MMR5) bands (Fig. 4.51). In the 0.76-0.90 μm band the relationship was negative. In the 1.15-1.30 μm band, canopy reflectance remained approximately constant throughout the season because of the similarity of canopy and soil reflectance in this portion of the spectrum.

The high correlation between canopy temperature and reflectance is due to bare soil exposed to the view of the sensor. The reflectance of dry soil is high relative to wet soil. Similarly, the surface temperature of dry soil tends to be high during midday while wet soil tends to be cooler. Hence the correlation between canopy temperature and reflectance is really a correlation between soil surface temperature and reflectance.

Between stages 3.3 and 8.3, no correlation was present between canopy temperature and reflectance. As the crop matured, however, and leaves began

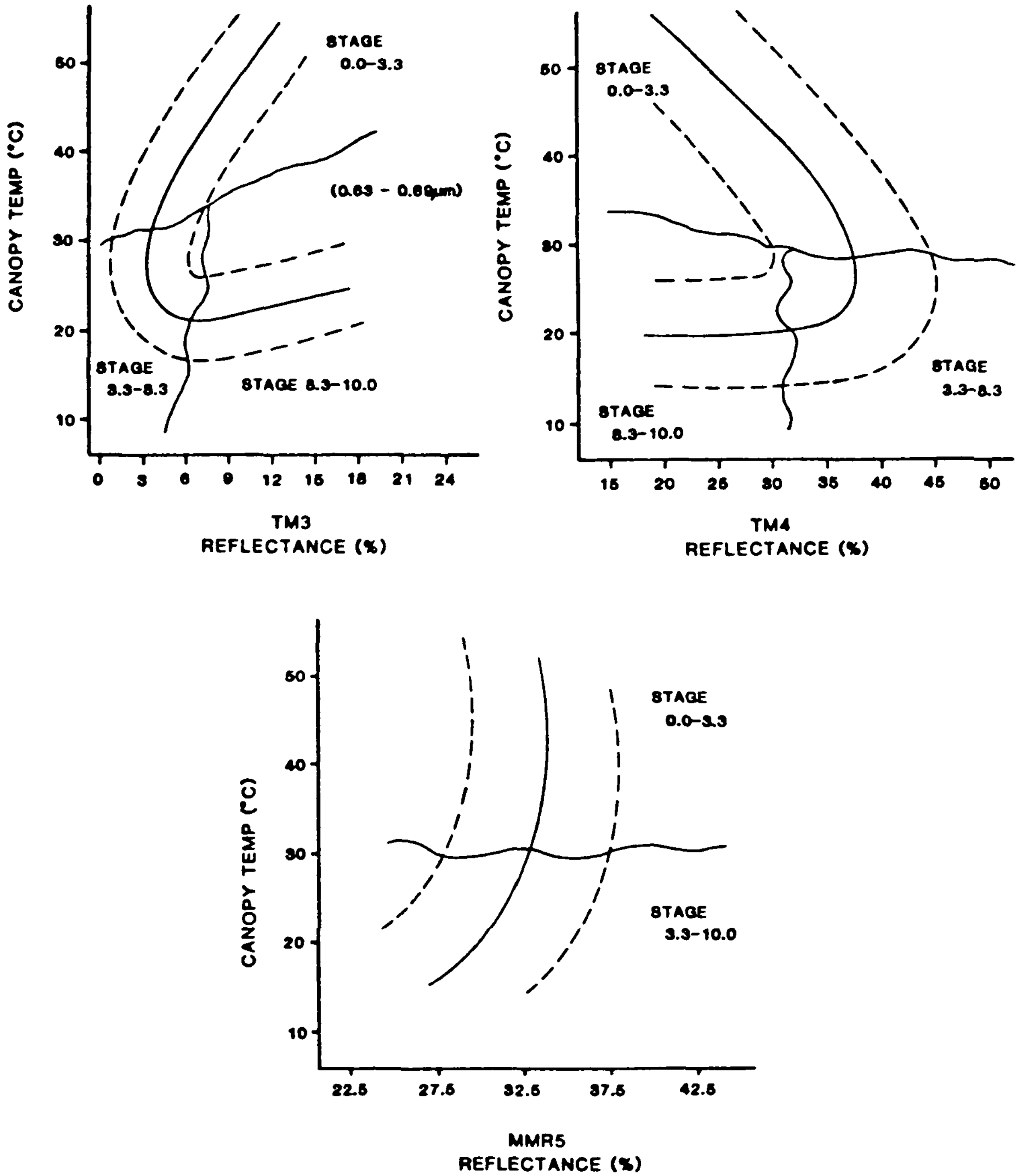


Fig. 4.51 Relationship between canopy temperature and reflectance data for two corn hybrids. Data are omitted for clarity. Dotted lines indicate the extremes of the measured data. Solid lines indicate trends lines.

senescing, canopy reflectance increased although canopy temperature remained relatively cool. In the 0.76-0.90 μm band, reflectance decreased as a result of decreased multiple reflectance.

These results suggest the possibility of using canopy temperature reflectance relationships to infer phenological stage or percent ground cover. These estimates may be useful in decreasing the systematic errors discussed in Section 4.7.6. Frequent observations (at least weekly) would be required. Three general crop stages can be specified: a) precanopy cover; b) midseason; c) dry-down or grain-fill period.

4.8 Design Considerations for Planning of Intensive Remote Sensing Field Experiments

Two approaches are possible in designing remote sensing field experiments. Approach 1 is to use regression analysis to treat the data from an entire season as a single data set. General conclusions concerning differences between treatments can be reached. This approach allows the use of many treatments, with relatively few replications, since hidden replication occurs as the plots are sampled periodically throughout the season. This is the design approach generally employed at the Sandhills Agricultural Laboratory.

The second approach is to use Analysis of Variance techniques to analyze data on an intensive (day-to-day) basis. This means that many replications must be available, thus limiting the total number of possible treatments, but this method has several advantages over approach 1. Data collected on a single day can be independently analyzed and definitive conclusions reached. Detailed data analysis is possible. Day-to-day differences can be interpreted with confidence. The number of days throughout the season on which data is collected is not a primary concern, as it is in approach 1.

The purpose of this section is to describe the theoretical sample sizes needed to conduct agronomic and remote sensing research using approach 2. Confidence levels for appropriate statistical tests will also be discussed.

4.8.1 Statistical Analysis of Intensive Remote Sensing Field Experiments

"When appropriate, data must be analyzed and summarized by statistical methods" (Buxton, 1982). Statistical methods are particularly appropriate for remote sensing applications since the inherent randomness of biological material creates many incidental variations that tend to obscure characteristic differences among classes of interest, such as crop type or moisture stress levels (Swain, 1978).

One major purpose of statistical theory is to help an investigator determine objectively whether means from two different treatments are the same. If statistical theory declares that the two means are different, then it can be concluded, with a known level of confidence, that they are different. But, when statistics fail to indicate a difference between two means, caution must be exercised in concluding that the two means are, in fact, the same. The experimental design or the data precision may be inappropriate for the detection of the desired differences (Steel and Torrie, 1980).

4.8.2 Statistical Errors

Regardless of which conclusion is reached, there is a possibility it is wrong. Type I error (alpha) is the probability of stating that significant differences exist between two means that come from the same population. Type II error (beta) is the probability of failing to detect a significant difference between two means that come from different populations. The power of a statistical test (1-beta) is the ability of a statistical test to detect differences between means that come from different populations (Steel and Torrie, 1980). Clearly, both alpha and beta levels should be low. When an experiment is designed to detect differences, beta is the error rate of concern.

When results are reported for statistical tests between treatment means, it is important to report the most appropriate error rate. If the conclusion is reached that two samples are different, then alpha is the appropriate error. If the conclusion is that the two samples are not different then beta is the appropriate error rate. Alpha and beta are not necessarily the same for a given set of data.

4.8.3 Tests of Significance

The size of the sample from which a test of significance is calculated is extremely important. With a small sample, statistical differences can be found only when the measurements differ greatly. Thus, an investigator using small samples can only say, when no differences are found, that the sample size is too small to adequately test for differences. With large samples, even extremely small differences between two measurements will be declared significant. Hence, the investigator may then state, "Although statistically significant, the difference was too small to be of practical importantance, and was ignored in the subsequent analysis" (Snedecor and Cochran, 1976, p. 29).

4.8.4 Calculation of Sample Size

The number of replications available for tests of significance is extremely important. With only a few replications, statistical differences can be detected only when the differences involved are large. When many replications are available, even extremely small differences will be declared statistically significant. It is the experimenter who must decide whether a statistically significant difference is of any practical importance (Snedecor and Cochran, 1976).

The number of replications per treatment required for an experiment can be calculated directly:

$$r > 2*(Z_{a/2} + Z_b)^2*(s/d)^2 \quad (4.6)$$

where r = number of replications per treatment; s = an estimate of the population standard deviation; d = the true difference to be detected; $Z_{a/2}$ = the Z value associated with a given level of alpha (Type I error); Z_b = the Z value associated with a given level of beta (Type II error). If d is expressed as a percent of the mean, eq. (4.6) becomes:

$$r > 2*(Z_{a/2} + Z_b)^2*(CV/P)^2 \quad (4.7)$$

where CV = coefficient of variation of the population of interest and P = the difference to be detected as a percent of the mean. It must be remembered that eq. (4.7) is an estimate of the theoretical minimum number of replications needed. The actual number needed may be greater (Steel and Torrie, 1980).

The effect of within-treatment variance on sample size is clear, however. Unless the coefficient of variation is relatively small, the number of replications required to detect small differences rapidly becomes impractical (Fig. 4.52). The number of replications is also dependent on the levels of alpha and beta chosen (Table 4.19).

Equation (4.7) also provides a tool for critically analyzing data reported in the literature. Many results are reported for which "no significant differences" were detected. Yet the error level reported is alpha, not beta. Assume, for instance, that the results of a paired t-test comparing CO_2 fluxes using 20 data points over two different canopies indicate no significant difference. The results may be reported as having an error probability

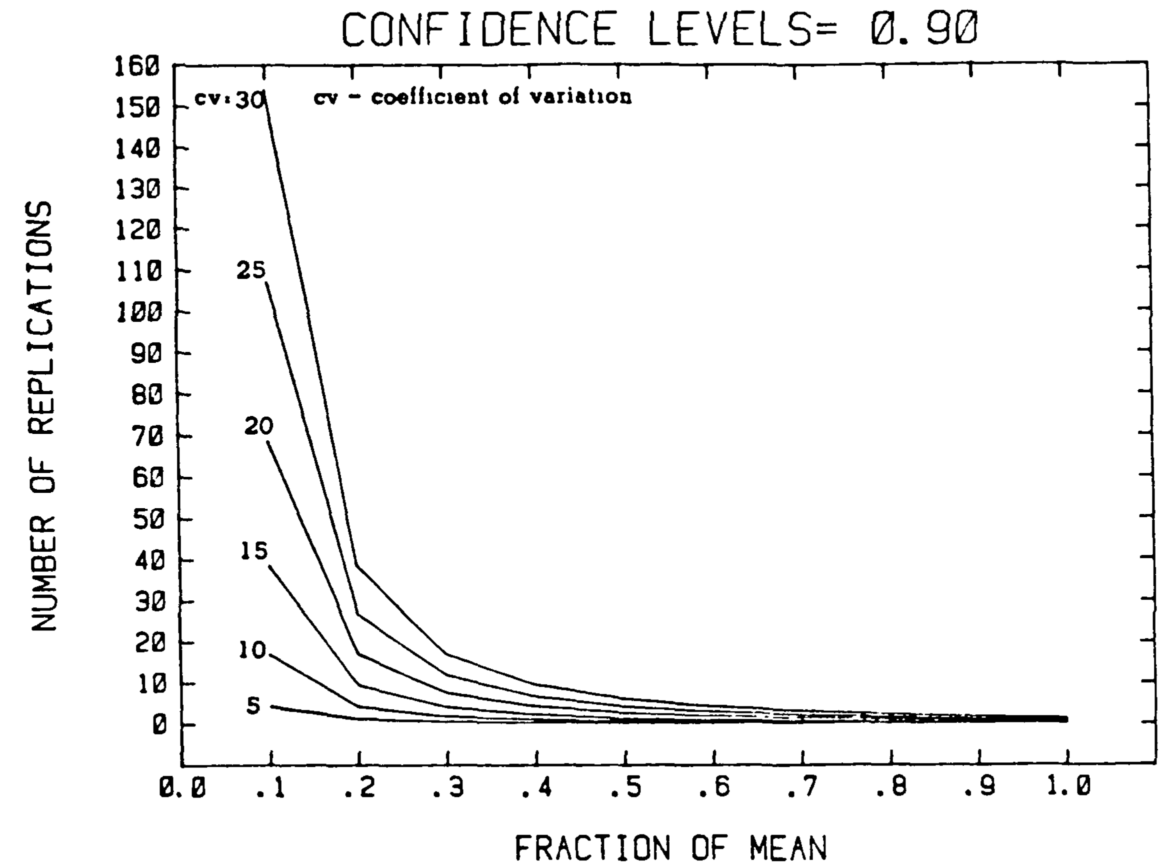


Fig. 4.52 Theoretical number of replications needed for experiments with alpha and beta levels of 0.10, as a function of the coefficient of variation of the experimental material and differences to be detected as a fraction of the mean.

Table 4.19 Replications needed for alpha and beta. Differences as a percent of the mean.

OBS	CV	1%	3%	5%	8%	10%	15%	20%
				Levels of .01 and .01				
1	1	29.6	3.29	1.186	0.463	0.296	0.1317	0.0741
2	5	741.0	82.33	29.640	11.578	7.410	3.2933	1.8525
3	10	2964.0	329.33	118.560	46.312	29.640	13.1733	7.4100
4	15	6669.0	741.00	266.760	104.203	66.690	29.6400	16.6725
5	20	11856.0	1317.33	474.240	185.250	118.560	52.6933	29.6400
				Levels of .05 and .05				
1	1	25.9	2.88	1.037	0.405	0.259	0.1152	0.0648
2	5	648.0	72.00	25.920	10.125	6.480	2.8800	1.6200
3	10	2592.0	288.00	103.680	40.500	25.920	11.5200	6.4800
4	15	5832.0	648.00	233.280	91.125	58.320	25.9200	14.5800
5	20	10368.0	1152.00	414.720	162.000	103.680	46.0800	25.9200
				Levels of .1 and .1				
1	1	17.06	1.896	0.682	0.267	0.1706	0.0758	0.0426
2	5	426.50	47.389	17.060	6.664	4.2650	1.8956	1.0662
3	10	1706.00	189.556	68.240	26.656	17.0600	7.5822	4.2650
4	15	3838.50	426.500	153.540	59.977	38.3850	17.0600	9.5962
5	20	6824.00	758.222	272.960	106.625	68.2400	30.3289	17.0600

of alpha = 0.05. Further, assume that the coefficient of variability of the differences in the paired data points is 20%. Solving eq. (4.7) for Z_b, beta can be calculated (Table 4.20). It can be seen that beta is dependent on the size of the differences to be dectected. If 10% differences are desired, then beta = 1.0, a 100% probability of error. If 20% differences are desired, then beta = 0.12. It is clear that when statistical t-tests indicate no significant differences, beta should also be reported. If beta is not reported, then it is implied that alpha=beta. In this example, we could only conclude at beta = 0.05, that differences of 20% or greater did not exist in the CO_2 fluxes.

Equation (4.4) or Tables 4.19-4.20 can now be used to determine the number of replications needed for intensive remote sensing experiments. Mean daily coefficients of variation (data was obtained over a 2-4 hour period) for nonstressed plots resulted in CVs ranging from 4 to 17%. The majority of values were in the 5-10% range (Table 4.21). Note the low CV values for canopy temperature. Transforming the data (model M86) significantly increased CVs before day 200, the time period before 100% soil cover. After day 200, transforming the data reduced CV values by approximately 50%. CV values of around 5% for transformed data were typical.

4.8.5 Agronomic Design

It is also important to characterize plots agronomically. Coefficients of variability for agronomic parameters are typically in the 20-30% percent range (Table 4.22). This means that the number of replications needed for detecting agronomic differences of 15% or less is very large. Assuming CVs are 20% and differences are selected at alpha and beta levels of .05, 26 replications per treatment would be required. If alpha and beta are increased to 0.1, then 17 replications per treatment would be necessary. Hence, pairing

Table 4.20 Beta levels (probability of type II error) as a function of available replications, coefficients of variability and differences to be detected (D) as a percent of the mean. Alpha (type I error) is assumed to be 0.05.

Coeff. of Variation	Number of Replications 5	10	15	20	25	30	40	50	75	100
					D = 5% of the mean					
5	1.0	0.39	0.22	0.12	0.06	0.03	0.006	0.001	0.000	0.000
10	1.0	1.0	1.0	1.0	1.0	1.0	0.39	0.29	0.14	0.06
15	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.47	0.34
20	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
					D = 10% of the mean					
5	0.11	0.006	0.0002	0.00	0.00	0.00	0.000	0.000	0.000	0.000
10	1.0	0.39	0.22	0.12	0.06	0.03	0.006	0.001	0.000	0.000
15	1.0	1.0	1.0	0.44	0.34	0.27	0.16	0.09	0.02	0.003
20	1.0	1.0	1.0	1.0	1.0	1.0	0.39	0.29	0.16	0.06
					D = 20% of the mean					
5	0.00	0.000	0.0000	0.000	0.000	0.0000	0.000	0.000	0.000	0.000
10	0.12	0.006	0.0002	0.000	0.000	0.0000	0.000	0.000	0.000	0.000
15	0.44	0.15	0.05	0.01	0.003	0.0007	0.000	0.000	0.000	0.000
20	1.0	0.39	0.22	0.12	0.06	0.03	0.006	0.001	0.000	0.000

Table 4.21 Coefficients of variability for daily thematic mapper reflectance data over non-stressed corn at the Sandhills Agricultural Laboratory, 1982. LAI Model M86 is included for comparison.

Day of Year	N	TM1	TM2	TM3	TM4	MMR5	TM5	TM7	TEMP	M86
					B73xMO17					
149	5	3.198	2.827	3.147	2.508	2.802	2.669	3.156		-26.8
167	5	1.067	1.488	2.151	1.354	1.837	1.595	1.240		-518.0
172	5	2.674	2.628	3.293	1.298	1.910	2.210	2.233		18.2
179	12	6.770	7.087	9.600	7.094	5.865	5.309	6.481	3.308	15.8
196	21	7.057	7.171	14.750	6.662	4.023	6.175	16.530	4.010	5.6
200	12	5.956	6.826	13.100	8.106	5.099	4.531	14.190	5.009	5.4
201	17	7.574	7.297	12.400	7.116	5.635	7.568	17.380	3.431	4.4
212	5	1.803	4.017	5.279	2.762	2.724	2.991	3.200	3.226	2.0
213	13	10.470	12.690	14.400	6.373	6.724	8.847	13.730	7.319	4.1
220	13	8.966	10.880	9.747	10.310	7.501	6.592	10.650	3.532	5.7
229	13	9.687	10.450	10.960	7.542	6.232	7.153	11.250	3.745	3.2
230	13	8.940	9.494	10.320	8.873	8.145	8.843	11.850	3.100	1.9
235	13	8.737	9.192	9.180	6.503	6.141	7.254	9.414	6.293	3.5
244	13	8.286	7.545	7.906	5.897	5.509	6.469	8.154	3.132	3.1
252	13	5.804	8.677	7.722	5.771	5.605	7.095	9.902	4.741	4.8
261	5	5.647	4.563	6.428	9.926	6.539	5.650	6.700	3.500	7.0
272	13	11.900	10.280	13.980	9.645	7.469	10.440	14.070	6.956	22.5

Table 4.21 (con't)

Day of Year	N	TM1	TM2	TM3	TM4	MMR5	TM5	TM7	TEMP	M86
					Pioneer 3901					
149	12	7.207	8.644	8.913	7.350	5.017	3.729	2.986		-38.9
167	13	6.753	7.781	8.952	6.479	5.949	5.544	4.233		323.3
172	13	11.200	10.840	11.230	7.850	5.795	6.095	5.633		77.8
179	25	12.640	13.120	16.730	8.835	7.382	8.994	11.330	7.710	32.2
194	10	25.530	22.580	36.140	7.328	4.818	16.580	30.650	13.538	29.5
195	12	6.732	5.951	14.090	10.330	5.513	4.829	14.530	6.501	8.4
200	16	4.937	5.195	8.774	5.780	3.251	2.553	8.662	6.134	4.6
201	33	5.539	6.752	12.600	8.616	5.151	5.478	11.910	4.500	7.5
204	10	11.680	11.940	16.390	7.462	7.360	10.050	16.620	4.315	7.0
212	12	6.994	8.591	9.202	6.188	5.026	5.357	8.205	3.201	3.6
213	25	9.161	12.040	10.440	5.965	5.424	7.689	11.360	8.142	5.2
220	25	8.145	8.940	9.313	5.562	5.245	6.994	10.940	5.222	3.6
229	25	6.870	7.774	8.316	6.411	6.276	5.901	8.242	4.474	3.3
230	25	8.212	8.288	9.223	7.734	7.293	7.067	8.343	2.985	2.5
235	25	6.167	5.850	6.469	5.846	5.189	5.360	6.842	6.837	2.7
244	25	5.769	5.688	6.810	5.337	4.542	4.663	5.721	5.233	2.9
245	42	11.180	12.760	12.210	10.640	10.060	11.090	12.570	11.868	5.1
252	35	9.875	12.270	15.140	7.935	6.197	7.599	12.570	16.686	8.8
261	13	9.352	11.250	31.970	11.940	4.355	13.280	30.030	4.369	24.2
272	25	9.472	9.177	8.802	7.618	5.715	6.289	9.351	6.325	13.5

Table 4.22 Coefficients of variability for agronomic parameters from fully irrigated plots of Pioneer 3901 and B73XMo17.

Day of Year	LAI	Wet leaf weight	Wet stalk weight	Dry leaf weight	Dry stalk weight
			Pioneer 3901		
152	--	23.6	--	15.7	--
158	--	18.4	--	23.3	--
167	26.6	24.6	34.1	30.5	36.3
174	24.0	20.2	29.9	20.6	25.8
179	22.6	16.1	21.7	15.1	19.0
189	28.7	24.5	31.4	19.9	20.9
195	40.8	20.6	31.2	19.1	46.0
202	26.6	16.9	18.5	43.4	23.0
212	20.2	20.0	17.2	20.1	18.7
213	19.2	12.1	16.4	13.9	26.4
220	16.2	15.8	11.6	14.7	14.5
235	15.8	12.9	14.1	10.2	14.5
252	10.8	8.2	6.5	7.4	7.0
261	14.9	12.5	7.8	13.5	12.1
			B73xMo17		
152	--	28.5	--	28.9	--
167	56.7	28.8	39.8	26.3	39.7
174	35.0	21.7	31.3	28.0	34.3
179	31.9	27.5	35.3	25.3	29.5
189	40.5	19.4	22.3	12.0	25.9
195	45.2	17.5	31.2	31.5	27.1
202	18.6	19.4	13.4	17.0	21.3
212	28.1	20.3	17.4	23.9	52.9
213	18.1	16.2	16.2	16.9	29.0
220	10.1	15.1	19.3	14.1	21.4
230	11.2	10.5	9.0	7.0	6.8
243	31.6	4.3	7.1	9.7	13.4
261	8.3	6.3	4.2	6.8	29.8

should be used to reduce CVs. If CV's values of paired agronomic data are assumed to be about 10%, eight pairs would be necessary to resolve differences of 15% at alpha and beta levels of 0.1.

The number of replications needed for a remote sensing field experiment thus depends on whether differences are to be measured as a function of individual wavebands or as a function of a data transformation. Sample size will also be affected as a function of data type. Reflectance experiments will require larger samples than thermal experiments. Data analysis procedures will also affect sample size. Paired analysis requires the fewest number of replications.

It is also possible to significantly reduce the required number of replications by reducing or elimininating the various factors that introduce variability into reflectance readings (Table 4.23). The most important factor to control, in terms of experiment design, is the solar elevation angle. This can be controlled indirectly by designing the experiment so that all essential data can be collected within a short period of time (Table 4.24). CVs for transformed data can be reduced to 2-3%.

4.8.6 Diurnal Effects on Reflectance Data

Hourly data were obtained for plot 19 on 2 September between 0800 and 1200 solar time. This plot was fully irrigated throughout the entire season. The data indicate a continuous change in canopy reflectance in all bands. These patterns agree with those reported by Kollenkark et al. (1981). Reflectance was relatively stable, however, in the visible and near infrared bands. Reflectance in the middle infrared bands increased almost linearly as a function of time (Fig. 4.53). Transformation of the data resulted in a linearly decreasing estimate of LAI with time, with a minimum at solar noon (Fig. 4.54).

Table 4.23 Potential sources of non-uniformity in agronomic and reflectance data among plots experiencing similar conditions.

Agronomic Data

a. area of a sample
b. number of replications
c. surface moisture on plant parts
d. diurnal changes in plant weight
e. insufficient drying of large samples
f. extraneous material, e.g. sand, soil, attached to plant parts
g. fertility differences among the plots
h. weed control problems

Reflectance Data

a. changes in solar azimuth and zenith angles
b. diurnal changes in canopy structure
c. soil background differences, e.g., shadowing, soil type, surface residue, slope
d. weeds
e. instrument leveling problems
f. locating of the precise "look area" of the instrument
g. changes in solar illumination characteristics due to haze, clouds or turbidity

Table 4.24 Coefficients of variabiltiy of Thematic Mapper data from Plots 36 and 38 (Pioneer 3901). These plots represent data from non-stressed corn, collected over a 5 minute interval. LAI model M86 is included for comparison.

Day of Year	TM1	TM2	TM3	TM4	MMR5	TM5	TM7	TM6	M86
174	4.2	3.6	5.5	3.3	1.9	2.2	3.2	0.01	38.2
179	6.7	5.6	8.3	5.6	3.1	3.5	5.6	4.9	22.1
195	4.2	3.2	12.2	10.3	5.2	3.2	15.5	8.5	7.7
200	3.0	2.8	7.9	6.4	3.5	1.9	9.1	5.6	4.0
202	2.8	2.9	6.1	6.8	3.1	2.5	9.1	3.9	4.9
213	10.0	11.0	11.1	7.3	6.1	6.6	7.6	4.2	1.7
220	5.7	6.2	6.8	3.8	2.4	2.9	4.8	3.1	2.4
229	8.4	8.4	9.2	8.2	7.5	7.1	8.1	4.6	2.5
230	6.3	6.7	7.4	7.4	7.2	7.1	8.1	1.6	2.2
235	3.0	3.8	4.3	4.0	3.0	2.6	3.4	1.8	2.1
243	3.2	2.5	3.5	4.2	3.5	2.9	2.9	3.0	1.7
252	4.9	6.1	6.1	5.3	4.5	3.9	4.4	1.9	1.6
272	11.1	11.5	10.5	8.8	6.4	6.4	7.6	2.8	6.4

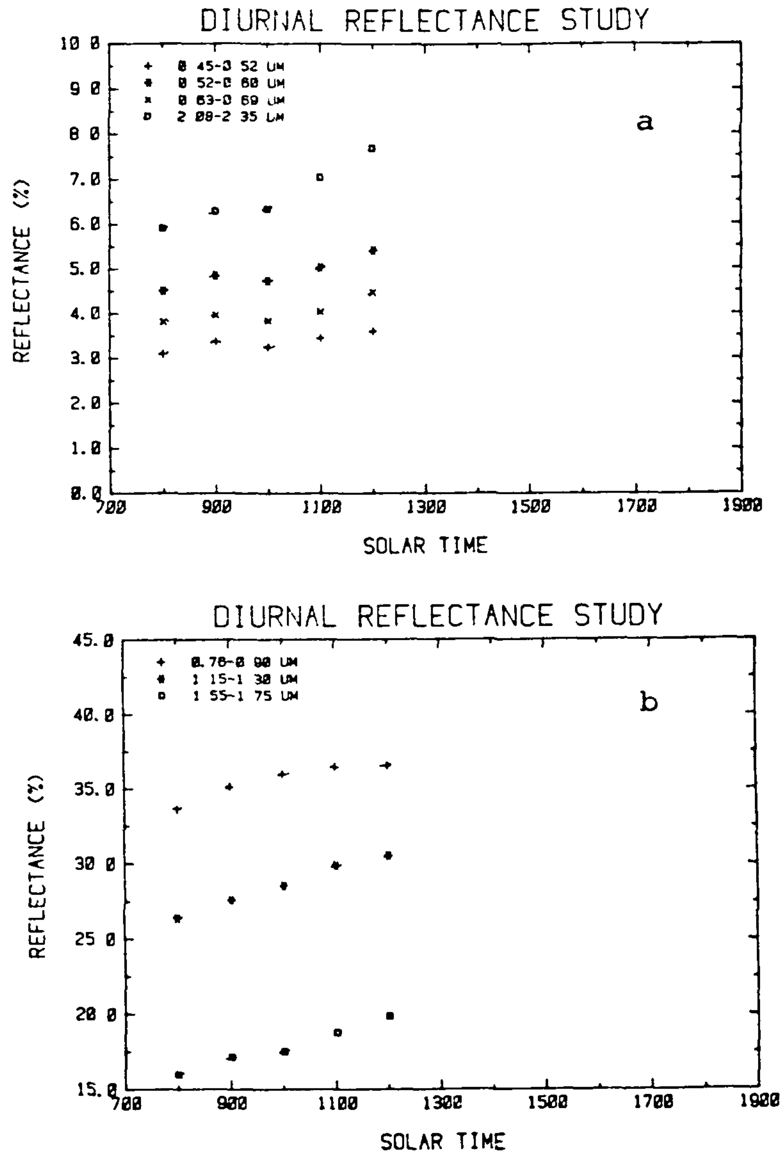


Fig. 4.53 Canopy reflectance over plot 19 in several wavelength intervals on September 2, 1982.

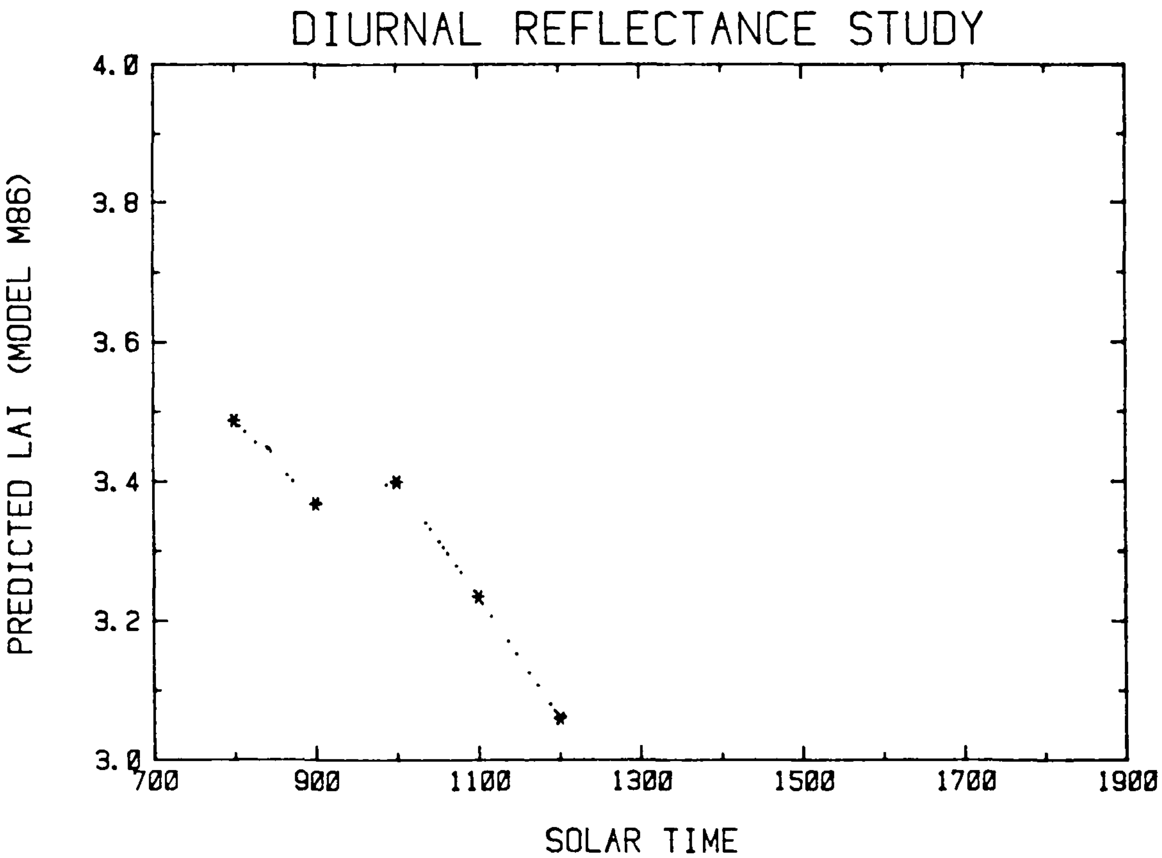


Fig. 4.54 Predicted LAI, using model M86, over plot 19 on September 2, 1982.

These results suggest that reflectance readings for use in paired t-tests should be taken over a short time interval, say 30 minutes or less. More research is needed to develop LAI transformations that are relatively insensitive to diurnal changes in solar insolation.

Vertical canopy temperatures made with either the PRT-5 or Barnes 12-1000 tended to be warmer than angular canopy temperatures made with the Telatemp Ag-42 (Figs. 4.55-4.56). The standard deviation of the regression line was less for the Barnes 12-1000 (3.39 C compared to 4.49 C for the PRT-5), indicating the value of the larger field of view of the Barnes 12-1000. It should be remembered that the Telatemp has a small field of view; it covered an area 300 mm in diameter. Reduced variation in the differences between vertical and angular canopy temperatures could be expected if IRTs having wide fields of view were used. The trends should remain the same.

4.9 Cupid Model Predictions

The comprehensive plant-environmental model Cupid is used to describe the processes and interactions occurring in the soil-plant-atmopshere system with a minimum of input data (Norman, 1979, 1982). Input requirements fall into five classes: (a) ambient environment; (b) plant characteristics; (c) soil characteristics; (d) site factors; and (e) initial conditions. Ambient environmental requirements can be met with remote automated weather station measurements of incident radiation, air temperature, air relative humidity, wind speed and precipitation at several meters above the crop with measurements of soil temperature and soil water at 1 or 2 m depth. The most important plant characteristics needed are leaf area index, leaf spectral properties, leaf angle distribution, canopy height, rooting depth and the dependence of stomatal conductance and photosynthesis on light, temperature and

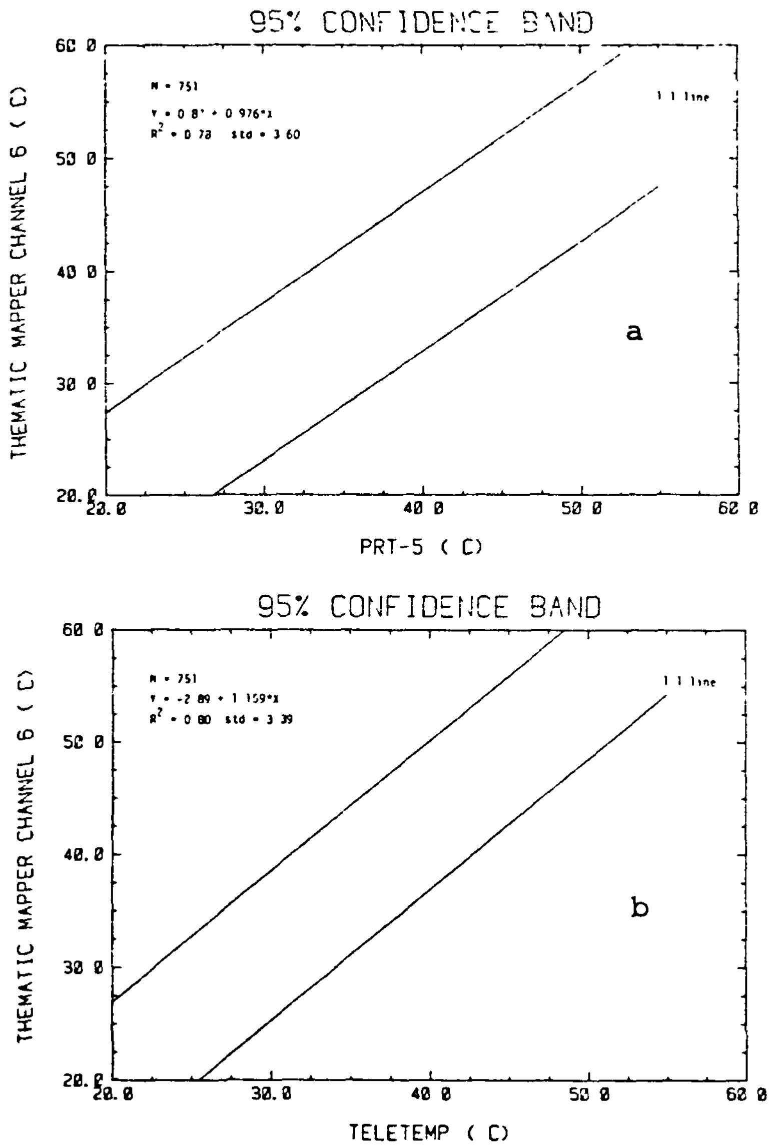


Fig. 4.55 Relationship between corn canopy temperature as measured with the thermal band of the Barnes 12-1000 versus a) a vertically mounted PRT-5 and b) obliquely held infrared thermometer. Data were collected throughout the 1982 season over two corn hybrids at SAL.

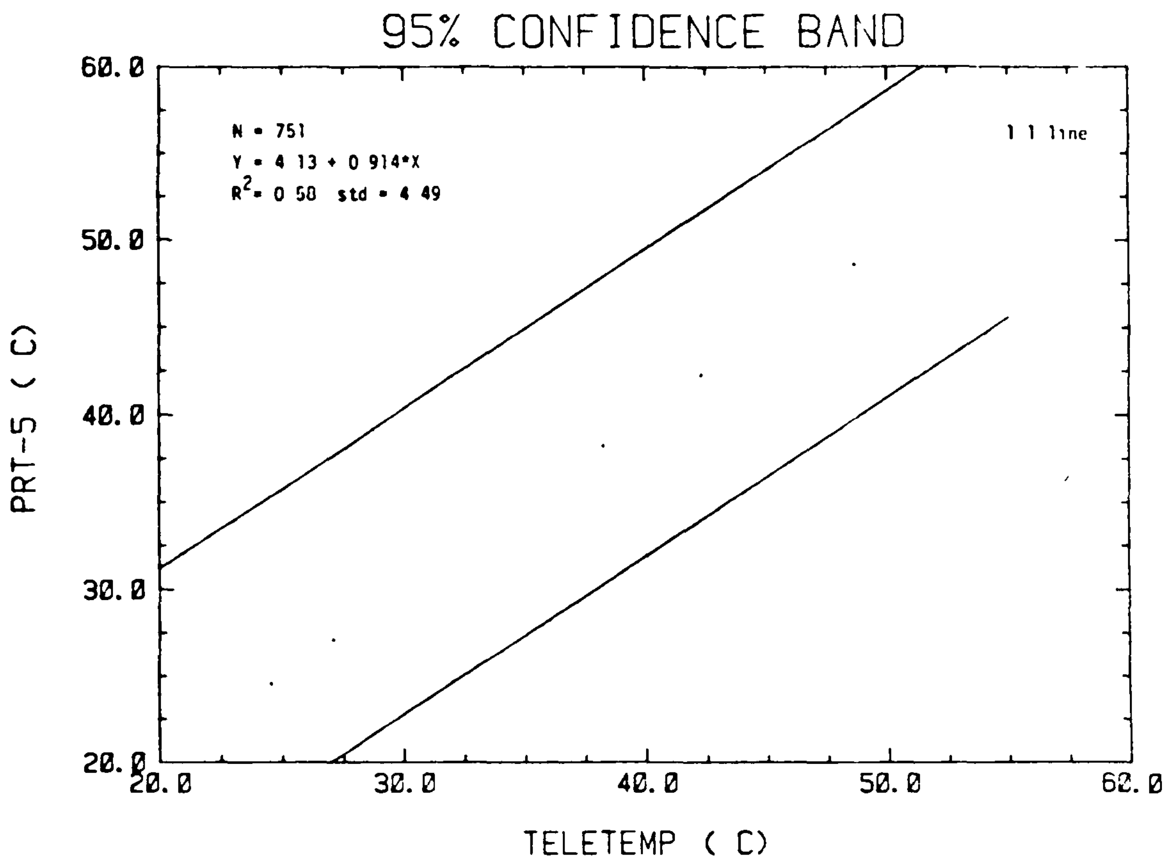


Fig. 4.56 Relationship between corn canopy temperatures measured with a vertically mounted PRT-5 and an obliquely held infrared thermometer. Data were measured on two corn hybrids throughout the 1982 season.

leaf water potential. Soil texture, soil reflectance as a function of soil wetness, bulk density, soil water release curves and thermal and hydraulic properties as a function of water content are important inputs. Site factors like latitude, longitude and slope are simple to obtain. When the model is first started, an initial profile of soil temperature and soil water content is necessary.

The structure of Cupid is based on defining the relation between individual foliage elements and their immediate environment, then integrating over the canopy to determine the collective effect of all the elements considered. To accomplish this result, the canopy is divided into layers and leaves within each layer are divided into leaf angle classes so that radiative exchange processes can be included in a general way. Soil and the atmosphere immediately above the canopy are also divided into layers. This structuring enables the boundary conditions for the soil and atmosphere to be defined so that profiles of radiation, air temperature and vapor pressure, leaf temperature, soil water content, intercepted rainfall or irrigation, dew formation and canopy hemispherical reflectance and canopy bidirectional reflectance can be predicted.

4.9.1 Comparison of Greenness Measured with the MMR and Predicted Greenness from the Cupid Model

The model Cupid can be used to estimate greenness for corn canopies growing at different water stress levels. In this comparison, only GGG plots were used (plots 8, 18 and 20). Treatment 1 is defined as 100% irrigation and treatment 4 is defined as a dryland treatment. Treatments 2 and 3 received intermediate amounts of water. The spectral properties of leaves and soil used in Cupid are summarized in Fig. 4.57. Results are summarized in Figs. 4.58-4.62.

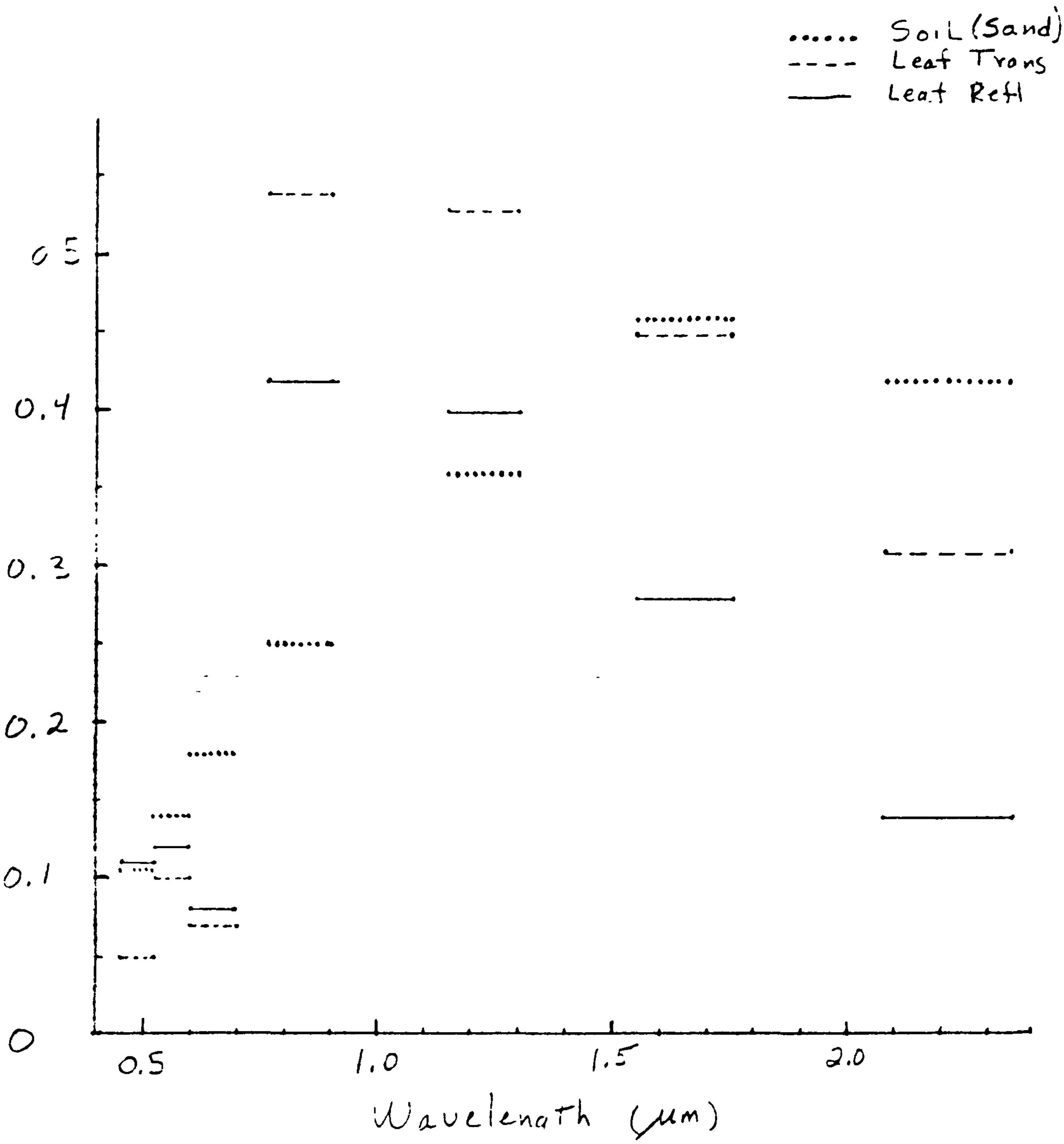


Fig 4.57 Soil and leaf reflectance properties used as inputs into the Cupid canopy reflectance model.

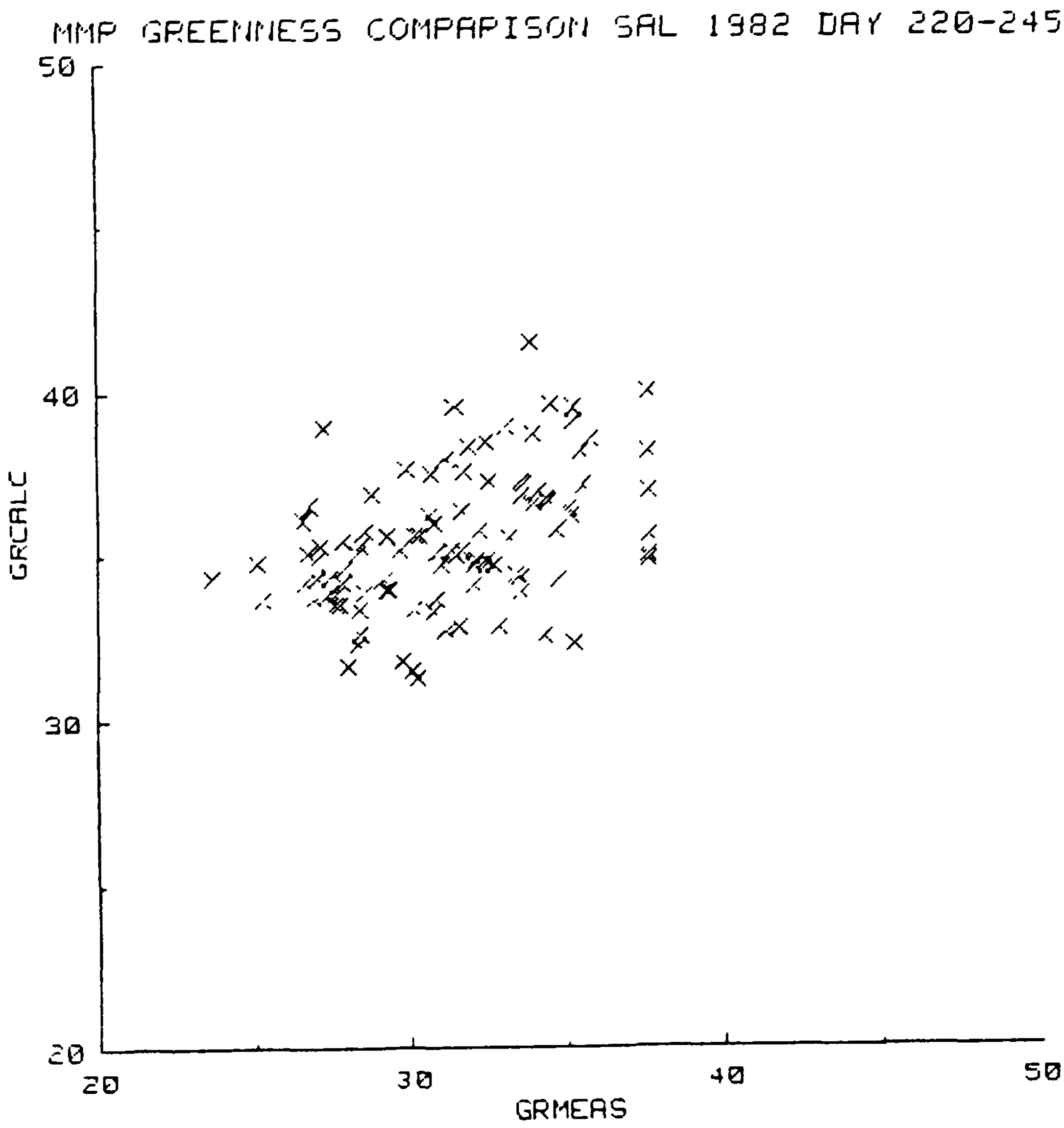


Fig 4.58 Measured greenness (GRMEAS) versus calculated greenness (GRCALC) for corn plots 8,18, and 20.

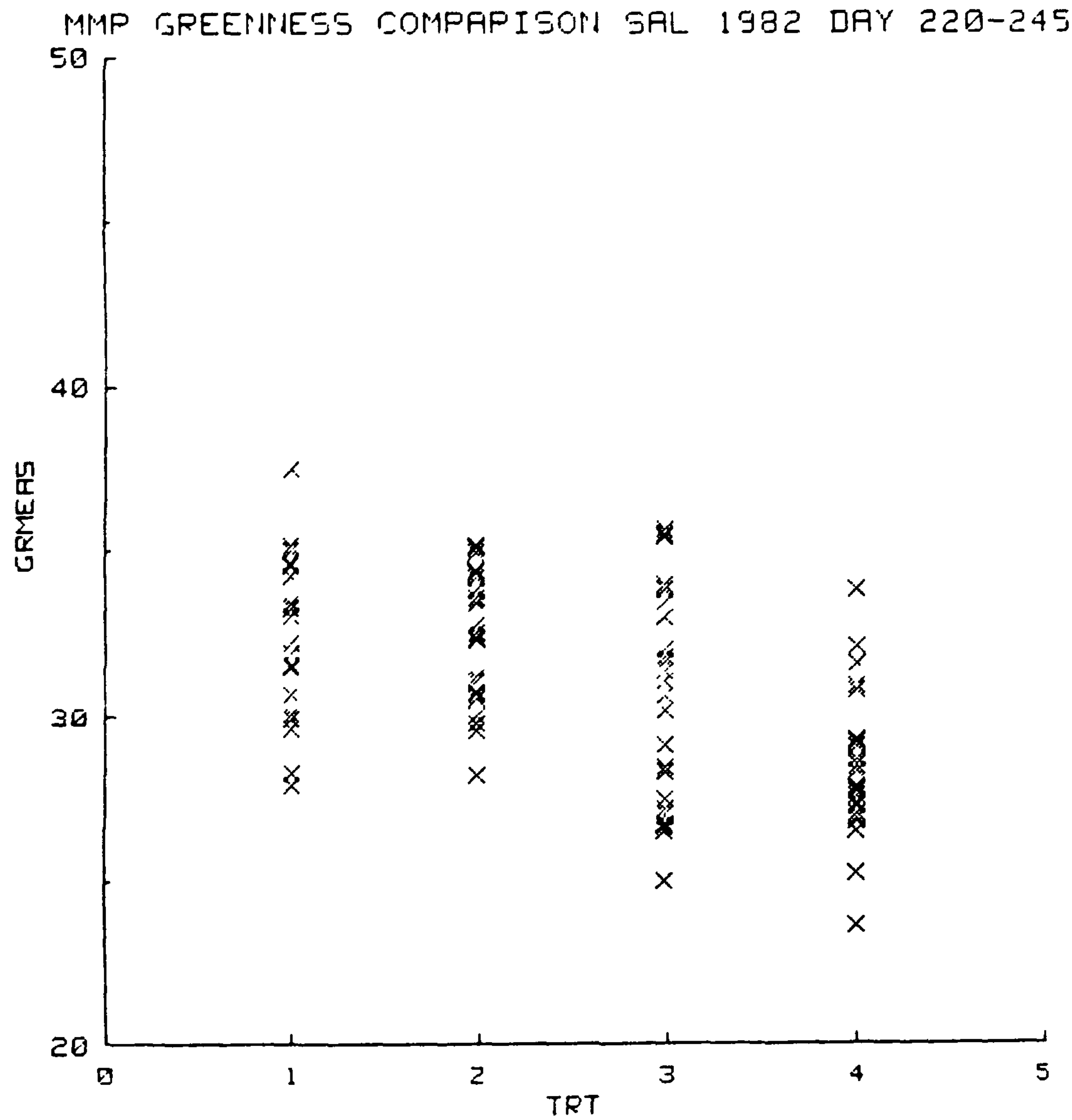


Fig 4.59 Measured greenness values (GRMEAS) for plots 8,18 and 20 as a function of moisture treatment. Treatment 1 is fully irrigated and treatment 4 is dryland. Treatments 2 and 3 are intermediate.

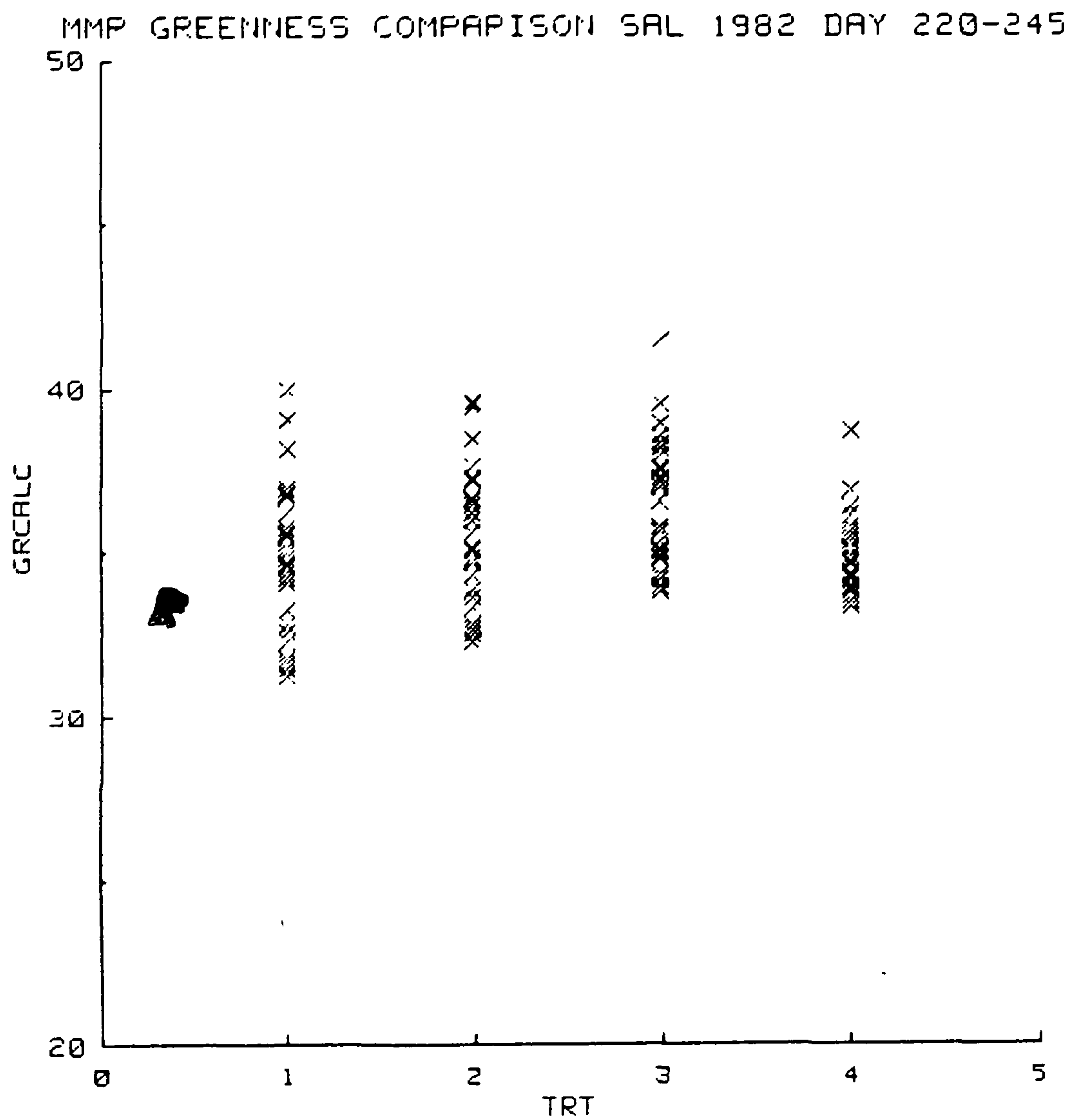


Fig 4.60 As in fig 4.59 for calculated greenness values (GRCALC).

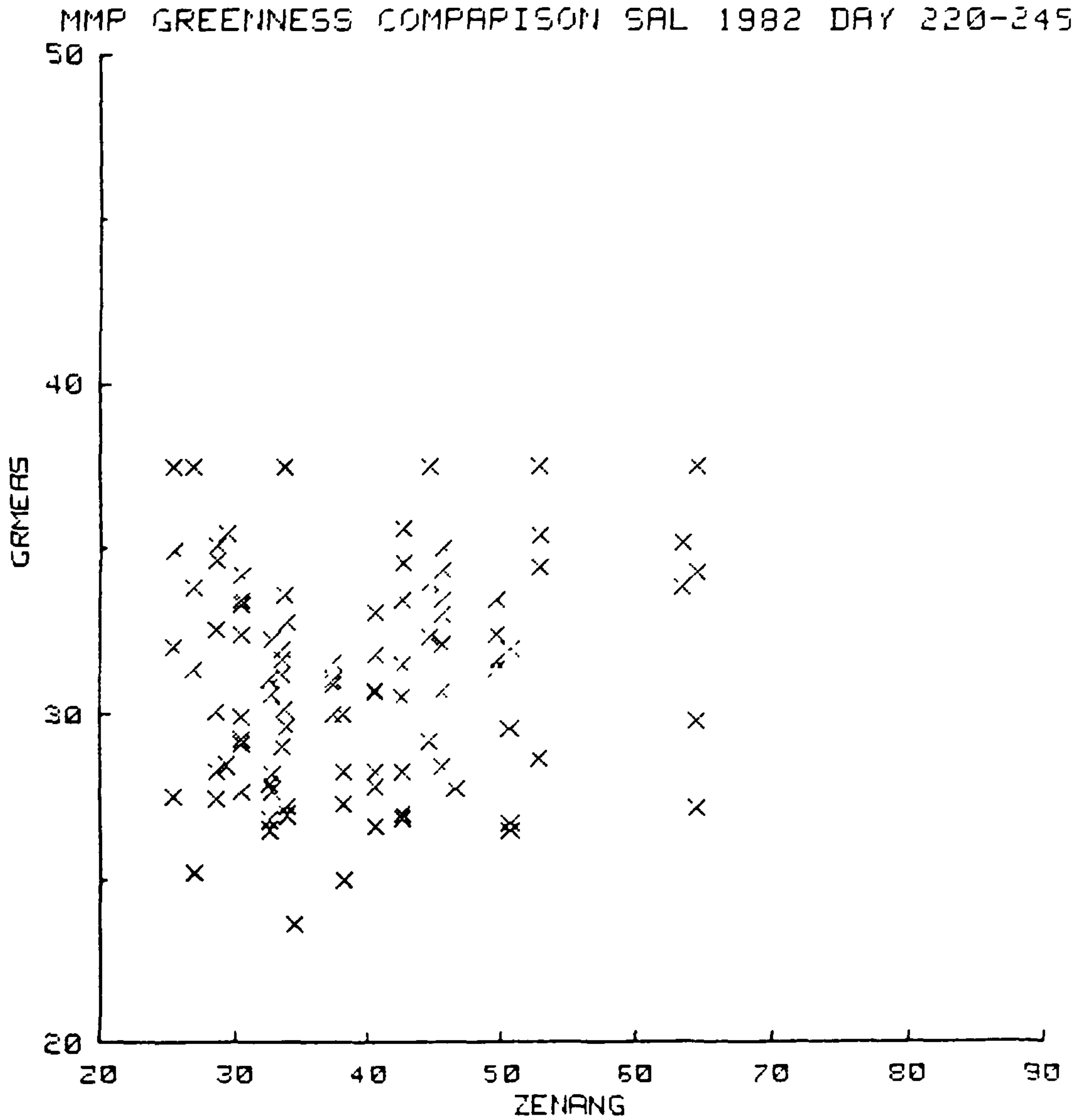


Fig. 4.61 Relationship between measured greenness (GRMEAS) and zenith angle (ZENANG) for corn.

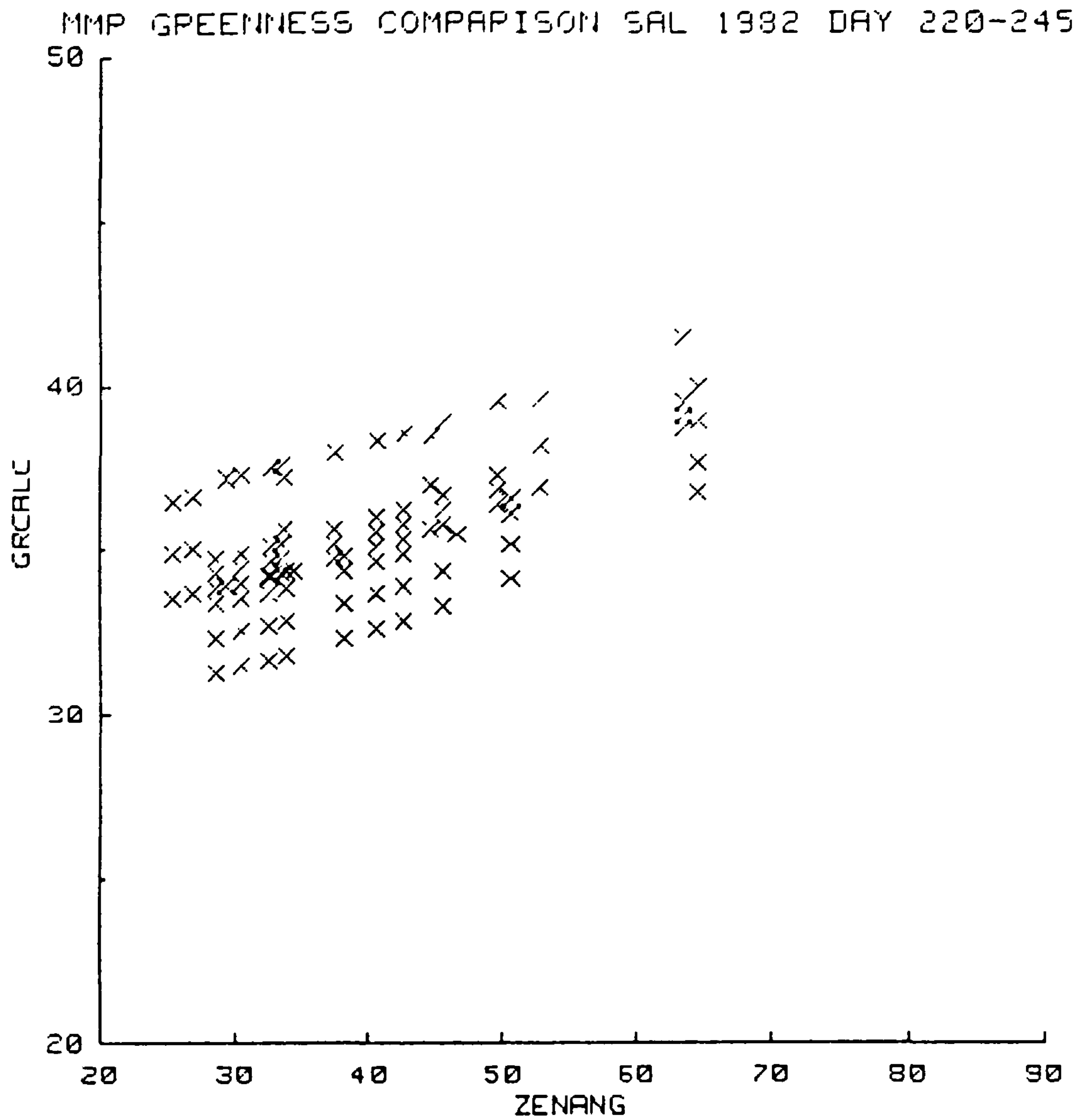


Fig. 4.62 As in Fig. 4.61 for calculated greenness (GRCALC).

4.9.2 Comparison of Bidirectional Measurements with Model Predictions

A standard data set was distributed from LARS at Purdue University in August, 1982. Selected results from that comparison are included in Figs. 4.63 to 4.66. The results include two wavelength bands (0.6-0.7 µm, 0.8-1.1 µm) and two zenith angles (30°, 61°). The general pattern of the measurements and model outputs are quite similar and most results agreed within about 10%.

The effect of leaf angle distribution on canopy bidirectional reflectance was investigated by using Cupid with leaf angle distribution inputs that approximated vertical leaves and horizontal leaves. Similar canopies with predominantly vertical leaves produce bidirectional reflectance patterns that vary more with view and sun angles than canopies of horizontal leaves. In addition, canopies with vertical leaves tend to have lower reflectances. This is true in visible and near infrared bands. Figs. 4.67-4.68 show results for the 0.8-1.1 µm band.

4.9.3 Measurements of Direct and Diffuse Sky Radiation Components with a Standard Reference Panel

Radiation that impinges on a canopy comes directly from the solar beam and also from the sky. Most canopy radiation models require that incident radiation above the canopy be partitioned into direct beam and sky diffuse radiation. To measure both direct beam and sky diffuse radiation with a standard barium sulfate reflectance panel, we constructed a shadow disc to shade that part of the reference panel viewed by a radiometer. Thus, two reference readings were obtained, one with the shadow disc blocking the direct sun so only sky radiation was contributing to radiometer output. A sketch of the shadow disc is given in Fig. 4.69. The horizontal board that supports the apparatus pivots just below the calibration panel.

Of course this shadow disc, which subtends a half-angle of 18°, blocks a

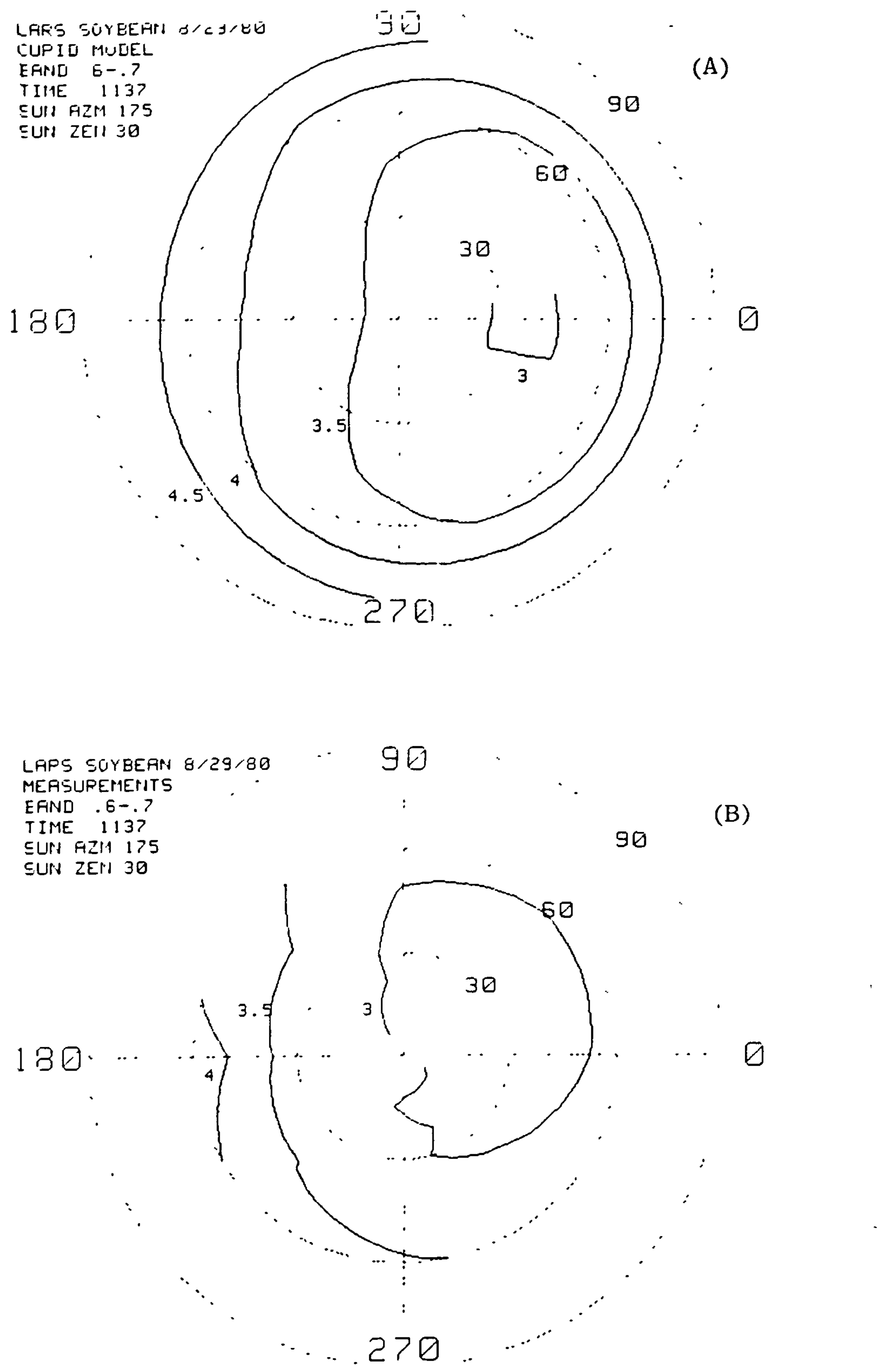


Fig. 4.63 Predicted (A) and measured (B) bidirectional reflectance countours for the 0.6-0.7 μm waveband at 1137 central standard time. A zero degree azimuth represents north and 270 degrees is west. When the azimuth of the viewer is the same as the azimuth of the sun, the sun is directly behind the viewer and the canopy appears brightest.

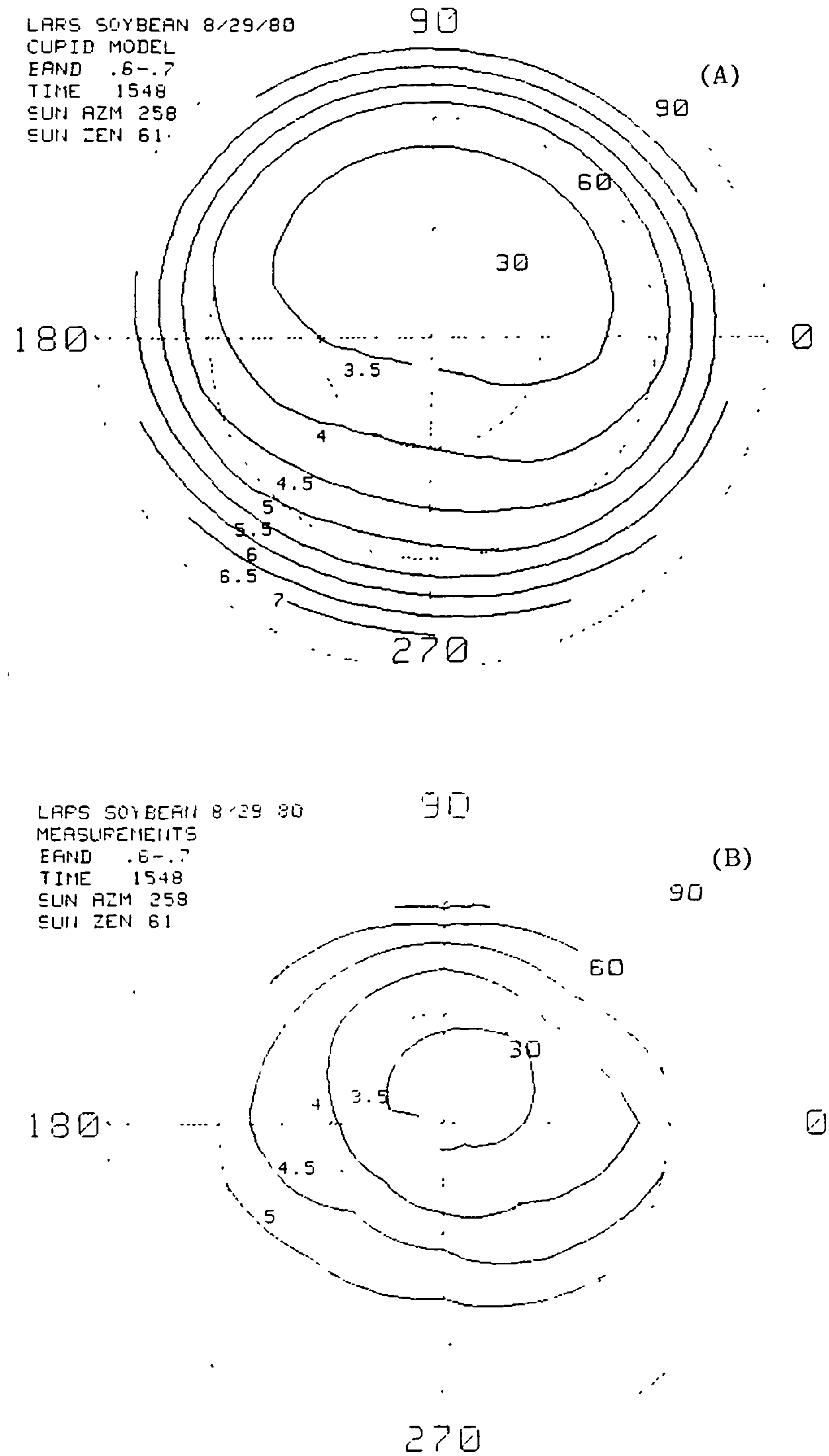


Fig. 4.64 Same as Fig. 4.63 for 1548 central standard time.

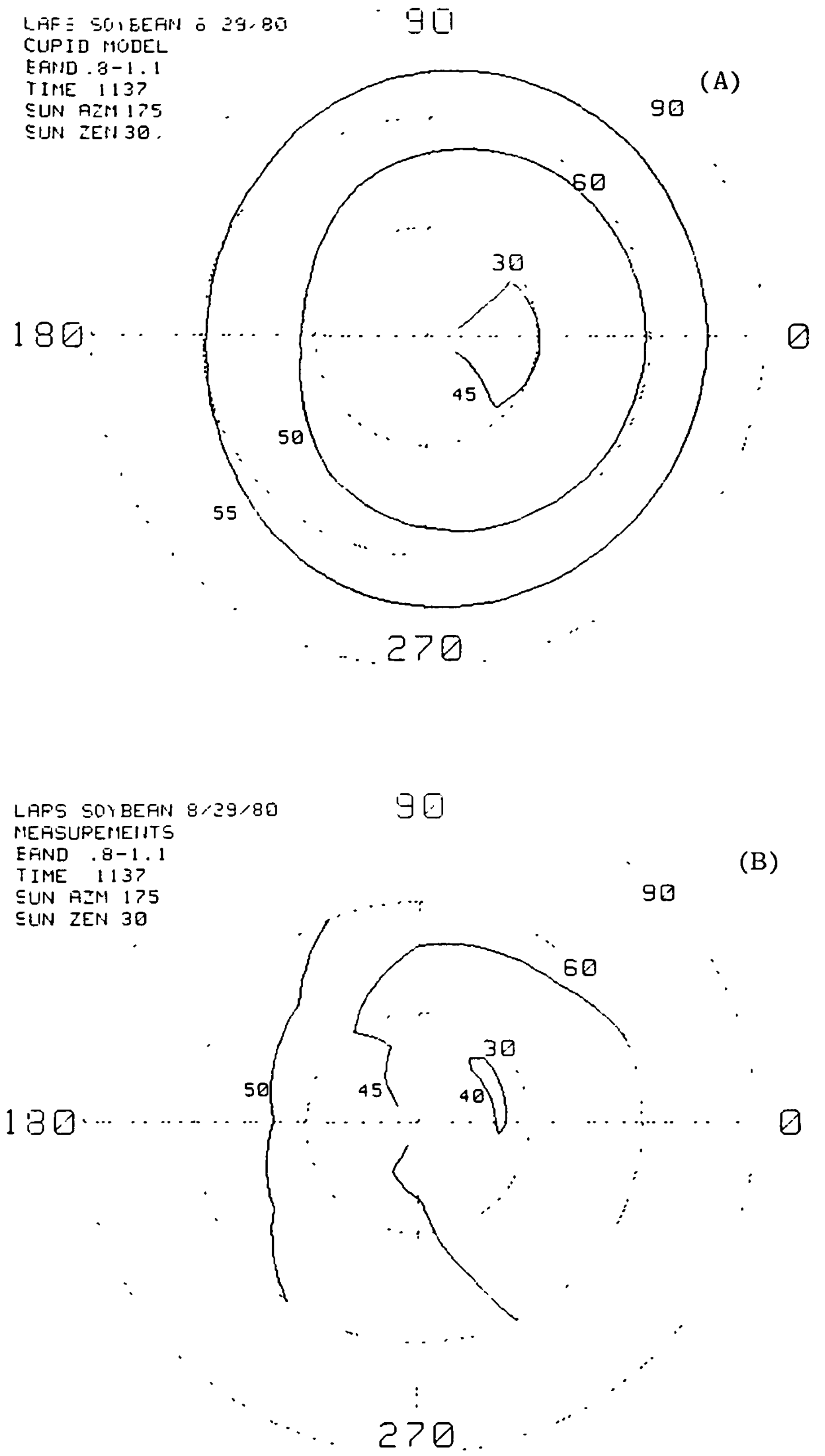


Fig. 4.65 Same as Fig. 4.63 for the 0.8-1.1 μm waveband.

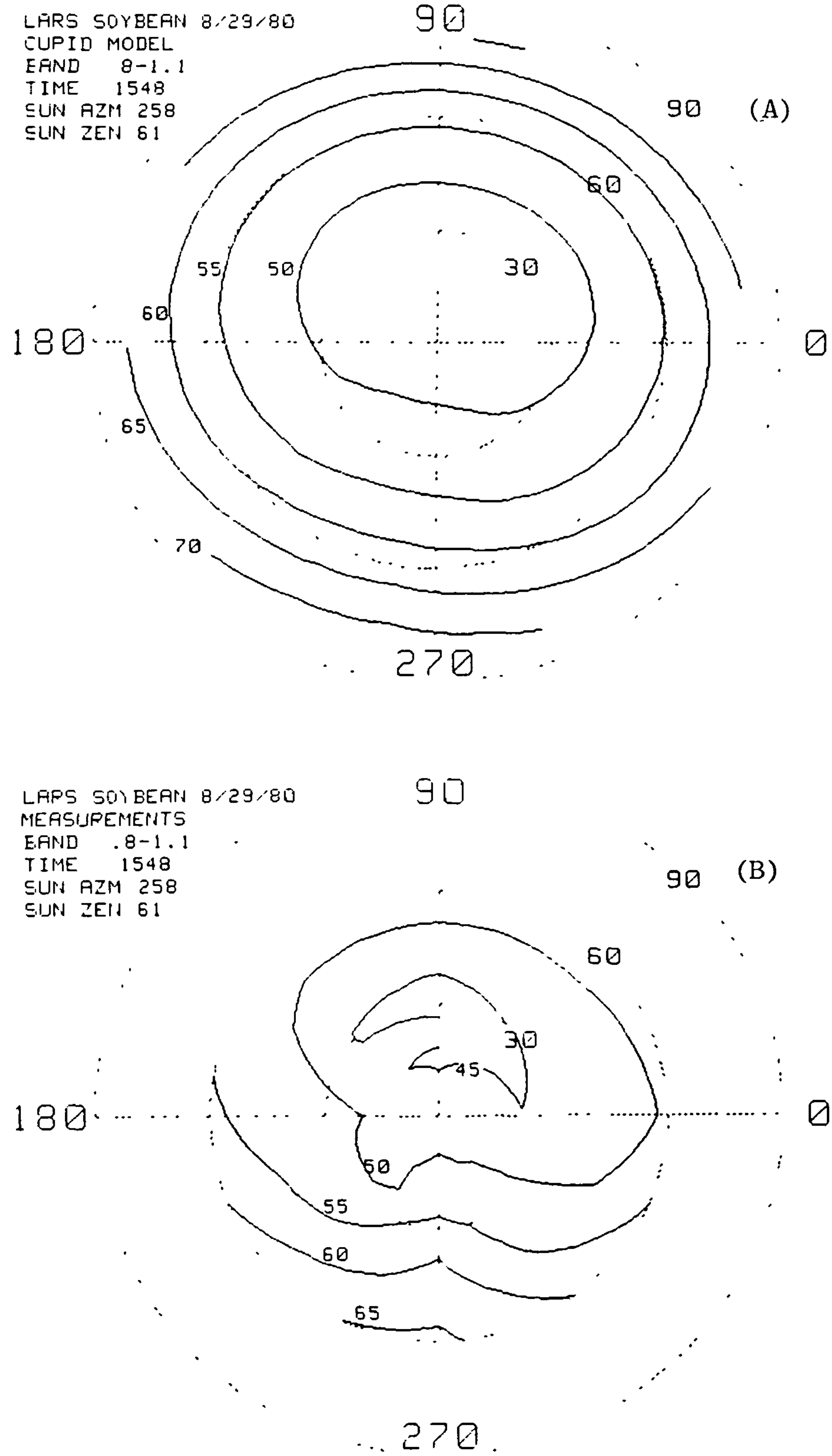
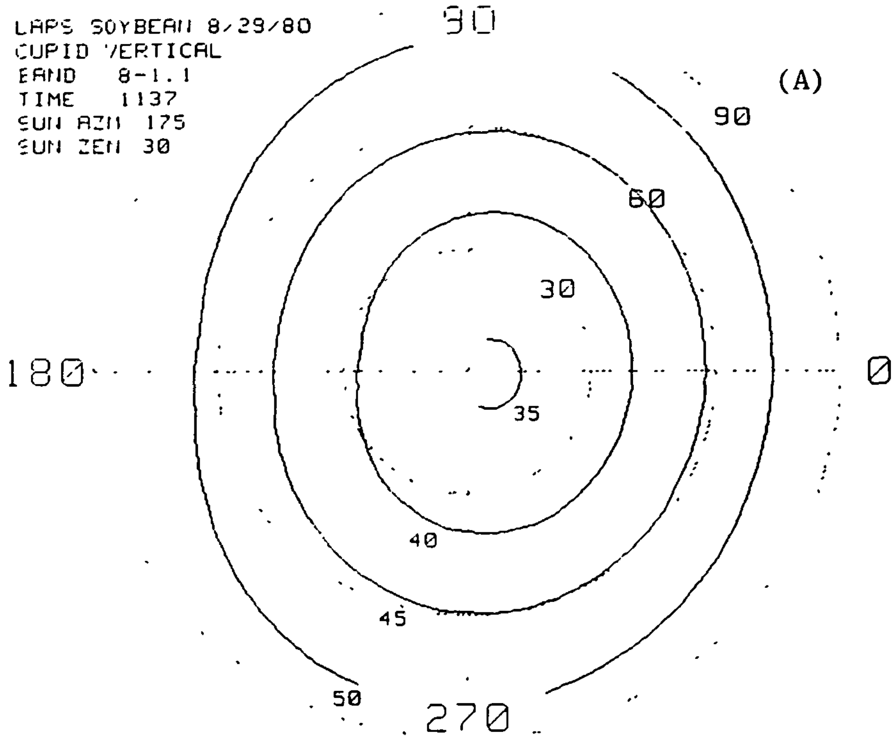


Fig. 4.66 Same as Fig. 4.63 for 0.8-1.1 μm waveband and 1548 central standard time.



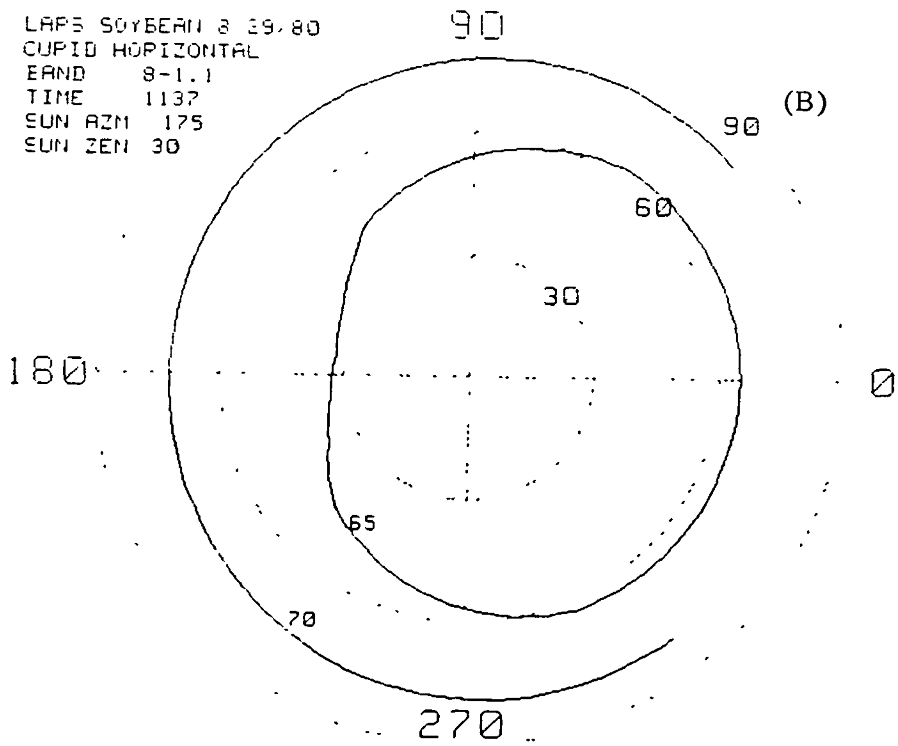
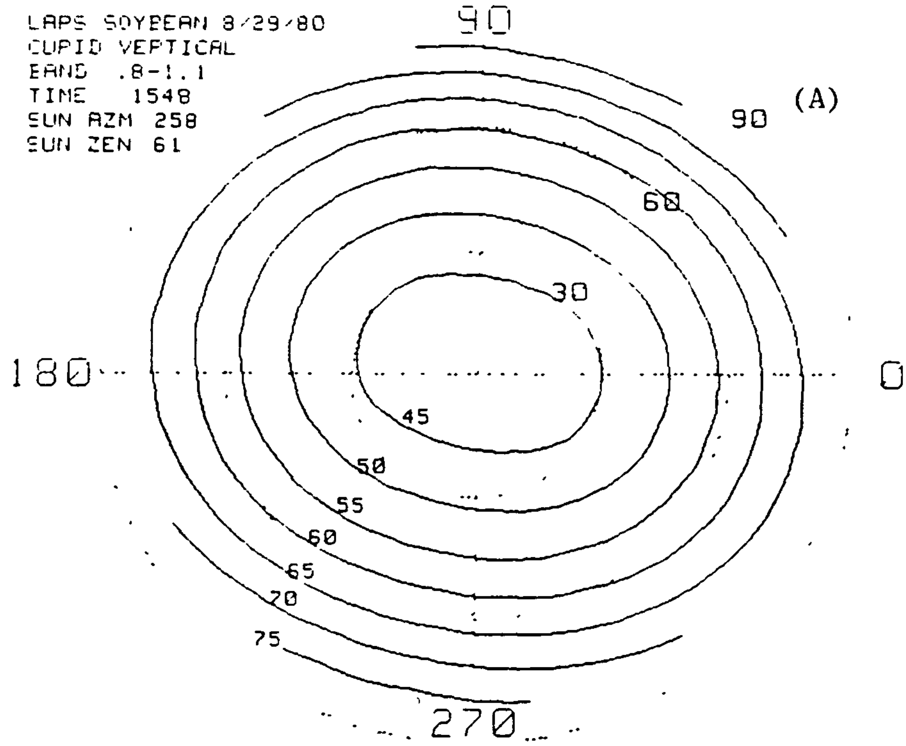


Fig. 4. 67 Same as Fig. 4.63 for canopies with (A) vertical and (B) horizontal leaf angle distributions.



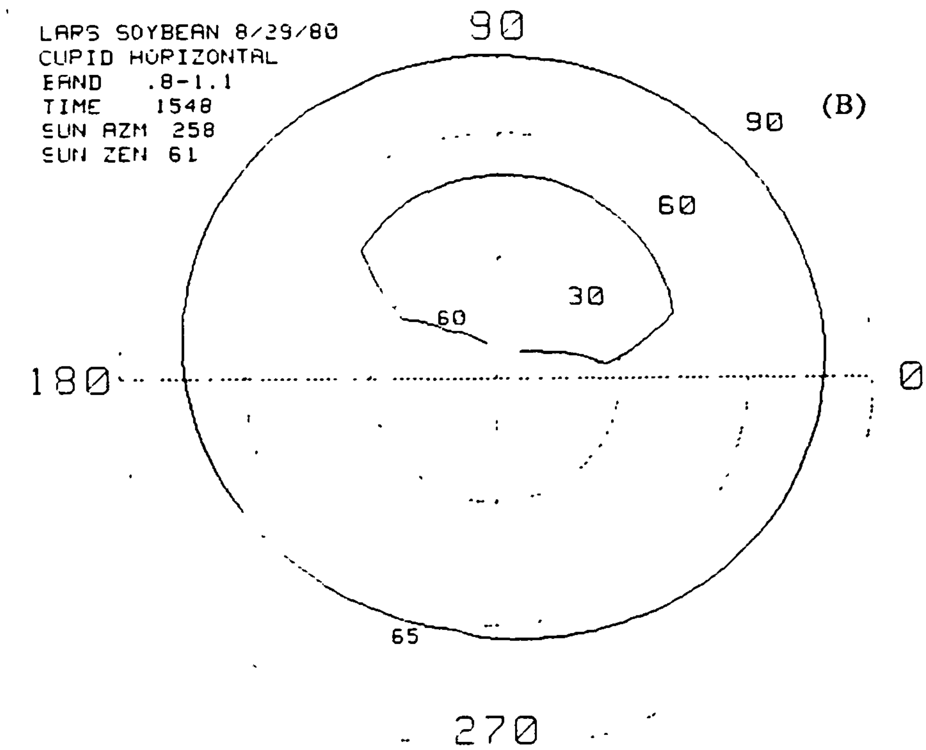


Fig. 4.68 Same as Fig. 4.67 at 1548 central standard time.

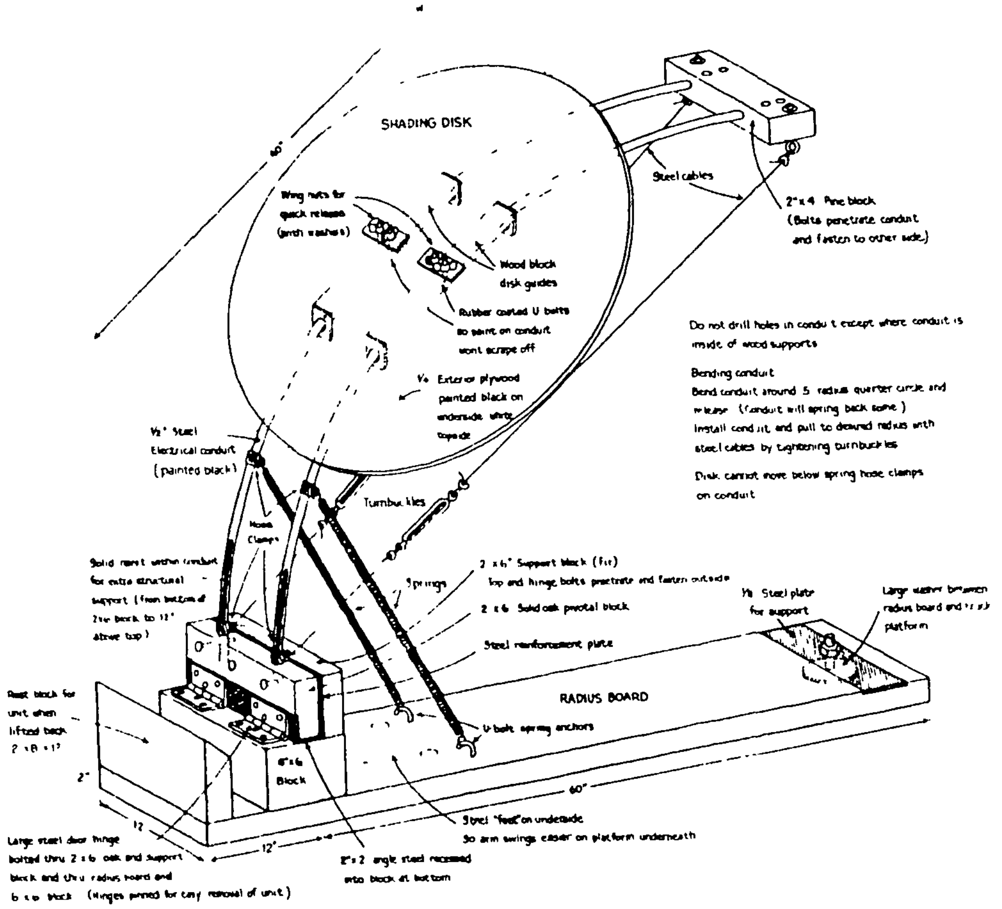


Fig. 4.69 Diagram of the shadow disk used to obtain measurements of direct beam and diffuse radiation with a barium sulfate coated reflectance panel.

portion of the sky radiation. The amount of radiation blocked depends on the zenith angle of the center of the disc and the distribution of sky radiation. Calculations of the percent blockage for an isotropic sky and a typical clear sky are in Table 4.25. More blockage results from the clear sky because the brightest region of a clear sky is near the sun and this is the region blocked by the disc. Measurements were made with a clear sky with the shadow disc placed at a 90° azimuth relative to the solar azimuth (thus not obscuring the sun), and these agree with calculations. Cloudy sky blockage measurements also were made. They are slightly larger than isotropic sky calculations because the brightest region of an overcast sky tends to be near the zenith.

The fraction of total radiation above the canopy that is in the direct beam is plotted against solar zenith angle for the seven MMR wavelength bands in Figs. 4.70 and 4.71. For solar zenith angles less than about 70°, the fraction of total incident radiation on a horizontal surface that is direct solar beam is given in Table 4.26.

4.9.4 Indirect Measurement of Leaf Area Index and Leaf Angles at Night with a Light Bar in Corn

Canopy leaf area index and mean leaf angle can be determined indirectly by measuring the fraction of the length of an illuminated light bar (placed on the soil surface) that can be seen from various angles above the canopy. An 8-foot lucite rod 1 inch in diameter was illuminated with a 12-volt bulb mounted on each end. The illuminated bar then was photographed from three zenith angles: 0°, 35° and 55°. The fraction of the length of the light bar that was visible on film as a function of the camera zenith angle is given in Fig. 4.72. The four corn plots contained a continuous gradient of available moisture from no irrigation (dry) to full irrigation (wet). Inversion of these "gap-fraction" data yield the leaf area index and mean tip angle results

Table 4.25 Percent blockage of an isotropic and clear sky with the shadow disk.

Condition	Zenith Angle	Blockage
<u>Theory</u>		
Isotropic Sky	0°	7%
	15°	5%
	45°	4%
Clear Sky	15°	16%
(azimuth of disk 90°	45°	14%
from sun azimuth)	15°	2%
<u>Measurements</u>		
Cloudy sky	20°	0.5-2%
Clear sky (azimuth of disk 90° from sun azimuth)	15°	7-9%

Table 4.26 Fraction of total incident solar radiation attributable to direct beam radiation. Values are for solar zenith angle less than 70°.

Band	Wavelength Interval (μm)	Fraction Direct Beam
TM 1	0.45 - 0.52	0.80
TM 2	0.52 - 0.60	0.86
TM 3	0.60 - 0.69	0.89
TM 4	0.76 - 0.90	0.91
MMR 5	1.15 - 1.30	0.93
TM 5	1.55 - 1.75	0.95
TM 6	2.08 - 2.35	0.97

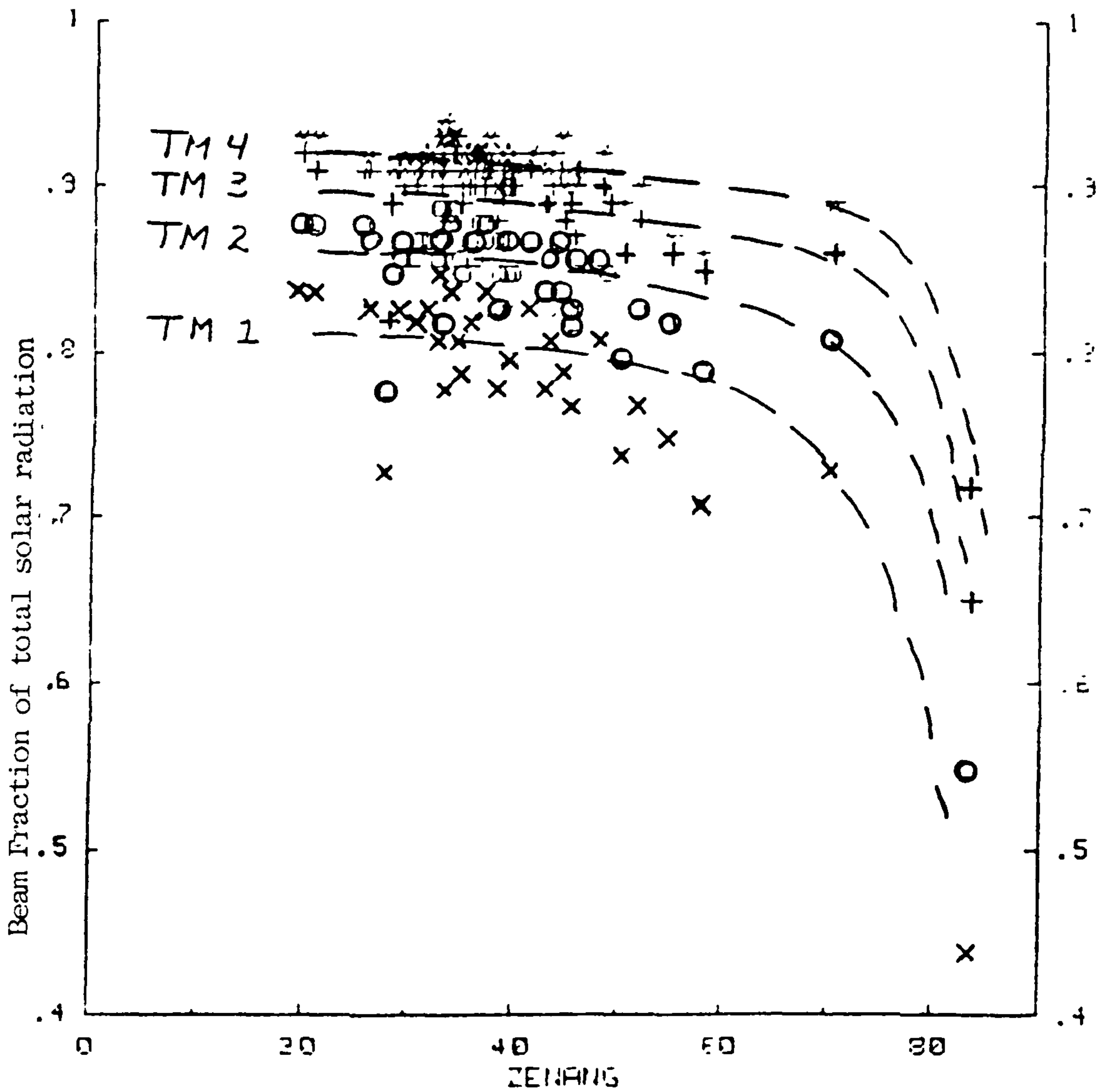


Fig. 4.70 Fraction of total incident solar radiation attributable to direction beam radiation as a function of zenith angle for TM bands 1, 2, 3 and 4.

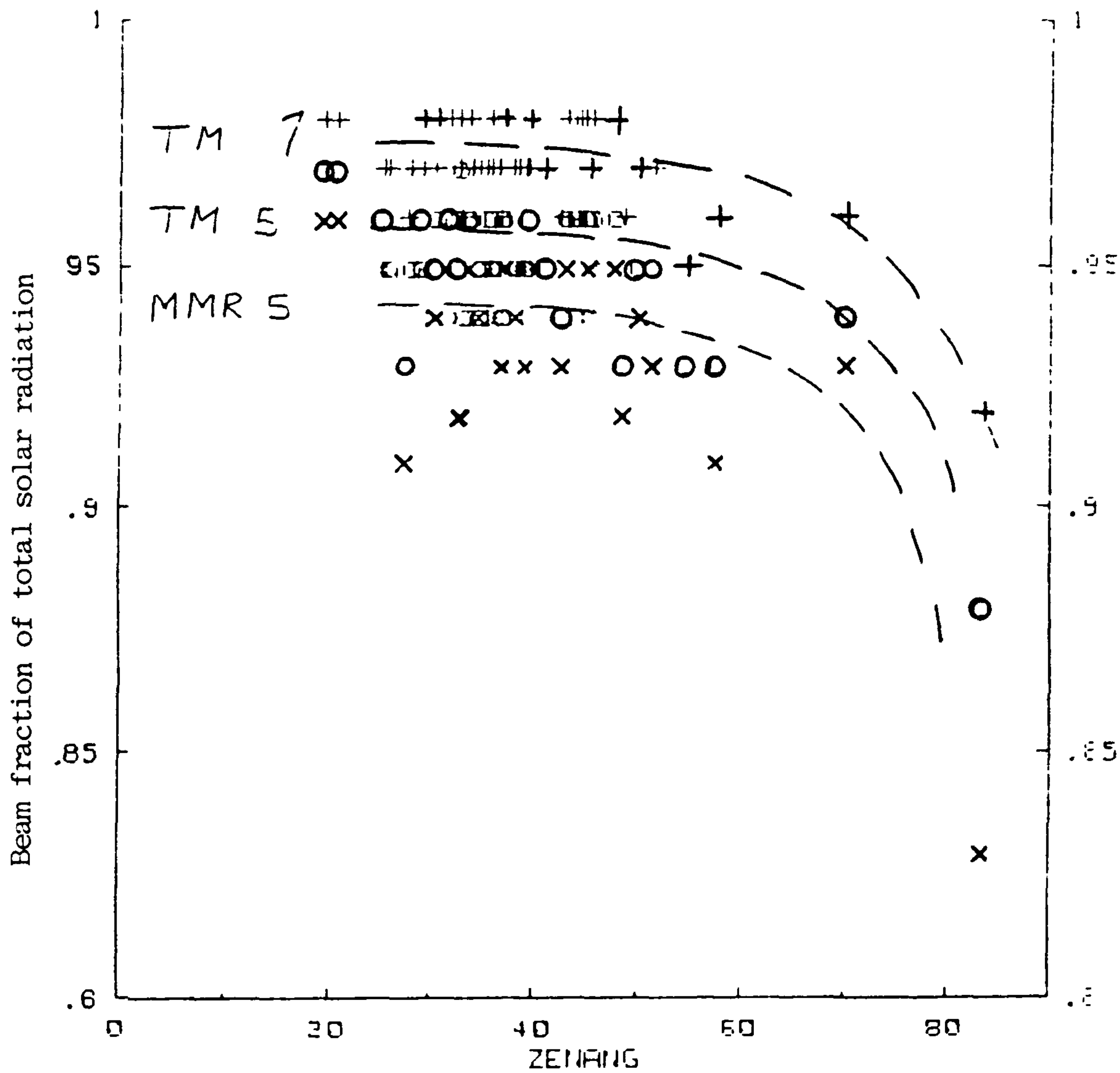


Fig. 4.71 As in Fig. 4.70 for TM bands 5 and 7 and MMR band 5.

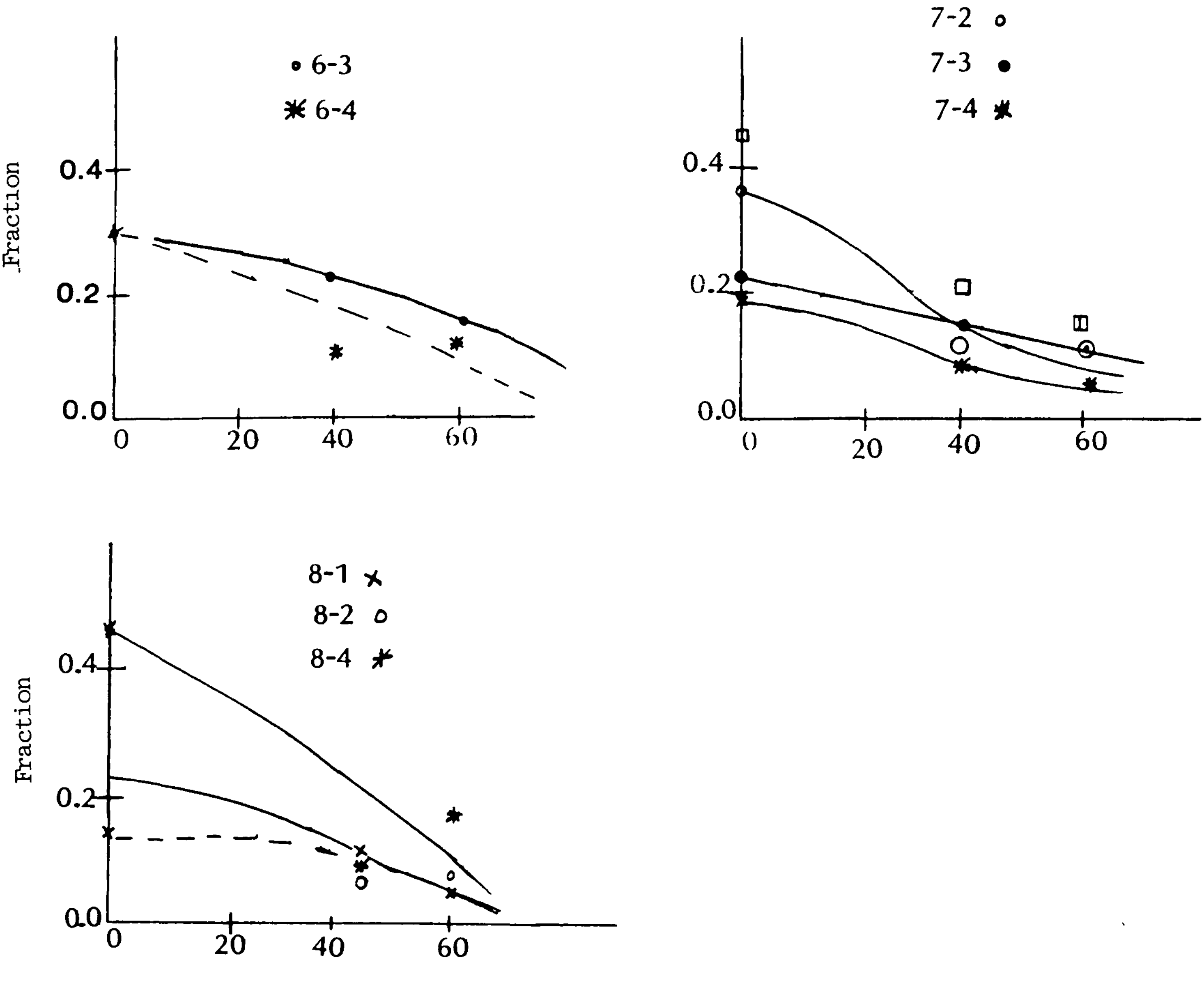
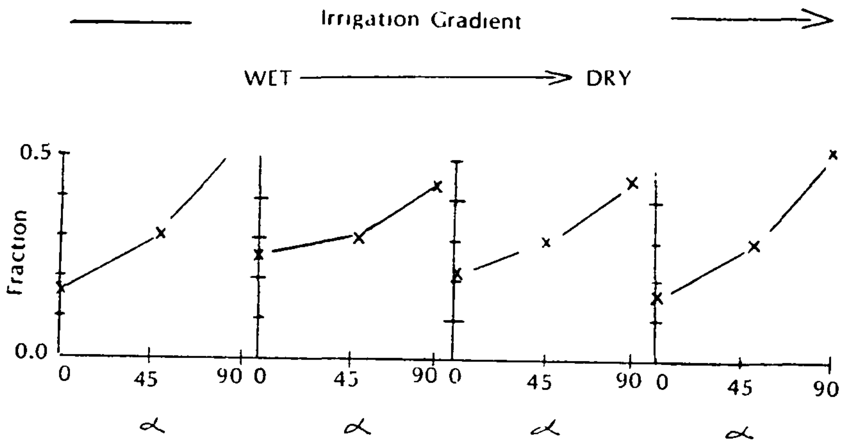


Fig. 4.72 Fraction of light bar visible in the corn canopy as a function of camera zenith angles.

shown in Fig. 4.73.

Results from three corn plots each containing four different levels of water availability are shown in Fig. 4.74. The direct leaf area index measurements were made before and after the indirect measurements on 3 August, 1982. The range plotted in Fig. 4.74 reflects the difference in direct leaf area index measurements made on the two dates when the corn leaves were no longer expanding. These ranges represent a rough measure of the repeatability in direct leaf area index measurements.



LAI INVERTED	3.2	3.0	3.0	2.7
LAI MEASURED	3.6	4.0	3.3	3.4
MEAN TIP ANGLE	58	54	54	56

Fig 4.73 Fraction of leaf area inclined at various angles α, where α is the leaf inclination angle.

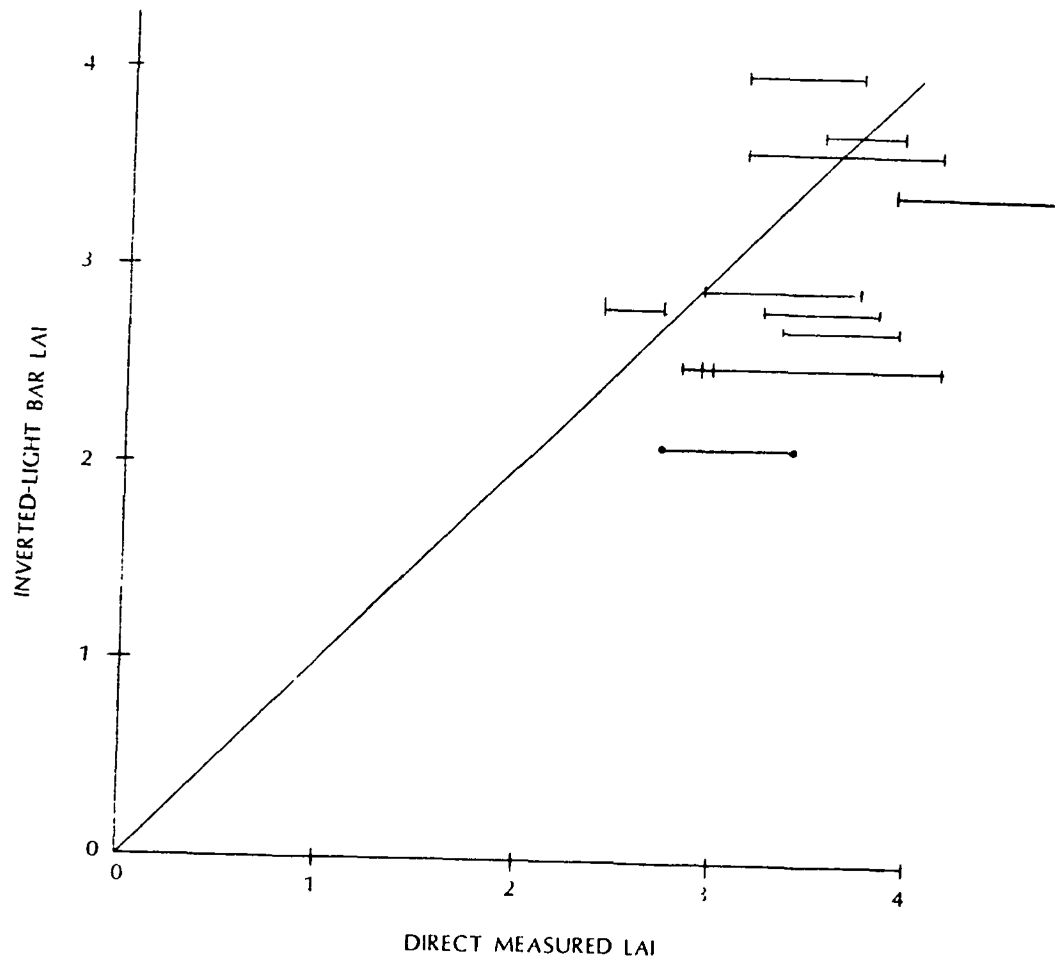


Fig 4.74 Direct measured leaf area index versus estimated leaf area index using data from an illuminated light bar. Light bar data were acquired on August 3. Direct measurements were made between August 2-4.

5. SUGGESTIONS FOR FUTURE RESEARCH

One of the major unresolved areas in relating reflectance measurements to crop canopy development is the effect of diurnal changes in solar insolation and canopy reflectance characteristics on vegetative indices for estimating leaf area, phytomass or phenology. Operational remote sensing applications may conceivably use data acquired at many different times of day. Consequently, further research is needed to determine methods of minimizing diurnal effects.

Another unresolved question concerns the effect of active moisture stress on canopy reflectance, i.e., do reflectance changes occur as a result of stomatal closure? This problem is particularly difficult to solve since reflectance differences between stressed and nonstressed canopies may also be influenced by vegetative development differences.

The literature indicates that narrow band reflectance measurements are potentially useful for crop identification applications. Narrow band reflectance measurements are conceivably useful for moisture stress detection. Field research using narrow band radiometers is, therefore, encouraged.

This study has demonstrated that current phenological estimation techniques for corn are reasonably accurate but subject to systematic bias. Additional study is encouraged in methods of eliminating this bias. Development of phenolgoical estimation techniques for crops other than corn is encouraged.

This study has also demonstrated that the soil is an important component of canopy reflectance data. Remote sensing of soil characteristics--for example, productivity potential--and the use of reflectance data transformations for classifying soil properties are encouraged.

Estimations of grain yields in corn are improved by combining canopy reflectance and temperature data. The model presented is an improvement over existing techniques, but is not entirely satisfactory. Further research is required to determine the most effective methods of combining reflectance and temperature data for use in corn yield models. These techniques should be extended to other crops.

Current crop identification techniques are based on statistical methods. Additional study of data transformation procedures and multicrop/surface reflectance data is encouraged to deepen our understanding of fundamental differences in the reflectance spectra of these surfaces.

One problem associated with virtually all remotely sensed data from aircraft or satellites is the effect of soil/crop slopes and azimuths, i.e., not all fields are flat. Techniques for estimating slopes and azimuths of fields should be studied. Correcting remotely sensed data for these effects could then be accomplished through canopy modeling procedures, assuming the bidirectional reflectance characteristics of the canopies of interest are understood in sufficient detail.

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