USING INFRARED RADIATION FOR ASSESSING CROP WATER STATUS

by

Jan Zinyk

A thesis
presented to the University of Manitoba
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requirements for the degree of
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ABSTRACT

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The present study was conducted to determine whether crop water status could be predicted on the basis of middle infrared (1.4 through 2.4 um) relative reflectance curves obtained by a ground-based remote sensing system.

Plots of Neepawa hard red spring wheat were grown in a greenhouse to which a mobile spectroscopy laboratory was attached. Plants of given treatments were stressed to different soil water contents. Reflectance measurements of the crop canopy were obtained from tillering through to maturity.

In the later stages of crop maturity, a decrease in water content resulted in an increase in relative reflectance. A significantly lower water content for the highly stressed treatment corresponded to an increased relative reflectance curve.

No consistent relationship between water potential and relative reflectance could be determined. When water content did not differ significantly between treatments, no treatment predominated with a higher relative reflectance curve.

No wavelength was suggested as an indicator of water stress. The water absorption bands did not provide the same correlation between water potential and relative reflectance as observed between water content and relative reflectance.

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Chapter I

INTRODUCTION

This project was designed to compare middle infrared reflectance measurements (between 1.40 and 2.40 micrometers) of water-stressed and unstressed Neepawa hard red spring wheat, and thereby determine whether degree of stress can be predicted from variations between spectral curves. Variation in the spectral curve of a typical leaf in the region of 1.40 to 2.40 um can be attributed to water content of leaves. In fact, in this area of the middle infrared (MIR) the absorption spectrum of water and the absorption curve of a leaf are not statistically different (Allen et al, 1969,1970). There are two water absorption bands in this MIR region: 1.43 and 1.95 um. As water content decreases, reflectance in these bands increases. The objective of this research was to determine whether a significant correlation exists between water stress, expressed either as water content or water potential, and some area of the middle infrared reflectance curves of the plant canopy.

Chapter II

LITERATURE REVIEW

In a typical spectral curve of a leaf, there are primarily three regions of interest (Hoffer, 1976):

1) the visible region from .40 to .70 um;
2) the near infrared region from .70 to 1.30 um; and
3) the middle infrared region from 1.30 to 2.60 um.

In the visible region, wavelengths are highly absorbed by pigments such as chlorophyll, carotenes and xanthophylls. Chlorophyll is the dominant pigment in green leaves and strongly influences absorption in this region. Absorption of visible radiation is essential as it provides excitation energy for chlorophyll molecules and is therefore important for photosynthesis.

In the near infrared region, radiation is highly reflected. This is a necessary survival mechanism of plants. By reflecting wavelengths in the near infrared region, damage to leaf components caused by overheating is prevented (Gates et al, 1965). The primary factor affecting reflectance in this region is cell structure (Gates et al, 1965; Myers and Allen, 1968; Knipling, 1970; Sinclair et al, 1973), but water content is also important (Gates et al, 1965; Sinclair et al, 1971).

In general, when a body is a good absorber in a given wavelength range, it is also a good radiator in the same range. High or moderate absorption of middle infrared wavelengths between 1.30 and 2.60 um is necessary in order for plants to be efficient radiators (Gates et al, 1965). Absorption in this region is attributable to water content of leaves (Gates et al, 1965; Thomas et al, 1967; Allen et al, 1969; Knipling, 1970; Carlson et al, 1971; Woolley, 1971; Gausman et al, 1973; Blum et al, 1978). There are three water absorption bands in this region: 1.43, 1.95 and 2.60 um.

2.1 MECHANISM OF LEAF REFLECTANCE

2.1.1 Early Studies Concerning Leaf Reflectance of Visible Wavelengths

The fundamental mechanism explaining exactly how cell structure affects reflectance from leaves has been continually revised since Coblentz (1913) first proposed internal reflectance. Based on the interaction of visible light with internal leaf structure and chlorophyll, Willstatter and Stoll (1918) presented a theory which stated that light travels in hydrated areas of cells until it encounters cell wall-intercellular air space interfaces. At these interfaces, total or critical reflectance occurs. There are two requirements for total reflectance (Willstatter and Stoll, 1918):

1) the energy must pass from a material with a high refractive index to a material with a low refractive index; and

2) the angle of incidence must be larger than the critical angle.

Spongy mesophyll appeared to be the leaf component best suited to meet these requirements due to its irregular cell shapes, diverse orientation of cell walls, and large intercellular spaces (Willstatter and Stoll, 1918).

Mestre (1935), also working with radiation in the visible region, reported that reflectance occurs both at the surface and within the leaf. At the surface, specular (mirror-like) and diffuse reflectance usually coexist (Mestre, 1935).

Within the leaf, reflectance is diffuse. As a result, the scattering power of the leaf is increased and the probability of light being absorbed is also increased (Mestre, 1935). It was for this reason that Mestre referred to the leaf as a "light trap"; the leaf surface would act as a barrier to exiting diffuse radiation if the angle of incidence was greater than the critical angle. Therefore, optical parameters of leaf surfaces affect reflectance of not only incident light but also light that has entered and is in the position of being reflected back out (Mestre, 1935).

Mestre did not believe that small particles in the cell cause scattering. Rayleigh's equation (applicable when particles are relatively small compared to the wavelengths) would predict an increased scattering as wavelengths decrease. This was not supported by experimental results.

Gates et al (1965) agreed with Mestre that Rayleigh scattering is not important since the scattering phenomena are not strongly wavelength dependent. Scattering within the leaf was determined to be of the Mie type, caused by structures similar in size to the wavelengths (such as chloroplasts and grana).

Mestre recognized that absorbing power is determined by absorption coefficients, concentrations of light-absorbing substances, distribution pattern of absorbing pigments and pathlength of radiation within the leaf.

As pathlength increases, scattering power increases (Mestre, 1935) and consequently absorption of radiation increases. The longer that radiation is in the leaf, the greater the chance of it being absorbed. Mestre however noted that a paradox existed: if pigment concentration or the absorption coefficient increased, absorption increased even though pathlength decreased.

2.1.2 Effect of Chlorophyll on Reflectance of Visible and Infrared Wavelengths

At the same time that work was being done to establish the effect of cell structure on leaf reflectance, studies concerning the absorption of radiation by chlorophyll were being conducted. Several researchers have shown that chlorophyll is the most important factor influencing absorption by green leaves in the visible region.

Coblentz (1913) and Shull (1929) were two of the early investigators of leaf pigment absorption in the visible region. It was Dinger (1941) who expanded into wavelengths between .75 and 2.6 um, reporting the absence of chlorophyll absorption in this interval. This indicated that in different regions of the spectrum, different factors are affecting the interaction of light with leaves. Gates et al (1965) confirmed that although chlorophyll is the major factor involved in absorption of visible light, it does not influence reflectance in the middle infrared (1.3 to 2.5 um).

2.1.3 Effects of Cell Structure on Reflectance of Infrared and Visible Wavelengths

As time progressed, more experiments were conducted in the infrared region. In 1941 and 1944, Obatan studied the effect of cuticle and epidermis on near infrared reflectance and concluded neither were very important sources of reflectance. The findings of Knipling's (1970) work in both the visible and infrared regions supported the insignificant effect of cuticular wax on reflectance. Myers (1975) also acknowledged that although the cuticle diffuses light, it reflects very little.

Gates and Tantraporn (1952) conducted reflectance studies in the middle and far infrared regions (from 1.0 to 25 um). They found that the ventral side of a leaf is more reflective than the dorsal side, which appears to support the Willstatter-Stoll theory. They also determined older leaves reflect more infrared radiation than younger leaves and shaded leaves reflect more than sun leaves. The opposite relationship had been found in the visible wavelengths by Billings and Morris (1951).

Woolley (1971) considered the effect of ventral and dorsal epidermal surfaces on reflectance of visible light. Both internal and external surfaces strongly reflect and refract visible light. The ventral epidermis, however, has mesophyll cells along most of its inner surface. Once light gets past the external surface it has no trouble penetrating deeper into the leaf (Woolley, 1971). Therefore, dorsal epidermal surfaces act as greater barriers than ventral epidermal surfaces not only before visible light enters the leaf, but also once light is inside the leaf (Woolley, 1971).

The importance of intercellular spaces was recognized by Colwell (1956) when he compared infrared reflectance curves of rust-infected wheat and disease-free wheat. He observed a lower reflectance of the diseased wheat which could be attributed to the spread of fungal hyphae through intercellular spaces, thereby decreasing volume of air space.

Thomas et al (1966) found young compact leaves are less reflective than older leaves with more lacunose structure because they contain fewer cell wall-air space interfaces and vacuole size increases with age. As plants dehydrate, reflectance increases.

These researchers suggested that in addition to cell and air space size and shape, an increased solute concentration within cell cytoplasm could increase reflectance by increasing the refractive index of cytoplasm.

Gausman (1974) proposed the same line of reasoning, acknowledging the importance of not only cell wall-air space interfaces but also differences in refractive indices between cellular constituents.

Gates et al (1965) reported that several substances affect reflectance: cell walls, water-containing solutes within cells, intercellular air spaces and pigments. In the near infrared, Gates et al (1965) believed reflectance was dependent on cell shape, cell size and amount of intercellular space. However, they could not explain the exact relationship between cell size and intercellular space that would cause the changes in reflectance observed as plants mature.

When plants are very young, air spaces between spongy parenchyma cells are large and therefore the high reflectance observed at this stage is in accordance with expectations (Gates et al, 1965). As leaves mature, cells enlarge and reduce the amount of intercellular space. Again, the decreased reflectance at this stage is explanable. However, as maturity progresses, reflectance increases. This does not agree with the Willstatter-Stoll theory on reflectance which would predict decreased reflectance as cells collapse and intercellular space is reduced (Gates et al, 1965).

Knipling (1970) stated that high reflectance in the near infrared (.70 to 1.30 um) is due to scattering caused by the internal cellular structure of the leaf and little or no absorption. It is because of scattering of radiation and low absorption that reflectance and transmittance spectra are similar (Knipling, 1970). Internal reflectance was proven when leaves vacuum-infiltrated with water produced a lower reflectance (Knipling, 1970). This was similar to findings by Seybold (1932).

Knipling suggested that it is not the volume of intercellular space that determines reflectance, but rather the number or total area of cell wall-intercellular space interfaces. As plants dehydrate adjacent cells separate and cell contents shrink away from interior cell walls (Knipling, 1970). By increasing the number of interfaces in this manner, increasing reflectance can be explained independent of leaf volume (Knipling, 1970).

2.1.4 The Diffuse Cell Wall Reflectance Hypothesis

Sinclair et al (1971) agreed with Knipling that it was the number of interfaces that determined reflectance, not the volume of intercellular space. However, Sinclair et al attributed the increased reflectance observed between .7 and 1.3 um as plants mature to changes in water content as well as changes in internal leaf structure. Gausman et al (1970) believed the increased reflectance was due to an increase in number of intercellular spaces in the mesophyll.

Sinclair et al (1973) were dissatisfied with prior theories on light reflectance from leaves. The Willstatter-Stoll theory, for example, adequately explained observations of reflectance in the visible region of the spectrum (on which it is based), but could not account for observations in the infrared region.

An example of the incongruity of this theory is encountered when considering near infrared reflectance (.72 to 1.3 um) as leaves mature. The reorientation of cell walls as cells dehydrate and collapse should decrease reflectance according to Willstatter-Stoll's theory since intercellular space is reduced (Sinclair et al, 1973). In actuality, reflectance is increased (based on wavelengths between 1.04 and 1.07 um).

Another disagreement with the Willstatter-Stoll theory is evident when comparing sun leaves and shade leaves. Sun leaves have thicker palisade layers and the spongy mesophyll cells are more tightly packed. Since there is less intercellular space, the Willstatter-Stoll theory would predict a lower reflectance which is opposite to experimental findings at 1.04 to 1.07 um (Sinclair et al, 1973).

Sinclair et al (1973) proposed a new hypothesis that would explain the relationship between reflectance and three histological differences of leaves. This diffuse cell wall reflectance hypothesis, based on the findings of the scattering of a one millimeter-diameter light beam, states that since cell walls are diffusive in nature, a greater proportion of reflectance will be diffuse than specular (Sinclair et al, 1973). Moreover, the greater the number of cell walls encountered by the radiation (the closer the cell walls are to each other), the greater the reflectance (Sinclair et al, 1973).

The three histological aspects of leaves studied by Sinclair and co-workers were:

1) the dorsal side versus the ventral side, studying both monocots and dicots;

2) depth of the palisade layer (using sun leaves and shade leaves); and

3) changes in structure due to water loss.

In the first case, radiation hitting the dorsal side of a leaf encounters spongy mesophyll and associated intercellular spaces before palisade cells, and therefore reflectance would be higher according to the Willstatter-Stoll theory. Although true for visible wavelengths, the opposite is observed in the infrared region (Sinclair et al, 1973).

The diffuse reflectance hypothesis explains the lower reflectance on the dorsal side of the leaf on the basis that since the palisade layer on the ventral side is thick and cells are packed close together, more cell walls are encountered in a shorter pathlength. This would increase the probability of radiation being reflected back out of the leaf (Sinclair et al, 1973). Palisade cells contain more chlorophyll pigments than spongy mesophyll cells, readily explaining the decreased reflectance in the visible region.

The effect of total thickness of cell wall material can also explain how depth of the palisade layer affects reflectance of light. This is in accordance with Mestre's reasoning: the longer the diffuse radiation is within the leaf, the greater the chance of it being absorbed. Since sun leaves have a thicker palisade layer than shade leaves, they will be more reflective in the near infrared.

Study of the third case (structural changes due to water loss) showed that as moisture content within a leaf is reduced, cells collapse and cell walls are arranged closer together. Reflectance is increased in the infrared, agreeing with the diffuse cell wall hypothesis.

It therefore appears that in each of these three cases of histological differences, the diffuse reflectance theory is supported.

2.2 COMPARISON OF REFLECTANCE OF SINGLE LEAVES AND CANOPIES

Reflectance curves of plant canopies and single leaves differ both qualitatively and quantitatively (Knipling, 1970). Monteith (1965) determined that reflectance for a canopy is less than for a single leaf. The amount of scattering was said to be dependent on random leaf orientation and angle of sun elevation (Monteith, 1965). With respect to the latter, as the sun approaches the zenith, sunlight penetrates deeper into the canopy (Monteith, 1965). Another factor affecting the scattering coefficient is leaf area index (LAI). As LAI increases, leaf transmission decreases (Monteith, 1965). For a single leaf, transmission decreases as angle of incidence increases, whereas for a crop canopy, transmission is independent of the angle of incident light but will be less than transmission at the zenith (Monteith, 1965).

Knipling (1970) noted that differences between reflectance of single leaves and plant canopies arise due to general attenuation of radiation in a canopy caused by illumination angle, leaf orientation, shadows and background. This attenuation results in a lower percent reflectance from a canopy than from a single leaf, supporting Monteith's findings. Steiner and Gutermann (1966) reported that whereas a canopy may reflect 3 to 5 % of the visible and 35 % of the near infrared light, a single leaf will reflect 10 % of the visible and 50 % of the near infrared light.

Thomas et al (1967) conducted research on the effects of soil salinity on the reflectance of both single leaves and crop canopies of field cotton. Findings indicate that reflectance of single leaves increases as soil salinity increases, whereas the opposite relation exists for canopy reflectance. This provides evidence of the differences between reflectances of single leaves and canopies (Thomas et al, 1967).

Myers et al (1966) warned that near infrared reflectance of spectral curves from single leaves should not be used to predict reflectance from crop canopies. Near infrared light penetrates the canopy where multiple reflections and interactions within the canopy occur, thereby altering light quality. Moreover, the top of the canopy enhances reflection in the canopy by serving as a barrier to exiting radiation (Myers et al, 1966).

Knipling (1970) stated that when a crop is subjected to stress, differences between single leaf and canopy reflectance are due not to changes in individual leaves but rather to the reduction of total leaf area. If stress conditions persist, there is a reduction in leaf number, a change in leaf orientation and a slowing or cessation of growth (Knipling, 1970). As LAI is reduced, the proportion of nonfoliage components and shadows increases, resulting in lower reflectance (Knipling, 1970).

Woolley (1971) researched the differences in reflectance between thick leaves and stacks of thin leaves. Although it was expected that the two would have similar infrared reflectance curves, it was found that the stacks of thin leaves have much less prominent water absorption bands. This is due to air spaces between layers and the difference in number of cutinized epidermes (Woolley, 1971).

Colwell (1974) cited two examples of the differences between single leaf reflectance and canopy reflectance. Firstly, Fox (1973) found white pine needles reflect more at approximately .75 um than oak leaves. When comparing the canopies of these two tree species, the inverse is indicated.

The second example was extracted from work conducted by Soviet scientists (Colwell, 1974). Hemispherical[1] reflectance values between .71

and .79 um for individual aspen leaves and birch leaves are similar. Canopy reflectance of these tree species, on the other hand, are noticeably different, aspen having 29.0 % reflectance and birch having 42.4 % reflectance (Colwell, 1974).

2.2.1 Factors Affecting Crop Canopy Reflectance Curves

Crop canopy reflectance curves are much more difficult to interpret than single leaf reflectance curves due to the introduction of several complex factors that do not apply to single leaves (Hoffer, 1967):

1) variations in LAI and ground cover;

2) variations in maturity;

3) cultural practices;

4) changes in reflectance and emission characteristics caused by disease and/or moisture stress;

5) canopy geometry including direction of seeding, row width and lodging; and

6) environmental variables.

Myers and Allen (1968) recognized additional factors that influence canopy reflectance:

1) the absorption of radiation in certain spectral bands by atmospheric constituents such as oxygen, carbon dioxide and water vapor;

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[1] Hemispherical reflectance is reflectance from a plane surface, with the incident and reflected radiation occurring on the same side of the plane.

2) the intensity of source radiation which varies with numerous conditions; and

3) the nonuniformity of solar radiation across the spectrum.

Colwell (1974) listed several parameters which would affect canopy reflectance: hemispherical leaf reflectance, transmittance of leaves, amount and arrangement of leaves, components other than leaves, soil background, solar zenith angle, incidence angle and azimuth angle.

Gausman et al (1971) stated that plant reflectance is determined by plant reproductive structures, soil background, leaves, branches, dew, pesticide residues, dust and many other factors. They recognized leaves as the most important contributors to reflectance, and suggested that once the effects of leaf aging on optical properties are known, canopy reflectance will be interpreted more accurately.

2.2.2 Importance of LAI and Leaf Orientation in Determining Crop Canopy Reflectance

The effect of LAI and leaf orientation have been studied by many researchers. In 1966, Baker and Meyer studied the relationship between reflectance from a cotton crop and LAI. They concluded that when LAI reaches approximately 3, the percent radiation intercepted by the canopy begins to level off.

Gausman and Allen (1973), working on thirty species of plants, found that as the number of leaf layers increases, reflectance increases. However, reflectance eventually levels off at a value termed infinite reflectance. Gausman and Allen (1973) determined that in the visible and middle infrared (1.5 to 2.5 um) regions, a LAI of 2 results in infinite reflectance; in the near infrared (.75 to 1.35 um), a LAI of 8 is required (due to high transmission through leaves).

Gausman et al (1976) did further work in this area and revised the LAI required for infinite reflectance between 1.35 and 2.50 um from 2 to 3. They extended their research to observe dead leaves, and found that 2 or 3 stacked leaves produce infinite reflectance across the entire wavelength interval between .5 and 2.5 um.

Bauer (1975) stated that if LAI is between .5 and 3, near infrared reflectance increases linearly. When LAI is greater than 3, reflectance does not change much (Bauer and Cipra, unpublished).

Leamer et al (1978), studying wheat cultivars, reported that once 25 % of the ground is covered by plants, all spectral curves display the same features characteristic of vegetated areas.

These researchers found that the area of ground covered by vegetation has a greater effect on reflectance between .45 and 2.50 um than does stage of physiological development. The LAI required for infinite reflectance between .75 and 1.35 um would rarely be attained since wheat canopies are seldom 8-leaf-layers thick (Leamer et al, 1980). Leamer et al (1980) revised their statement on effect of developmental stage, recognizing that near infrared reflectance (.75 to 1.35 um) could be closely related to stage of physiological development as long as leaf numbers increase. Once senescence of lower leaves commences (at the booting stage), reflectance decreases at these wavelengths.

2.2.3 Effect of Illumination Angles on Crop Canopy Reflectance

The importance of sun angle on reflectance has been well studied. In 1957, Davis reported that as the angle of the sun varies, so does reflectance of grass.

Gates et al (1965) stated that the amount of solar radiation that a plant absorbs is a function of not only light intensity and specular distribution of energy, but also the angle of solar incidence on the plant surface. Gates and Tantraporn (1952) determined that at a 65 degree angle of incidence, crop reflectance of wavelengths between 1.5 and 25 um is usually less than 5 %. In comparison, at a 20 degree angle of incidence, less than 3 % reflectance occurs (Gates and Tantraporn, 1952).

Egbert and Ulaby (1972) studied the importance of angles on reflectivity. They noted that by determining the effect of angles on reflectance, optimum time of day and direction of flight for aerial photographs could be selected.

For example, in all spectral bands between .45 and .70 um, reflectivity is greatest for azimuth angles of 0 and 180 degrees and large angles of incidence (Egbert and Ulaby, 1972). Steiner and Gutermann (1966) and Salomonson and Marlatt (1966) pointed out that reflectance is greater if observed downsun rather than upsun.

Egbert and Ulaby recognized the importance of three angles: incidence angle, azimuth angle and zenith angle. By choosing the correct combination of angles, maximum contrast between the plants and soil background could be attained (Egbert and Ulaby, 1972).

2.3 REFLECTANCE MODELS

Bonner (1962) suggested that the extinction of light as it passes through a crop canopy could be explained with the Bouguer-Lambert-Beer law. Light intensity would decrease exponentially as pathlength through the canopy increased. Inadequacies of applying this law to crop canopies were evident to Monteith. The nonuniformity of light distribution across the canopy (influenced by crop geometry) and the changing of specular composition as radiation passes through the canopy are two sources producing error.

Monteith (1965) presented a more accurate model of light distribution in field crops by using light intensity, the fraction of light passing through a unit leaf layer without interception, leaf transmission and LAI.

Allen and Richardson (1968) agreed with Monteith that the Bouguer-Lambert-Beer law was of limited usefulness, because it only accounted for transmittance. The Kubelka-Munk (K-M) theory, on the other hand, incorporated both reflectance and transmittance values (Allen and Richardson, 1968). Allen and Richardson (1968) and Allen et al (1970) successfully applied the K-M theory and Duntley equations to 2, 4, 6 and 8 stacked leaves. They stated that almost all relations used previously to describe scattering of light within a canopy were merely variations of this theory. Reflectance and transmittance for stacked leaves are functions of total leaf area, an absorption coefficient, a scattering coefficient and background reflectivity (Allen and Richardson, 1968). These same optical parameters could be measured for a canopy.

Idso and deWit (1970) pointed out that the extension of the K-M theory used by Allen and Richardson was not accurate because this model was based on uniform leaf distribution and leaf orientation. Furthermore, the Allen-Richardson model did not consider the effect of sun elevation angle varying throughout the day, subsequently altering scattering and absorption coefficients (Idso and deWit, 1970).

Idso and deWit proposed a theory where the three most important parameters are scattering coefficients of the individual leaf for direct solar radiation, diffuse skylight and light transmitted through vegetation. The leaf distribution function of the crop, LAI, canopy density, direct solar radiation and diffuse skylight must also be determined (Idso and deWit, 1970).

Suits (1972), like Idso and deWit, found shortcomings with the model presented by Allen and Richardson (1968), and therefore expanded this model to account for multiple leaf layers having different biological components. In Suits' model, reflectance is recognized as being non-Lambertian. Bidirectional reflectance is predicted on the basis of crop geometry and spectral properties of randomly distributed canopy components.

2.4 EFFECT OF WATER ON LEAF REFLECTANCE

Water is often a major limiting factor of optimum wheat yield. The effect of water shortages on crop growth and photosynthesis makes it desirable to predict crop water status quickly and accurately. The possibility of using remote sensing for this purpose has been recognized.

2.4.1 Influence of Absolute Water Content on Reflectance

The overwhelming influence of water on middle infrared spectral curves was illustrated by Gausman and Allen (1973) when they were able to simulate absorption of a compact leaf (between 1.35 and 2.50 um) by absorption of an equivalent water thickness. (Equivalent water thickness is the thickness of a layer of water that will account for total absorption in the middle infrared (Knipling, 1970).)

Thomas et al (1966) stated that both relative turgidity and water content affect reflectance throughout the .4 to 2.5 um interval. Tucker (1980) called the region between .7 and 2.5 um a liquid water absorption band having three orders of magnitude, basing this on the absorption spectrum of pure liquid water ascertained by Curcio and Petty (1951).

Allen et al (1969) showed that the absorption spectral curve of a corn leaf could be accounted for by superposing the absorption coefficients of chlorophyll and pure liquid water. They attributed any discrepancies in reflectance between 1.4 and 2.5 um to other leaf substances or inaccuracies of the water absorption spectrum.

Thomas et al (1966) noted that infrared reflectance of cotton was more closely related to leaf water content than relative turgidity. A large part of the variability in reflectance could be explained by differences in leaf water content. Furthermore, relative turgidity has no effect unless it is less than 80% (Thomas et al, 1966).

Water content had a definite effect on corn leaf reflectance at 1 um (Thomas et al, 1971). A decrease in water content by 2.7 % resulted in reflectance increasing from 39.3 % to 44.5% (Thomas et al, 1971). As water content continued to decrease, the decrease in reflectance was attributed to changes in internal structure.

Al-Abbas et al (1974) found from their work on maize leaves that there is a positive correlation between moisture content and absorption of light at 1.45 and 1.93 um. They furthermore noted that leaf moisture content and leaf thickness were strongly correlated.

Thomas et al (1967) stated that reflectance is most affected by absolute water content and relative water content at 1.45 um, and also at 1.65 and 2.20 um.

Whereas others (Knipling, 1970; Colwell, 1974) claimed that visible radiation is a better indicator of stress than near infrared radiation, Thomas et al (1971) found that the increase in visible reflectance (.4 to .75 um) normally associated with decreased leaf water content is not always observed.

Tucker (1980) found that the spectral regions where reflectance is best correlated with equivalent water thickness are 2.10 to 2.35 um, 1.83 to 1.88 um, 1.42 to 1.82 um and 1.90 to 2.05 um. The relationship between reflectance and equivalent water thickness are slightly nonlinear at 1.47, 1.65 and 2.15 um, and very nonlinear at 1.97 um (Tucker, 1980). Tucker concluded that leaf water content and reflectance are better correlated at wavelengths of moderate absorption than at wavelengths of high absorption.

2.4.2 Influence of Relative Water Content (Relative Turgidity) on Reflectance

Carlson et al (1971) found reflectance is strongly correlated with relative water content and specific leaf densities. The specific dry weight density (a thickness term measured in mg/cm^2) influences transmissivity more than reflectivity.

Woolley (1971) noted that when relative water content is decreased from 97 % to 77 %, species respond differently: corn leaves increase reflectance substantially, reflectance from soybeans remains about the same, and reflectance from cotton leaves decreases slightly.

At wavelengths of 1.45, 1.95 and 2.20 um, relative water content could account for at least 80 % of the variability in reflectance of corn, sorghum and soybean (Carlson et al, 1971).

Thomas et al (1971), working on cotton, corn and citrus, determined that both relative turgidity and water content are highly correlated with reflectance at 1.45 and 1.93 um. However, due to changing leaf structure, leaf water status could not be reliably predicted from reflectance.

Relative turgidity affects cotton leaf reflectance most significantly when it is less than 70 %, at which time leaves are wilted (Thomas et al, 1971). Thomas et al found differences in reflectance when relative turgidity was between 70 and 80 % were small, and relative turgidity could not be predicted on this basis.

Thomas et al (1971) stated that the combined effects of relative turgidity and leaf thickness on reflectance at 1.45 um were statistically significant (r=-.83). However, reflectance from osmotically stressed leaves was only slightly higher than from nonosmotically stressed leaves (Thomas et al, 1971).

2.5 EFFECT OF WATER STRESS ON LEAF AREA INDEX

It was mentioned earlier that leaf area index is an important factor affecting reflectance. This is applicable in determining whether a plant is under water stress: as water stress persists, leaf area index and leaf orientation both change.

Knipling (1970) found that stress was determined more by total leaf area being reduced than by changes induced in individual leaves. Bauer (1975) agreed, stating that changes in leaf area, leaf orientation, and amount of ground cover could be the key elements used as indicators of abnormal conditions.

Thomas et al (1977) reported that dehydration may be detected not only by increases in reflectance but also by changes in spectral composition due to changes in crop geometry during wilting. These researchers suggested that the changes in spectral composition may actually be the better indication of water stress.

2.6 PAST RESEARCH WITH SIMILAR INSTRUMENTATION

The instrumentation of this research project has been utilized in several crop monitoring experiments.

Tinker et al (1979) used a similar ground-based system to classify land use categories, crop maturity, crop type and disease status. Data in both visible (.35 to .75 um) and infrared (.75 to 1.85 um) regions were obtained from field plots of sod, soil, cereal and broadleaf crops. The ability to discriminate between land use categories (95.2 % accuracy) and crop maturity (93.3 % accuracy) was very good. The accuracy of classifying cereals specifically was low.

Glick et al (1982), using a similar system for measuring reflectance between .35 and .75 um, compared reflectance of wheat, barley, oats, sod and fallow plots. They determined that fallow could be discriminated from cereal crops throughout the season, and sod could be differentiated from cereal crops at preboot and anthesis. Wheat, oats and barley could be most accurately separated at anthesis. After anthesis, discrimination of these crops was low.

Pchajek (1983) used the same basic instrumentation for reflectance measurements between .35 and .75 um. His research project involved comparison of reflectance between root-rot infected and noninfected field plots of wheat.

Discrimination between diseased and nondiseased plots was best at the early tillering stage between .4 and .5 um, and between .6 and .7 um.

Berard (1982) conducted research with the same system used in the present study, measuring reflectance between 1.4 through 2.4 um. His research was concerned with determining the possibility of correlating protein content with relative reflectance from a wheat canopy in a greenhouse. Five levels of nitrogen application were established. Protein content was determined for each plot and correlations were calculated for each .01 um interval between 1.4 and 2.4 um.

The best correlations between protein content and relative reflectance occurred at the beginning of heading: a correlation coefficient of -.72 was observed at 2.11 um.

Chapter III

MATERIALS AND METHODS

3.1 EXPERIMENTAL MATERIAL AND DESIGN

Two experiments were conducted in a plastic greenhouse to which a mobile spectroscopy laboratory was attached. In each experiment, Neepawa hard red spring wheat was sown in Graysville (Chernozemic) soil. Two soil fertility tests were performed on this soil: one prior to the first experiment, the second prior to the second experiment (Table 1). The permanent wilting point and field capacity were determined to be 5.6 % and 20.0 % respectively.

TABLE 1

CHARACTERISTICS OF GRAYSVILLE SOIL

TEST	TEXTURE	pH	NO3-N (ppm)	AVAILABLE P (ppm)	AVAILABLE K (ppm)
first	VFSL	7.3	16.3	7.2	51
second	VFS	7.6	90.0	8.0	45

Wooden boxes measuring 70 cm. by 70 cm. by 20 cm. deep were filled with soil (100 kilograms per box in experiment 1, and 113 kilograms per box in experiment 2). The seeding rate was 121 seeds per plot (box) which is equivalent to 75 kilograms per hectare. In experiment 1, nine plots were seeded February 19, 1982 and in experiment 2, six plots were seeded September 11, 1982. Plots were arranged in a completely randomized design and were periodically and systematically repositioned in order to minimize the effect of gradients along the greenhouse. Lighting consisted of high intensity metal halide lamps alternated with high pressure sodium vapor lamps. Plots were placed directly below these rows of lighting. Intensity of the lighting varied from 80 to 400 microeinsteins per square meter per second at the crop canopy, and from 20 to 100 microeinsteins per square meter per second at ground level. Timing of lights was set to simulate a fifteen hour day/ nine hour night. Day temperature was set at 23 C and night temperature at 13 to 16 C.

Plots were weeded by hand to maintain a clean stand, and treated with insecticides to control aphid populations. In experiment 1, Pirimore[1] was applied only once 28 days after seeding whereas in experiment 2, Pirimore was applied twice (34 and 65 days after seeding) and insecticidal soap[2] was applied three times (16, 28 and 31 days after seeding).

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[1] Supplier: Chipman Inc., Stoney Creek, Ontario, L8G 3Z1.
[2] Supplier: Safer Agro-Chem Ltd., Victoria, British Columbia.

Insecticides tended to leave water spots on the leaves. This may have affected reflectance but it was assumed that all plots were affected equally.

Plots were fertilized four weeks after seeding. In experiment 1, both 34-0-0 ammonium nitrate (16.4 grams per plot, equivalent to 125 kilograms nitrogen per hectare) and 10-52-10 phosphorus fertilizer (2.61 grams per plot, equivalent to 30 kilograms phosphorus per hectare) were added. Because the second soil test indicated a high concentration of N03-N (Table 1), in experiment 2 only 10-52-10 fertilizer was added at a rate of 45 kilograms phosphorus per hectare.

Plants were watered regularly and uniformly until the tillering stage which occurred five weeks after seeding. At this time stress treatments were initiated. All plots were watered to field capacity and allowed to dry to their calculated rewatering weights. In both experiments, there were three replicates of each treatment. The three treatments of experiment 1 consisted of drying the plots to:

1) 16 % water content (treatment A);
2) 12 % water content (treatment B); or
3) 8 % water content (treatment C).

In experiment 2, plots were dried to either:

1) 16 % water content (treatment A); or
2) 8 % water content (treatment C).

When the percent soil water content of at least two replicates of a given treatment decreased to their designated stress level, all three replicates were rewatered to field capacity.

Ideally infrared reflectance scans would be taken the night prior to rewatering all treatments. Treatment A would have been watered most recently (and most frequently), and treatment C would be without water for the longest period. At this time maximum variation between stress treatments should be exhibited. In experiment 1, the relative reflectance measurements were made independent of the watering schedule (Table 2). In experiment 2, the relative reflectance measurements and watering schedule were synchronized so scans would be taken the night prior to rewatering of all treatments.

TABLE 2

WATERING SCHEDULE FOR EXPERIMENT 1

DATE OF REFLECTANCE MEASUREMENT (days after seeding)	NUMBER OF DAYS SINCE LAST WATERING TREATMENT A	B	C
38	2	0	3
43	2	2	5
47	0	0	0
55	1	1	4
60	0	2	3
66	0	1	1
70	1	1	1
75	0	2	2
79	1	3	6
86	0	2	4
90	0	1	8
94	1	1	1
97	2	4	4

Treatments A, B and C were dried to 16, 12 and 8 % soil water content, respectively, before being rewatered. (A value of zero (0) indicates plots were watered that same day.)

3.2 INSTRUMENTATION AND PROCEDURE

The middle infrared spectrometer system developed by the Engineering and Statistical Research Institute (Agriculture Canada, Ottawa) was housed in a mobile laboratory that was connected to the plastic greenhouse by a wide passageway (Figure 1, 2). A window of the laboratory opened towards the greenhouse. Seven meters from the window, a viewing platform was constructed. This viewing platform consisted of a large scale raised on cement blocks. A plot was forklifted onto this scale and black cloth placed directly behind the plot (so that the background would be standard).

All scans were conducted at night in order to eliminate such intervening factors as sun angles and shadow effects imposed by the greenhouse structure. The overhead greenhouse lights were switched off. Two 1000 Watt quartz bromine studio lamps (Acme - Lite model 710SL) served as the light source during the scans. These lamps were placed adjacent to each other within one half meter of the viewing platform and were directed towards the plot on the platform. Three plants from each replicate were harvested, dried and reweighed to determine water content. In addition to conducting fresh weight - dry weight calculations on all plots, in Experiment 2 leaf water potentials were obtained from two replicates of treatment A and one replicate of treatment C. Merrill thermocouple screen psychrometers with calibration chambers (model 74-13C)[1] were used for these determinations.

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[1] Supplier: J.R.D. Merrill 'SPECIALTY EQUIPMENT', R.F.D. Box 140A, Logan, Utah 84321.

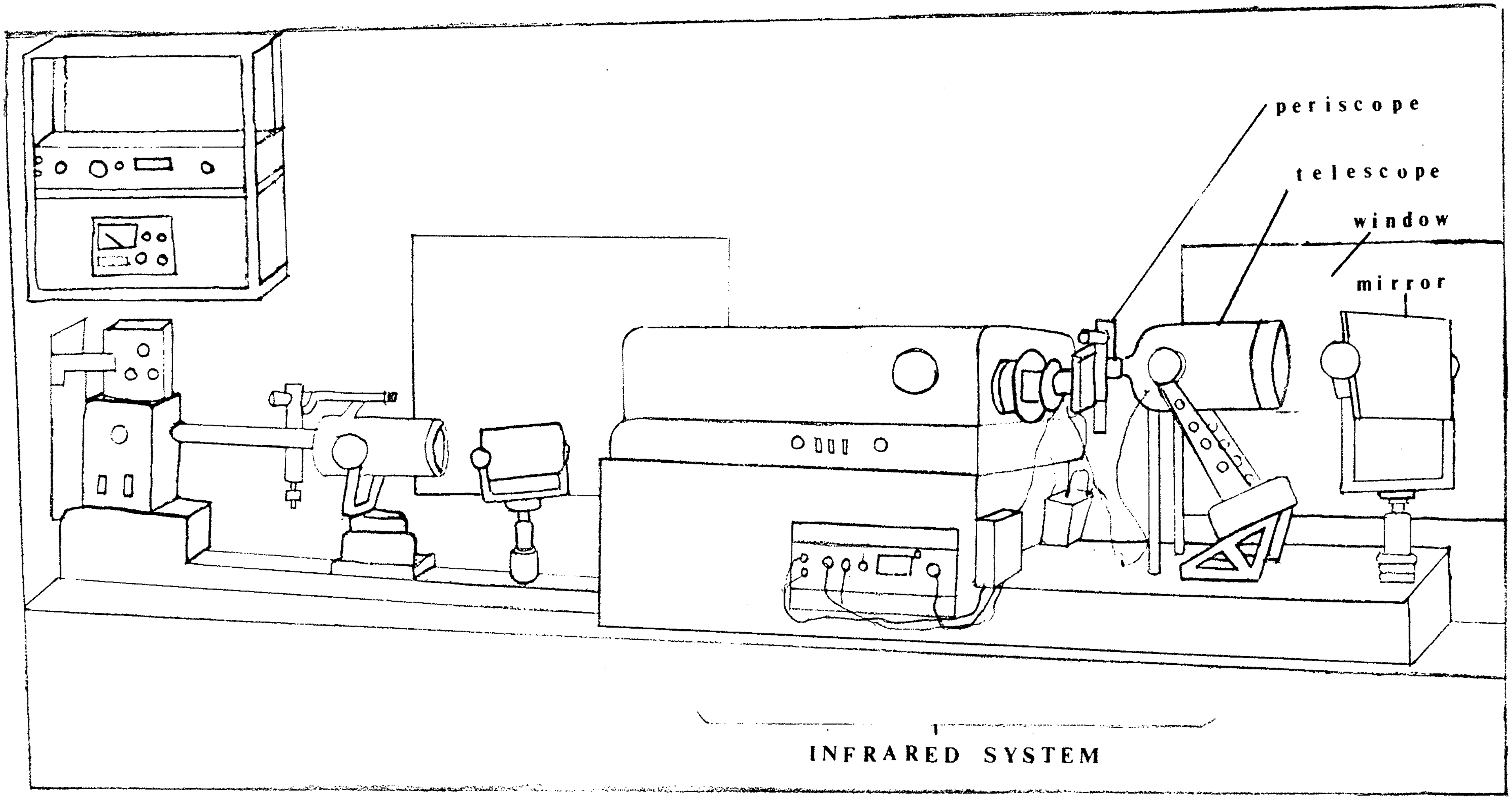


Figure 1: The mobile laboratory spectral system, excluding the data acquisition system, data processing unit and plotter.

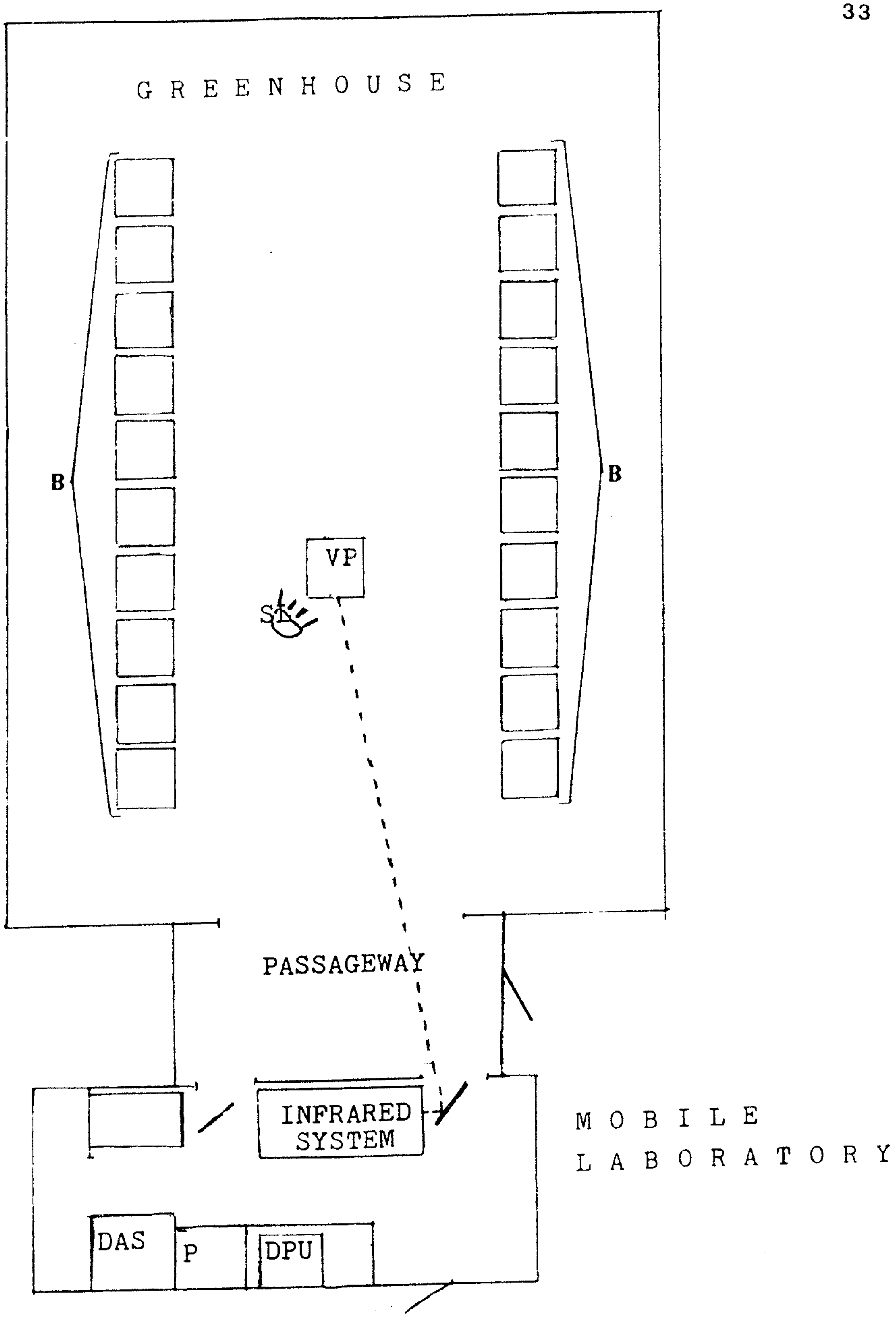


Figure 2: Schematic diagram of the experimental set-up : viewing platform (VP), studio lamps (SL), data acquisition system (DAS), plotter (P), data processing unit (DPU), plots (B).

After the plant samples were collected, the scanning procedure was started. A schematic diagram of the reflectance measuring system is shown in Figure 3. This instrumentation was used previously by Berard (1982). Glick (1982), Tinker et al (1979) and Pchajek (1983) used modifications of this system.

The Schmidt-Cassegrain telescope (Celestron, Field of View = .2834 degrees/cm) was focused on the wheat leaves. A flat front-surfaced folding mirror (M) located beside the open laboratory window was adjusted so that the energy reflected from the plot would hit the mirror and be directed into the telescope. Once in the telescope the energy was focused by a telecompressor lens (Tc) through the entrance slit (Si) of the monochromator (McPherson model 2051). Immediately before the beam of radiation entered the slit, the signal was chopped at a rate of 30 Hertz. The light passing through the slit was directed by a collimating mirror (Mc) towards the diffraction grating (G) which dispersed the light into distinct wavelengths. The angle of the grating changed throughout the scan, and thereby the relative intensity of radiation at each .0025 micrometer wavelength interval between 1.40 and 2.40 micrometers was measured. From the grating, the diffracted energy was reflected onto a focusing mirror (Mf) which then reflected the energy out of the monochromator through the exit slit (So). Next to this exit slit was the lead sulfide detector (D) which sensed the diffracted energy. The signal was amplified by the lock-in amplifier that gave relative reflectance values. Data were passed on to the Hewlett-Packard 3052A automatic data acquisition system (DAS) and the Hewlett-Packard 9825A data processing unit (DPU). The output was recorded on computer cassette (Hewlett-Packard 9162 - 0061 data cartridge) and a graph of rela-

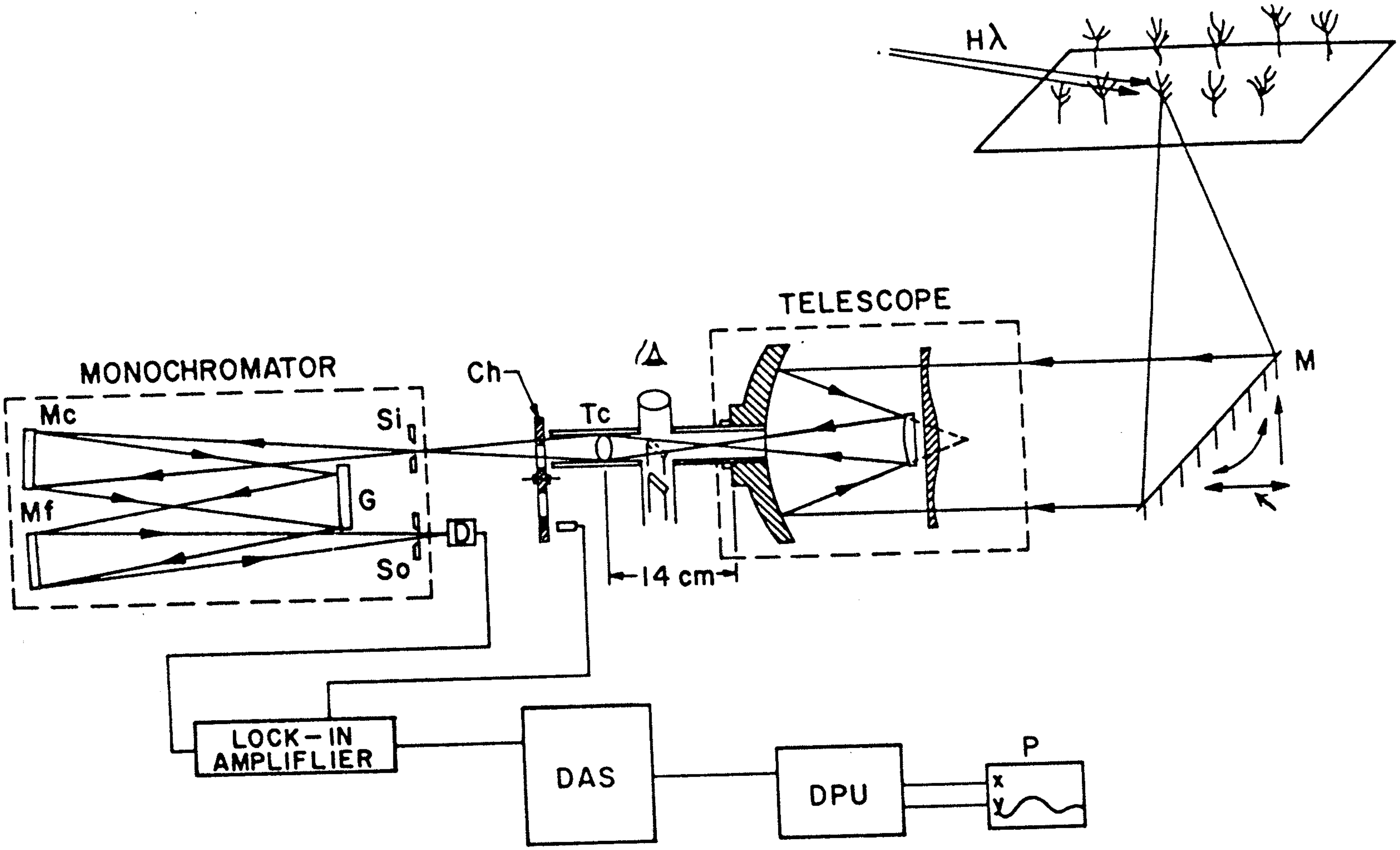


Figure 3: Diagram of the middle infrared spectral system: incident energy (Hλ); flat-folding mirror (M); telecompressor lens (Tc); chopper (Ch); entrance slit (Si); collimating mirror (Mc); grating (G); focusing mirror (Mf); exit slit (So); lead sulphide detector (D); data acquisition system (DAS); data processing unit (DPU); plotter (P).

From Berard (1982)

tive reflectance versus wavelength was obtained (using Hewlett-Packard plotter 9872A (P)).

The data collected in each scan were categorized as to plot number, sensitivity settings of the spectrometer, time, date and the location on the data cassette (file and track) where the information was stored. Output data were the wavelength and relative reflectance of the middle infrared radiation.

The scanned plot was removed from the platform and replaced by the next plot to be scanned. After all plots had been scanned, an anodized aluminum reflectance plate was set up vertically on a plot of bare soil. This plate had a honeycomb surface and had been calibrated in the visible region by the Engineering and Statistical Research Institute, Research Branch, Agriculture Canada. The energy reflected from this plate was assumed to represent the specular component of reflected middle infrared radiation, and was used to standardize the data.

Scans were started at tillering and were continued until grain filling. In experiment 2 mildew was noted on some plots just before the last three scan dates. On the last scan date of experiment 2, all plots had mildew. Mildew may have affected the amount of reflectance occurring at the leaf surface, and not all plots were infected at the same time or to the same degree.

After the final relative reflectance measurements were made, the data processing unit was interfaced with the University of Manitoba Amdahl 470/V8 computer system to transfer data into a system where statistical analyses could be performed.

A large degree of variability was found in the spectral reflectance curves. Therefore a time scan was run in which a single plot was scanned four times consecutively. Parameters measured concurrently with the scans included diffusion resistance, leaf temperature, relative humidity, and transpiration rate.

3.3 ANALYSES

Raw relative reflectance curves are highly variable due to such factors as noise and leaf area index. Examples of raw relative reflectance curves are given in Figures 4, 5, 6, 7, and 8. Each figure consists of three replicates of one treatment on a given date. (The date was randomly selected since the variation illustrated in these figures is representative of the experiments.)

Curves from 47 days after seeding were plotted for Experiment 1. The relative reflectance values for treatments A, B and C (treatment A being least stressed, treatment C being the most highly stressed) are plotted versus wavelength in Figures 4, 5, and 6 respectively.

In experiment 2, there were only two treatments, treatments A and C. Figures 7 and 8 were obtained by using relative reflectance values from 56 days after seeding.

It is evident that in both experiments 1 and 2 there was as much variation within treatments as between treatments.

Due to the great variation in spectral curves, attempts were made to reduce any differences not attributable to effect of water stress treatments. Three steps were taken to accomplish this:

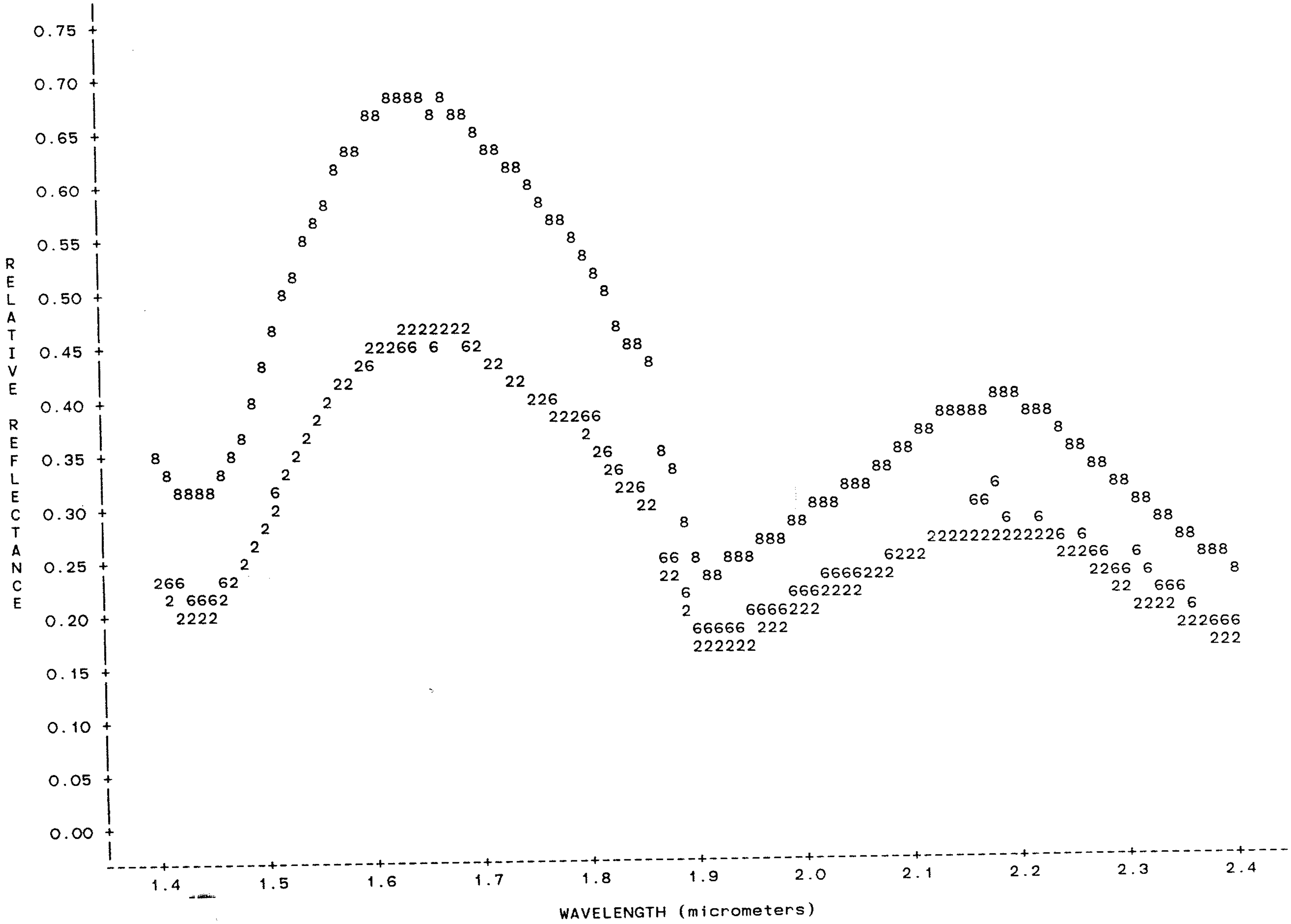


Figure 4: Raw relative reflectance curves for the three replicates of the least stressed treatment, treatment A (Experiment 1) at 47 days after seeding: plot 2(2), plot 6(6), plot 8(8).

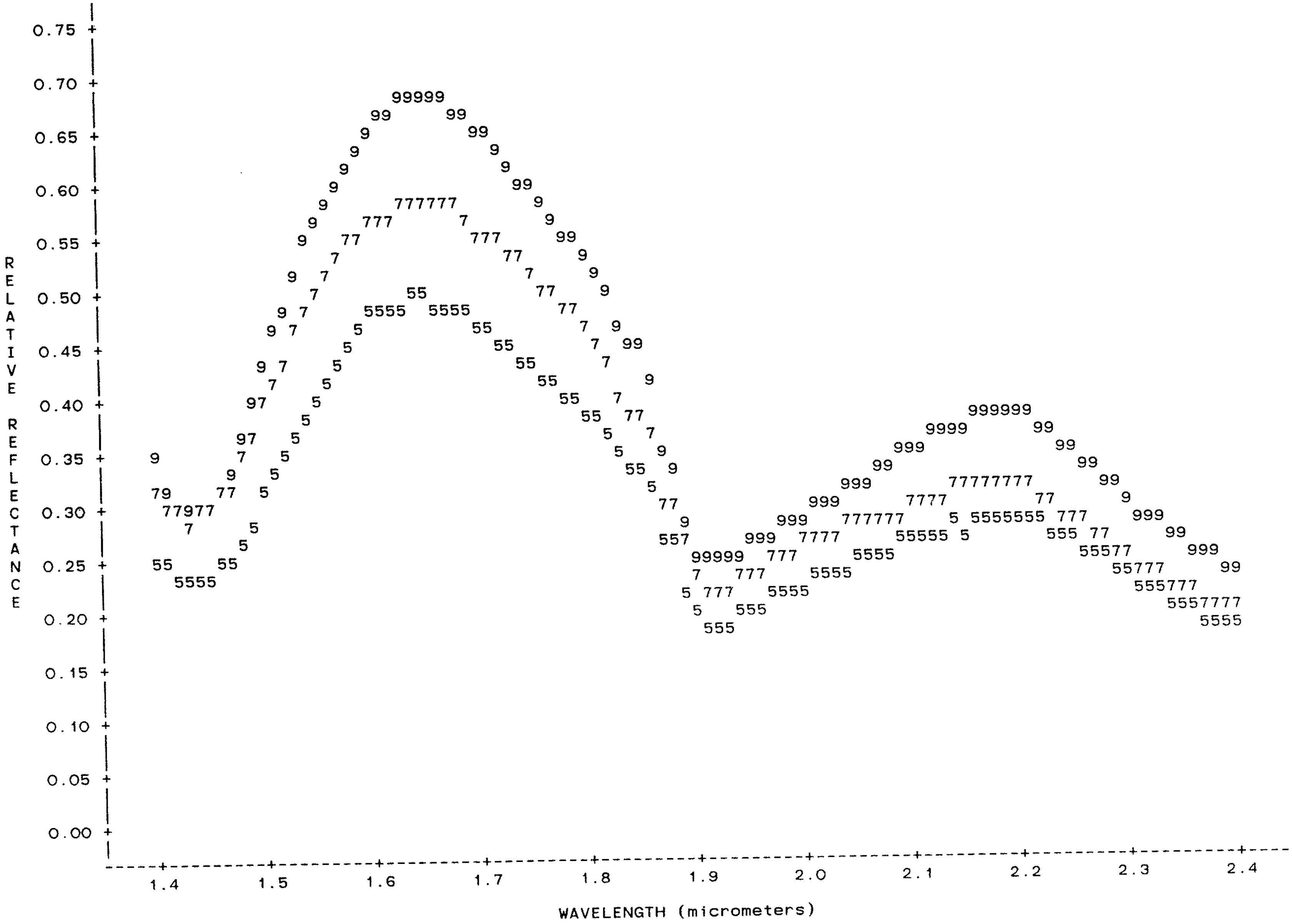


Figure 5: Raw relative reflectance curves for the three replicates of the moderately stressed treatment, treatment B (Experiment 1) at 47 days after seeding (late tillering/flag stage): plot 5(5), plot 7(7), plot 9(9).

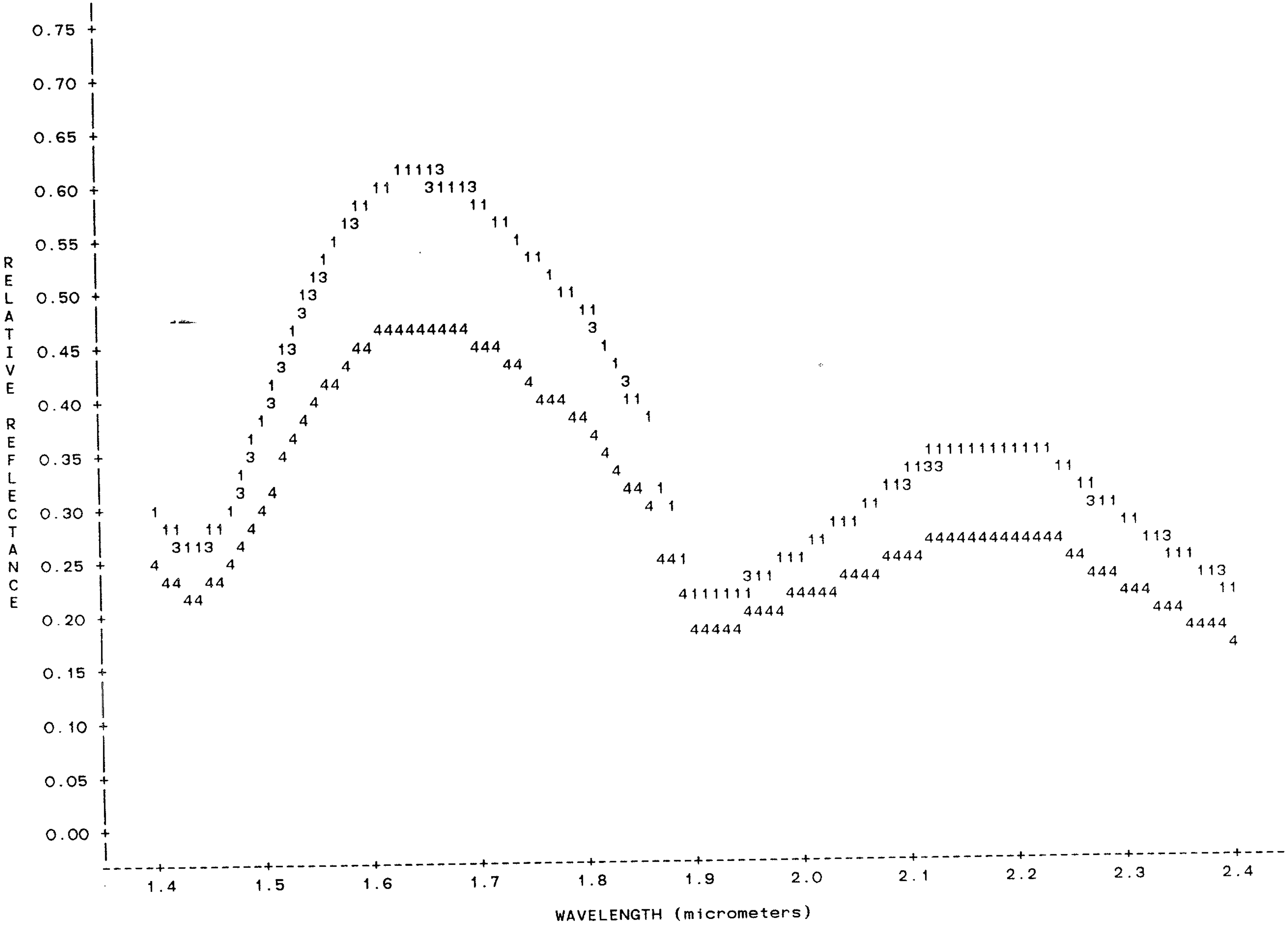


Figure 6: Raw relative reflectance curves for the three replicates of the highly stressed treatment, treatment C (Experiment 1) at 47 days after seedingg (late tillering/flag stage): plot 1(1), plot 3(3), plot 4(4).

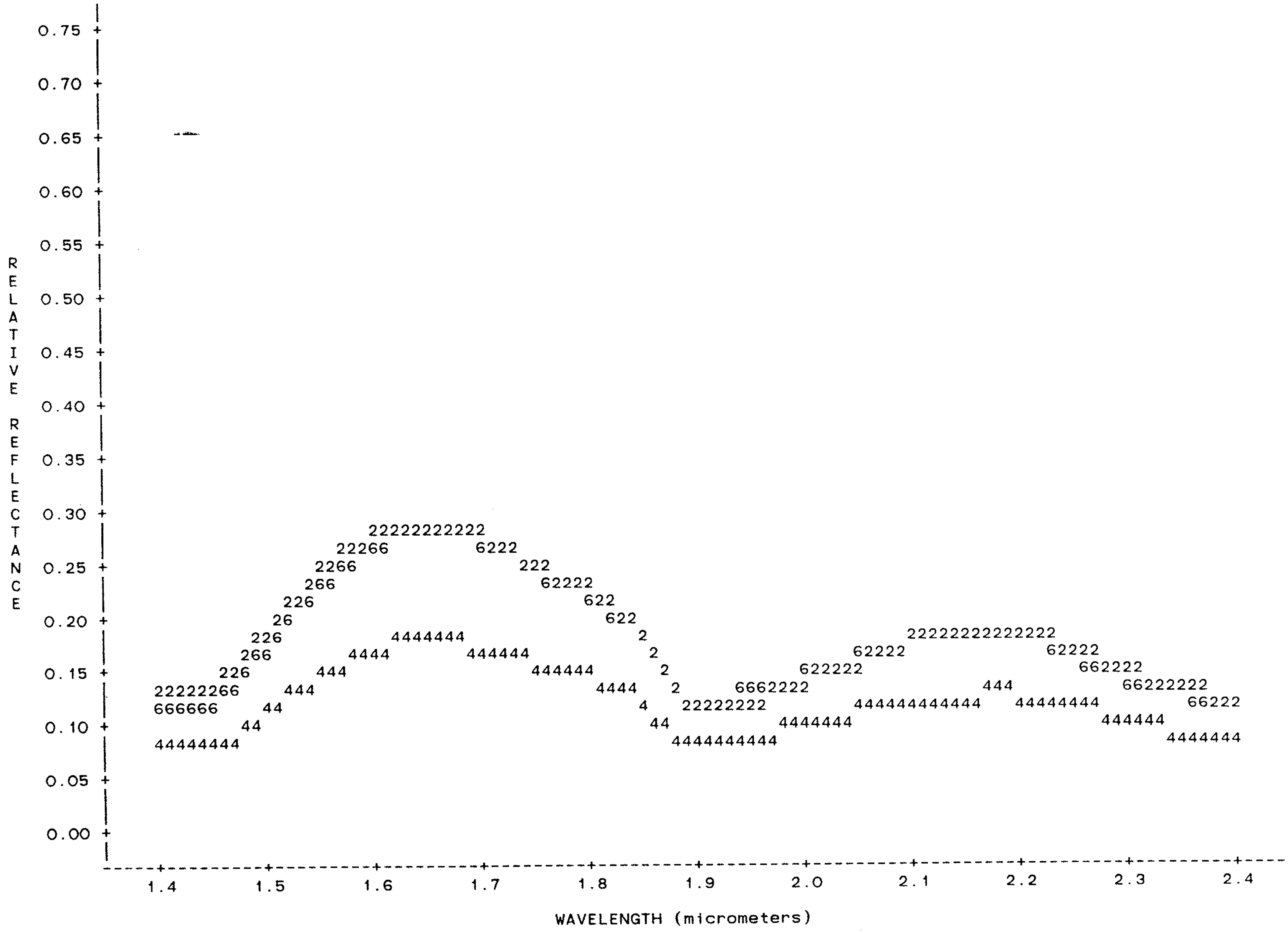


Figure 7: Raw relative reflectance curves for the three replicates of the least stressed treatment, treatment A (Experiment 2) at 56 days after seeding (flag leaf stage): plot 2(2), plot 4(4), plot 6(6).

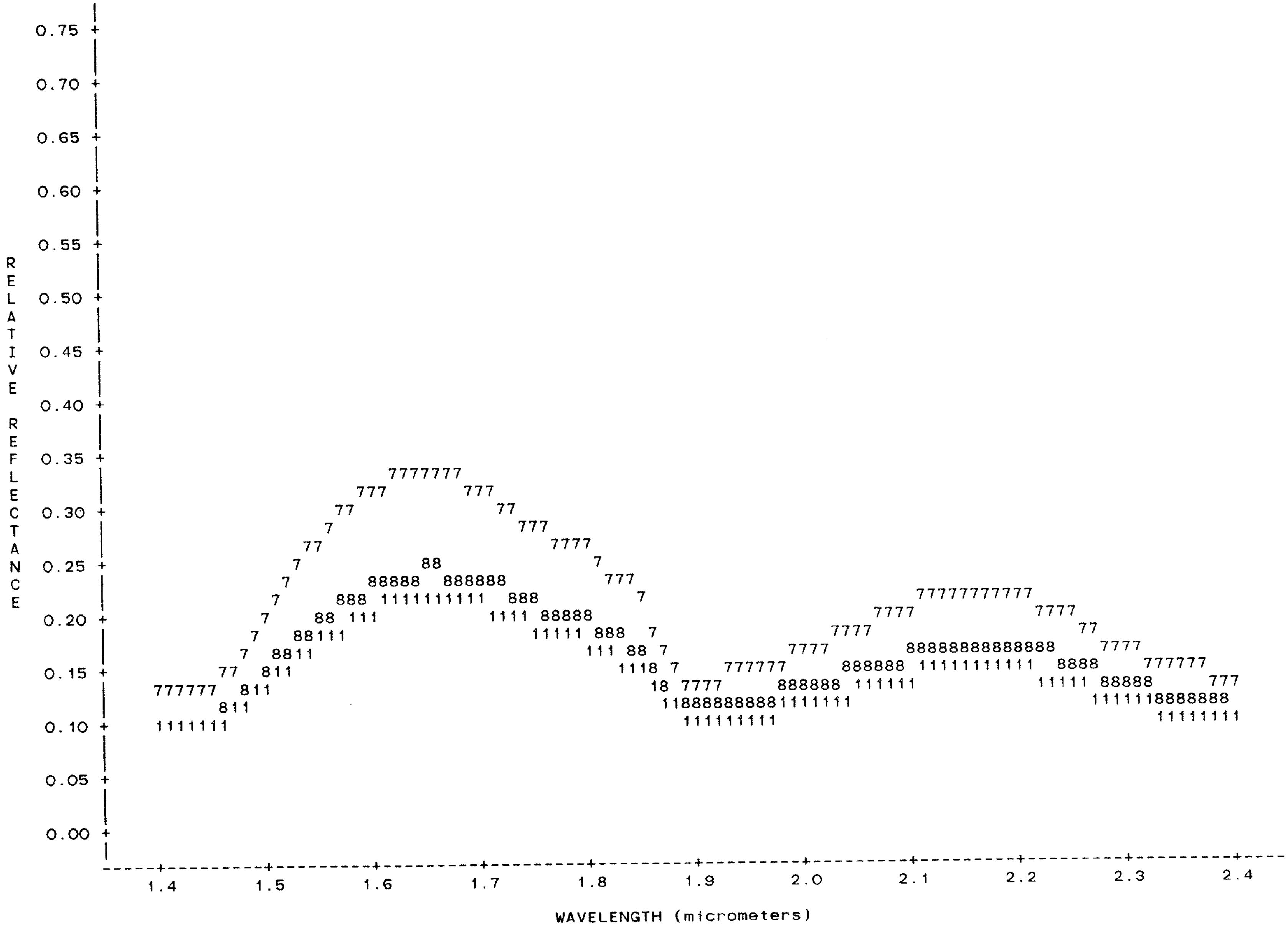


Figure 8: Raw relative reflectance curves for the three replicates of the highly stressed treatment, treatment C (Experiment 2) at 56 days after seeding: plot 1(1), plot 7(7), plot 8(8).

1) reduction of data points
2) subtraction of a standard
3) ratioing of curves

This approach was previously used by Berard (1982).

3.3.1 REDUCTION OF DATA POINTS

Middle infrared reflectance was measured from 1.40 to 2.40 micrometers in .0025 micrometer increments (401 data points). To improve the signal-to-noise ratio and thereby smooth out the spectral curves, reflectance was averaged over .01 micrometer intervals. This resulted in 101 data points per spectral curve.

3.3.2 SUBTRACTION OF A STANDARD

The next step was to designate a standard with which to compare all the reflectance curves of a given date. This standard would be subtracted from each reflectance curve. Two approaches were attempted.

The first approach was based on the fact that total reflectance can be divided into two components: diffuse and specular reflectance (Figure 9). When radiation encounters a leaf it can either be reflected from the leaf surface or can penetrate the leaf where it interacts with leaf components (being absorbed, transmitted or reflected). Specular reflectance occurs from very glossy leaf surfaces, and is mirror-like in nature (Sinclair, 1973). Diffuse reflectance occurs when radiation encounters rougher leaf surfaces (Sinclair, 1973) or when radiation penetrates the leaf (Mestre, 1935), interacts with the internal composition of the leaf and is ultimately reflected back out.

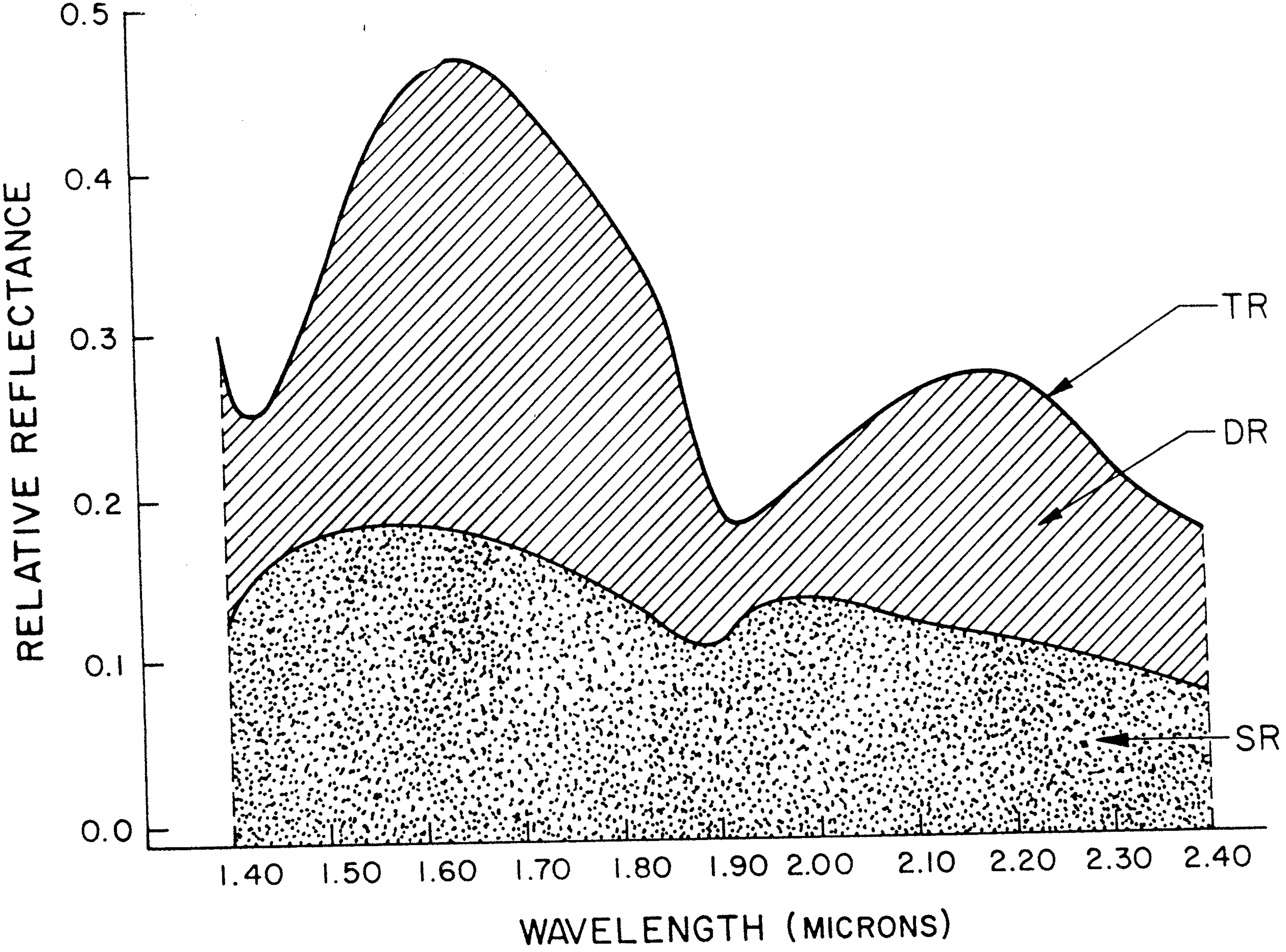


Figure 9: Schematic diagram of spectral reflectance components for a typical crop. TR, total reflectance; DR, diffuse reflectance; SR, specular reflectance.

From Berard (1982)

Since the specular component does not reveal any information about the leaves, it can be subtracted from the spectral curves without depreciating the value of the data (Rotolo, 1979).

Reflectance from the aluminum plate represented the specular component of the wheat canopy; it was measured for every set (date) of reflectance measurements. The raw relative reflectance curves (reduced to 101 data points) corresponded to the total reflectance curves. The reflectance values of the plate were much higher than the total reflectance from the plants. To ensure that positive numbers were obtained when subtracting the specular reflectance plate from total reflectance, the curve of the reflectance plate was ratioed down before being subtracted from the reflectance curves of the plots (see ANALYSES: RATIOING OF CURVES). This difference between total and specular reflectance was assumed to be the diffuse component of reflectance.

In the second approach to standardization of the reflectance curves, instead of using the reflectance plate to remove the specular component, for each date the average relative reflectance of the three replicates of the least stressed treatment, treatment A, was determined.

To eliminate the possibility of any negative relative reflectance values, this average relative reflectance curve of treatment A was ratioed down in the same manner as the reflectance from the plate (see ANALYSES: RATIOING OF CURVES). All plots on a given date would have this same standard subtracted from the raw relative reflectance curves. It was assumed that in this way differences beween treatments could be readily observed.

3.3.3 RATIOING OF CURVES

Once the specular component or the average relative reflectance of the least stressed treatment was subtracted, the effect of differences in leaf area index and leaf orientation between plots of all treatments was taken into consideration. The spectral curves of all plots measured on a given date were compared. The point where least variation (lowest coefficient of variation) occurred was assumed to be completely unrelated to treatment effects. The relative reflectance of all the spectral curves would be brought to the mean relative reflectance value at this data point. Each spectral curve would be multiplied by the ratio to which its reflectance at this point was adjusted. For example, in Figure 10 the least variation occurs at z um. The relative reflectance at z um of a single plot is x, and the relative reflectance of the mean of all the plots is y. The ratio by which to multiply the curve of the single plot is w, where:

$$w=y/x$$

3.3.4 STATISTICAL TESTS

In experiments 1 and 2, ANOVA and Duncan's test were performed for each date of relative reflectance measurements. The objective of these statistical tests was to determine whether mean relative reflectance values varied between stress treatments.

In order to do these tests a wavelength had to be selected. For experiment 2, the wavelengths at which best correlation occurred were extracted from the plots of correlation coefficients versus wavelength.

Because no statistically significant correlations could be determined for experiment 1, the dates of the two experiments were roughly matched up according to stages of development. (The plots were maturing at different rates (the greater the stress, the quicker the plants matured) and therefore the description of the stage of development is meant only as a means of comparing between experiments 1 and 2.) In this manner, the wavelengths with the strongest correlation coefficients in experiment 2 were assigned to experiment 1. However, reflectance values from other wavelengths were inserted to see if significance could be improved. The wavelengths which gave better results for analysis of variance and Duncan's test were recorded. When r is positive, reflectance decreases as stress increases (and water potential decreases).

To help minimize influence of noise on reflectance, data from the two wavelengths on either side of the selected wavelength were included in the analysis. (This approach was previously used by Berard (1982).) Thus, data from three consecutive wavelengths spanning .03 um would be used in ANOVA and Duncan's test. For example, if 2.20 um was the selected wavelength, average relative reflectance values from 2.19 through 2.21 um would be used.

In experiment 2, correlations were calculated between relative reflectance and water potential. The correlation coefficients were plotted versus wavelength. When r is negative, this implies that as stress increases (and water potential decreases), reflectance increases.

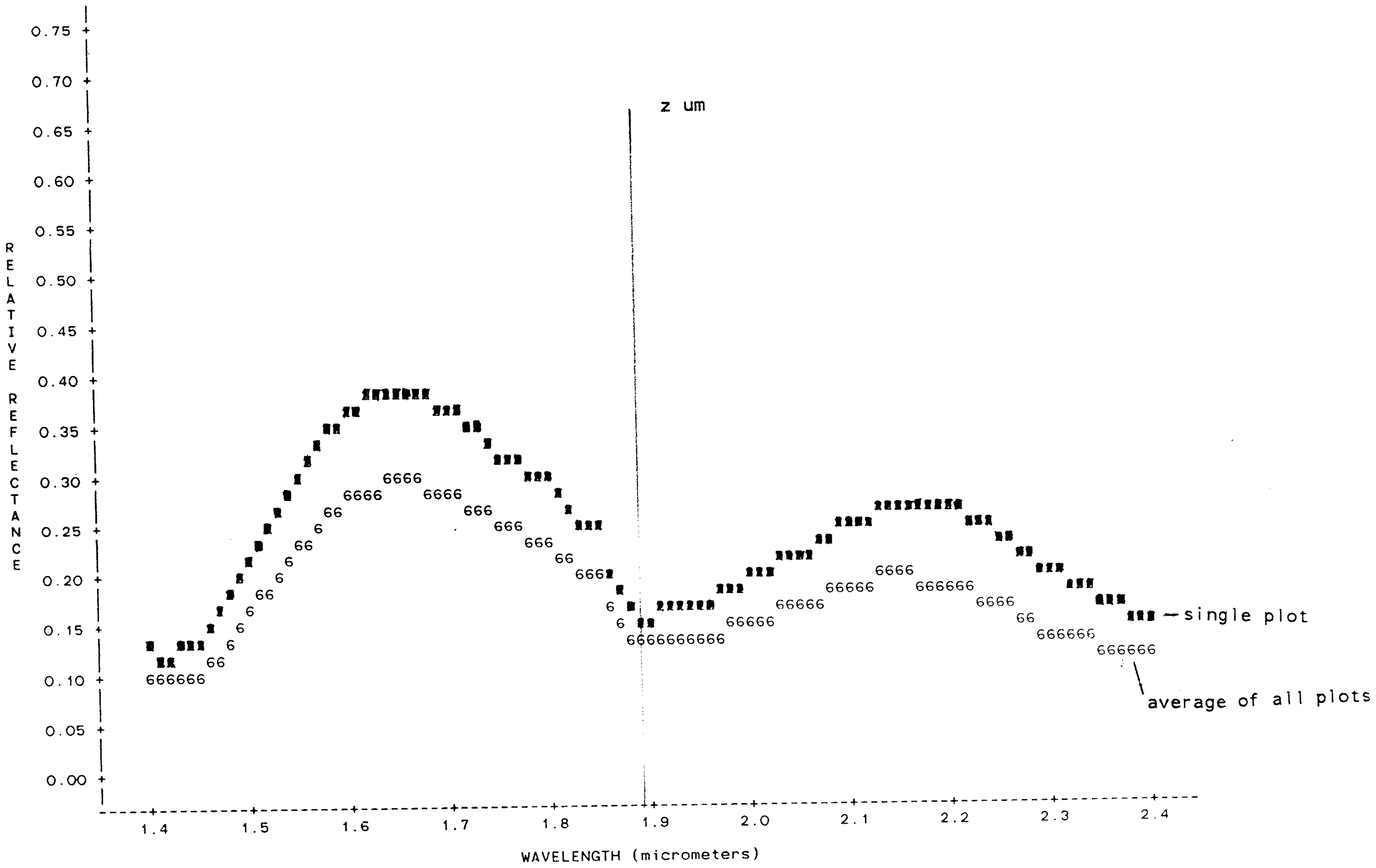


Figure 10: Ratioing curves of reflectance (after subtracting reflectance of the standard).

Chapter IV

RESULTS AND DISCUSSION

In experiment 1, treatments differed significantly in leaf water content (Table 3), but in experiment 2, leaf water contents were not significantly different between treatments (Table 4).

4.1 EXPERIMENT 1

For experiment 1, there were two approaches to analyzing the results for analysis of variance and Duncan's test:

METHOD 1) Three treatments of three replicates each were used in this method where the reflectance from the plate was designated the standard.

METHOD 2) As in Method 1, nine plots were used but in this approach the average relative reflectance of the three replicates of the least stressed treatment served as the standard.

Method 1 results from ANOVA are presented in Table A1 and findings from Duncan's test are summarized in Table 5. Wavelength intervals where tests were performed are given in the tables.

Method 2 ANOVA results are found in Table A2 and results from Duncan's test are given in Table 6.

When considering Experiment 1, the watering schedule (used as an indication of degree of water stress) as well as the average water content of the different treatments must be taken into account. In Table 7, all the dates are listed with results from Duncan's tests of relative reflectance and water content, as well as the number of days each treatment was stressed.

It is well known that a change in water content of a crop influences middle infrared relative reflectance in the area of the water absorption bands, 1.43 and 1.95 um. As water content decreases, reflectance increases. In order to focus on the effect of water stress, the possibility of interaction between water content and relative reflectance measurements must be examined.

TABLE 3

MEAN WATER CONTENTS OF PLANTS OF THE DIFFERENT TREATMENTS (Experiment 1)

DAYS AFTER SEEDING AND GROWTH STAGE	TREATMENT[1]	MEAN WATER CONTENT[2] (%)	DAYS AFTER SEEDING AND GROWTH STAGE	TREATMENT[1]	MEAN WATER CONTENT[2] (%)
38 tillering	A	83.0a	75 milk stage	A	72.9a
	B	81.9a		B	71.0ab
	C	81.0a		C	66.1 b
43 tillering	A	85.6a	79 soft dough	A	68.6a
	B	85.5a		B	68.3a
	C	84.7a		C	64.1a
47 late tillering/ flag	A	83.2a	86 soft dough	A	65.5a
	B	82.7a		B	62.9a
	C	81.9a		C	46.4 b
55 flag/boot/ heading	A	83.4a	90 soft dough	A	55.8a
	B	83.2a		B	46.7ab
	C	80.1 b		C	34.7 b
60 anthesis	A	81.5a	94 hard dough	A	44.5a
	B	79.4ab		B	41.2a
	C	77.3 b		C	17.1 b
66 6 days after anthesis	A	78.8a	97 hard dough	A	35.1a
	B	76.8a		B	29.7a
	C	72.9 b		C	17.3 b
70 10 days after anthesis	A	75.8a			
	B	75.0a			
	C	69.2a			

[1] Treatments A, B and C were dried to 16, 12 and 8 % soil water content, respectively, before being rewatered.

[2] The letter following the water content indicates Duncan's grouping at the 5 % level. Values having the same letter do not differ.

TABLE 4

MEAN WATER CONTENTS OF THE DIFFERENT TREATMENTS (Experiment 2)

DAYS AFTER SEEDING	TREATMENT	MEAN WATER CONTENT[1] (%)	GROWTH STAGE
46	A	86.90a	tillering
	C	86.67a	tillering
51	A	86.58a	tillering
	C	85.30a	tillering
56	A	85.36a	flag
	C	85.40a	flag
63	A	83.87a	flag/boot
	C	83.72a	flag/boot/heading
70	A	83.40a	anthesis
	C	83.98a	anthesis
75	A	81.02a	5 days after anthesis
	C	80.92a	5 days after anthesis
81	A	80.33a	11 days after anthesis
	C	79.31a	11 days after anthesis
87	A	77.59a	milk stage
	C	74.80a	milk stage
94	A	73.80a	soft dough stage
	C	73.37a	soft dough stage

In treatment A, plots were dried to 16% soil water content and rewatered to field capacity. In treatment C, plots were dried to 8% soil water content before being rewatered.

[1] The letter following the water content indicates grouping according to Duncan's test at the 5 % level. Values having the same letter do not differ.

TABLE 5

DUNCAN'S TEST FOR EXPERIMENT 1, STANDARDIZING RESULTS BY MEANS OF THE REFLECTANCE PLATE (METHOD 1)

DAYS AFTER SEEDING: 38 WAVELENGTH INTERVAL: 2.21-2.23 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	15.192 a
A	15.137 a
B	14.918 a

DAYS AFTER SEEDING: 43 WAVELENGTH INTERVAL: 2.21-2.23 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	15.797 a
B	15.600 a
C	14.872 b

DAYS AFTER SEEDING: 47 WAVELENGTH INTERVAL: 1.54-1.56 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
B	22.002 a
C	21.345 a
A	20.744 a

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 5

(continued)

DAYS AFTER SEEDING: 55 WAVELENGTH INTERVAL: 1.73-1.75 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
B	37.953 a
A	36.695 a
C	23.492 b

DAYS AFTER SEEDING: 60 WAVELENGTH INTERVAL: 1.73-1.75 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	21.846 a
B	19.893 a
C	18.045 a

DAYS AFTER SEEDING: 66 WAVELENGTH INTERVAL: 1.73-1.75 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
B	10.038 a
C	10.001 a
A	9.625 a

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 5

(continued)

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 1.70-1.72 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
B	24.648 a
C	24.643 a
A	24.238 a

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 2.21-2.23 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	8.933 a
B	8.925 a
C	8.908 a

DAYS AFTER SEEDING: 79 WAVELENGTH INTERVAL: 2.21-2.23 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	5.447 a
A	5.385 ab
B	5.347 b

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 5

(continued)

DAYS AFTER SEEDING: 86 WAVELENGTH INTERVAL: 1.96-1.98 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	6.096 a
B	4.748 ab
A	2.787 b

DAYS AFTER SEEDING: 90 WAVELENGTH INTERVAL: 1.78-1.80 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	14.161 a
B	11.422 b
A	9.709 b

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.78-1.80 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	3.937 a
B	2.700 b
A	2.255 b

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 5

(continued)

DAYS AFTER SEEDING: 97 WAVELENGTH INTERVAL: 1.78-1.80 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	5.416 a
B	4.687 a
A	1.948 b

---

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 6

DUNCAN'S TEST FOR EXPERIMENT 1, STANDARDIZING RESULTS BY MEANS OF TREATMENT A (METHOD 2)

DAYS AFTER SEEDING: 38 WAVELENGTH INTERVAL: 1.79-1.81 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	25.691 a
C	25.575 a
B	25.544 a

DAYS AFTER SEEDING: 43 WAVELENGTH INTERVAL: 2.21-2.23 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	15.797 a
B	15.600 a
C	14.872 b

DAYS AFTER SEEDING: 47 WAVELENGTH INTERVAL: 2.28-2.30 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	13.472 a
A	13.383 a
B	12.499 b

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 6

(continued)

DAYS AFTER SEEDING: 55 WAVELENGTH INTERVAL: 2.12-2.14 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	26.030 a
B	24.876 a
C	18.675 b

DAYS AFTER SEEDING: 60 WAVELENGTH INTERVAL: 2.12-2.14 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	13.959 a
B	12.731 b
C	10.889 c

DAYS AFTER SEEDING: 66 WAVELENGTH INTERVAL: 2.12-2.14 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	6.247 a
B	5.876 a
A	5.371 a

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 6

(continued)

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.20-2.22 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	18.217 a
B	18.180 ab
C	18.138 b

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 1.80-1.82 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	9.997 a
A	9.268 a
B	8.965 a

DAYS AFTER SEEDING: 79 WAVELENGTH INTERVAL: 1.81-1.83 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	5.906 a
B	5.105 a
A	2.284 b

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 6

(continued)

DAYS AFTER SEEDING: 86 WAVELENGTH INTERVAL: 1.63-1.65 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	11.873 a
A	11.692 b
B	11.681 b

DAYS AFTER SEEDING: 90 WAVELENGTH INTERVAL: 1.63-1.65 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	16.984 a
B	14.178 b
A	12.877 b

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.63-1.65 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	4.752 a
B	3.256 b
A	2.674 b

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 6

(continued)

DAYS AFTER SEEDING: 97 WAVELENGTH INTERVAL: 1.63-1.65 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	6.422 a
B	5.447 a
A	1.816 b

---

[1] Treatments A, B and C were dried to 16, 12, and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

4.1.0.1 COMPARING RELATIVE REFLECTANCE AND WATER CONTENT

The first step was to isolate the dates where analysis of variance indicated relative reflectance differed between treatments. Using Method 1, the four dates in this category were 43, 90, 94 and 97 days after seeding. There were three other dates where Duncan's test (but not analysis of variance) also indicated relative reflectance differed between treatments: 55, 79 and 86 days after seeding.

Duncan's test was conducted on average water content to determine on which dates treatments differed significantly (Table 3). The dates when one treatment differed in water content from at least one other treatment included 55, 60, 66, 75, 86, 90, 94 and 97 days after seeding (Table 7).

In Method 1, the five dates when both relative reflectance and water content differed significantly were 55, 86, 90, 94 and 97 days after seeding. Water content and relative reflectance of these five dates were compared.

At 55 and 94 days after seeding the treatment differing significantly in relative reflectance also differed significantly in water content. At 55 days after seeding, however, the correlation was positive. There was partial agreement at 86 days after seeding, when relative reflectance of treatment C was different from treatment A and water content of treatment C was different from both treatments A and B. The converse was observed at 90 days after seeding, when relative reflectance of

TABLE 7

TREATMENTS SIGNIFICANTLY DIFFERENT FROM OTHER TREATMENTS IN RELATIVE REFLECTANCE, WATER CONTENT OR WATER POTENTIAL (EXPERIMENT 1)

DAYS AFTER SEEDING	TREATMENTS DIFFERING IN RELATIVE REFLECTANCE				TREATMENTS DIFFERING IN PERCENT WATER CONTENT	DAYS FROM LAST WATERING			
	REF1	REF2	REF3	REF4		TREATMENT			
						A	B	C	
38	NONE	NONE				2	0	3	*
43	C	C				2	2	5	*
47	NONE	B				0	0	0	
55	C	C	C	C	C	1	1	4	*
60	NONE	ALL	ALL	ALL	A>C	0	2	3	*
66	NONE	NONE	NONE	C	C	0	1	1	
70	NONE	A>C				1	1	1	
75	NONE	NONE	C	C	A>C	0	2	2	
79	C>B	A				1	3	6	*
86	C>A	C	NONE	C>A	C	0	2	4	*
90	C	C	C	C	A>C	0	1	8	*
94	C	C	A	A	C	1	1	1	
97	A	A	A	A	C	2	4	4	

REF1 = Method 1 at the wavelength where best correlation probably occurs
REF2 = Method 2 at the wavelength where best correlation probably occurs
REF3 = Method 1 at 1.95 um
REF4 = Method 2 at 1.95 um
* = dates where at least one treatment differs from another by three or more stress days

treatment C was different from both treatments A and B, but water content of treatment C and B did not differ. At 97 days after seeding, treatment A had significantly different relative reflectance whereas treatment C had a significantly different water content.

In Method 1, the dates when neither relative reflectance nor water content differed significantly between treatments included 38, 47 and 70 days after seeding.

In Method 2, both relative reflectance and water content differed at 55, 60, 86, 90, 94 and 97 days after seeding. Differences in relative reflectance paralleled differences in water content on 55, 86 and 94 days after seeding. As with Method 1, correlation on 55 days after seeding was positive. On 60 days after seeding, treatments A and C differed in water content whereas all treatments differed in relative reflectance. On 90 and 97 days after seeding, Duncan's tests for Method 2 gave results comparable to findings for Method 1. On 38 days after seeding, neither relative reflectance nor water content differed between treatments.

As mentioned earlier, it has been shown that water content influences relative reflectance in the water absorption bands at 1.43 and 1.95 um. Therefore, on days when water contents varied significantly, analysis of variance was conducted on relative reflectance values from wavelengths of 1.94 through 1.96 um to determine whether treatments differed. It was hoped that this would provide the relationship between water content and relative reflectance cited in literature.

A comparison between Duncan's test on relative reflectance at 1.95 um and Duncan's test on water content revealed there was no consistent trend (Table 7). In Method 1, on 66 and 86 days after seeding relative reflectance did not differ between treatments whereas treatment C differed significantly in water content. In contrast, at 60 days after seeding all treatments differed in relative reflectance, but only treatments A and C differed in water content. This same absence of uniform association between water content and relative reflectance in the 1.95 um water absorption band was demonstrated in Method 2.

When looking for the best date to relate water content and relative reflectance in the area of the water absorption band, for both Methods 1 and 2, 55 days after seeding was the only time that relative reflectance of the three treatments corresponded to the actual variations in water content between treatments. However, the correlation was positive, contrary to what would be expected.

At 94 days after seeding, relative reflectance of the different treatments at 1.79 and 1.64 um (for Methods 1 and 2 respectively) also corresponded to the differences in water content. It is strange that there was correlation here but not at the 1.95 um water absorption band. (At 1.95 um, relative reflectance of treatment A was significantly different whereas it was treatment C that differed in water content.)

4.1.0.2 COMPARING WATER POTENTIAL AND RELATIVE REFLECTANCE

Having searched for a relationship between relative reflectance and water content, the next step was to determine whether water stress (independent of water content) affected reflectance values.

In order to concentrate on when water stress was most pronounced, only those dates when watering between any two treatments differed by three or more days were examined. (This gave better correlation than using only one or two days as criteria to differentiate between levels of stress.) The watering schedule indicated that 38, 43, 55, 60, 79, 86 and 90 days after seeding were in this group.

A comparison between relative reflectance and number of stress days indicated a relationship existed for Method 1. Recognizing each three days as a different degree of stress, 43, 55, 86 and 90 days after seeding differed in relative reflectance when number of stress days differed. On 66, 70, and 75 days after seeding, neither number of stress days nor relative reflectance differed significantly between treatments. However, on 38 and 60 days after seeding, the difference in number of stress days between two treatments was three, yet relative reflectance did not differ. The exact reverse was observed on data from 94 days after seeding; the watering schedule did not suggest any differences in degree of water stress between treatments, but relative reflectance of treatment C differed significantly. The best dates for using relative reflectance to suggest degree of water stress were 43, 55 and 90 days after seeding. Since water content of treatments differed at 55 and 90 days after seeding, relative reflectance may have been affected.

When comparing days of water stress and relative reflectance obtained in Method 2, the treatments differing in levels of stress also differed in relative reflectance on 43, 55 and 90 days after seeding. On 66 and 75 days after seeding, treatments did not differ in either level of stress or relative reflectance. On 60 and 86 days after seeding, treatments differing in level of stress overlapped with treatments differing in reflectance.

On both 47 and 70 days after seeding, there were treatments that differed in relative reflectance, even though all treatments were stressed the same number of days.

It was apparent that the number of days that plants were stressed did not determine the size of differences in relative reflectance between treatments. For example, in some instances there was a difference of only one in number of stress days that corresponded to a difference in relative reflectance (eg. 60 days after seeding). On other dates, one day (even two or three days) difference in stress days between treatments had no effect (eg. 75 and 79 days after seeding). Since there were no valid water potential readings this limited further examination of whether certain dates had larger water potential differences for a given number of stress days than others.

The two dates when number of stress days and relative reflectance differed between treatments and water content did not were 43 and 79 days after seeding. For 43 days after seeding, treatment C was stressed three days longer than A and B. This agreed with Duncan's test on relative reflectance, which also indicated treatment C was significantly different from the other treatments.

Results from 79 days after seeding were not attributable to either variation in water content or water stress. The least stressed treatment, treatment A, had relative reflectance values intermediate to the other two treatments. Treatment A had been stressed one day, whereas treatments B and C were stressed 3 and 6 days respectively.

In summary, the best dates for looking at a relation between water stress and relative reflectance were at 43 (tillering), 55 (flag/boot/heading) and 90 days after seeding (soft dough stage) for both Methods 1 and 2. Unlike at 55 and 90 days after seeding, water content did not differ between treatments at 43 days after seeding and therefore would not interfere.

4.2 EXPERIMENT 2

There were two objectives of this experiment:

(1) to determine if relative reflectance differed significantly between treatments; and

(2) to determine if there was a correlation between relative reflectance and water potential at any particular wavelength.

The first step was to determine if there was in fact a difference in water potential between the two treatments. The results of that analysis are shown in Table 8.

For all scan dates, analysis of variance (ANOVA) and Duncan's test were conducted to determine whether relative reflectance differed between treatments.

The first water potential readings were made 63 days after seeding. For this and all subsequent scan dates, a correlation of relative reflectance and water potential was plotted as a function of wavelength. Correlations were made using results standardized by Methods 3 and 4.

TABLE 8

T-TEST ON THE MEAN WATER POTENTIALS OF THE TWO TREATMENTS (Experiment 2)

DAYS AFTER SEEDING	TREATMENT	NUMBER OF PLOTS	MEAN WATER POTENTIAL (bars)	STANDARD DEVIATION	T	PROB>T
63	A	6	-7.20	2.41	.7918	.4544
	C	3	-9.07	4.95		
70	A	6	-7.37	1.20	2.0208	.0830
	C	3	-11.42	4.96		
75	A	6	-11.22	2.43	1.0475	.3352
	C	3	-12.83	2.43		
81	A	6	-9.02	1.49	2.9195	.0224
	C	3	-11.83	.96		
87	A	6	-8.17	1.54	2.5970	.0356
	C	3	-15.04	6.56		
94	A	6	-10.57	3.35	1.5775	.1587
	C	3	-14.63	4.28		

In treatment A, plots were dried to 16% soil water content and rewatered to field capacity. In treatment C, plots were dried to 8% soil water content before being rewatered.

There were four different approaches to standardizing the results obtained in experiment 2:

METHOD 1) Six plots (three replicates each of treatments A and C) were used. The reflectance plate served as the standard. No correlations were attempted with this method because water potential readings were not obtained from all plots.

METHOD 2) In this approach, three replicates each of treatments A and C were used. Results were standardized similarly to Method 1, except instead of using the reflectance plate as a standard, the average relative reflectance of the least stressed treatment, treatment A, was used.

There were no correlations attempted between water potential and relative reflectance.

METHOD 3) The three plots on which water potentials were determined were used in this method. This meant only two replicates of treatment A and one replicate of treatment C were considered. The water potential readings for these plots are presented in Table 9.

Relative reflectance from the aluminum plate was used as the standard.

METHOD 4) Results were standardized like Method 3, except the average relative reflectance of treatment A was used as the standard in place of reflectance from the plate.

For all reflectance measurements, both treatments A and C were at their minimum soil water content.

TABLE 9

DUNCAN'S TEST ON THE MEAN WATER POTENTIAL OF THREE PLOTS (USED IN METHODS 3 AND 4, Experiment 2)

DAYS AFTER SEEDING	PLOT[1]	NUMBER OF REPLICATES	MEAN WATER POTENTIAL (bars)	DUNCAN'S GROUPING[2]
63	A2	3	-6.84	a
	A1	3	-7.56	a
	C1	3	-9.07	a
70	A1	3	-6.96	a
	A2	3	-7.79	a
	C1	3	-11.43	a
75	A1	3	-8.83	a
	A2	3	-12.82	b
	C1	3	-12.83	b
81	A2	3	-8.79	a
	A1	3	-9.24	ab
	C1	3	-11.82	b
87	A2	3	-7.94	a
	A1	3	-8.40	a
	C1	3	-15.04	a
94	A2	3	-10.18	a
	A1	3	-10.96	a
	C1	3	-14.63	a

[1] Plots A1 and A2 were dried to 16% soil water content and rewatered to field capacity, whereas plot C1 was dried to 8% soil water content before being rewatered.

[2] Plots having the same letter do not differ at the 5% significance level.

4.2.1 RESULTS AND DISCUSSION OF METHODS 1 AND 2

ANOVA and Duncan's test are recorded in Tables A3 and 10 respectively for Method 1, and Tables A4 and 11 respectively for Method 2. A summary of the significant differences in relative reflectance is presented in

Table 15. On 51, 56, 75 and 87 days after seeding, reflectance of treatment C was significantly higher than reflectance of treatment A. On 46, 70 and 81 days after seeding, the inverse of this relation was observed.

On 63 and 94 days after seeding, there were no significant differences in reflectance between treatments. Reflectance of treatment C was greater than of treatment A on 46, 75 and 87 days after seeding. On the remaining three dates (63, 70 and 94 days after seeding), treatment A displayed higher reflectance values than treatment C.

On 51, 56 and 75 days after seeding, treatments did not differ significantly in relative reflectance.

Results of Methods 1 and 2 were not similar. The dates when analysis of variance suggested differences in relative reflectance between treatments were not similar between the two methods; the standard being subtracted did affect the results. Method 1 gave the better analysis of variance results.

TABLE 10

DUNCAN'S TEST FOR EXPERIMENT 2, STANDARDIZING RESULTS BY MEANS OF THE REFLECTANCE PLATE (METHOD 1)

DAYS AFTER SEEDING: 46 WAVELENGTH INTERVAL: 2.21-2.23 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	13.396 a
C	12.788 b

DAYS AFTER SEEDING: 51 WAVELENGTH INTERVAL: 1.55-1.57 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	15.400 a
A	12.631 b

DAYS AFTER SEEDING: 56 WAVELENGTH INTERVAL: 1.91-1.93 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	3.488 a
A	2.632 b

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 10

(continued)

DAYS AFTER SEEDING: 63 WAVELENGTH INTERVAL: 1.73-1.75 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	12.916 a
A	5.797 a

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.33-2.35 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	3.374 a
C	1.990 b

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 1.70-1.72 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	23.628 a
A	.881 b

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 10

(continued)

DAYS AFTER SEEDING: 81 WAVELENGTH INTERVAL: 2.34-2.36 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	51.121 a
C	.404 b

DAYS AFTER SEEDING: 87 WAVELENGTH INTERVAL: 1.95-1.97 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	15.668 a
A	.640 b

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.73-1.75 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	14.415 a
C	9.807 a

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 11

DUNCAN'S TEST FOR EXPERIMENT 2, STANDARDIZING RESULTS BY MEANS OF TREATMENT A (METHOD 2)

DAYS AFTER SEEDING: 46 WAVELENGTH INTERVAL: 1.68-1.70 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	5.266 a
A	3.839 b

DAYS AFTER SEEDING: 51 WAVELENGTH INTERVAL: 2.28-2.30 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	6.752 a
A	6.475 a

DAYS AFTER SEEDING: 56 WAVELENGTH INTERVAL: 1.83-1.85 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	5.651 a
C	5.521 a

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 11

(continued)

DAYS AFTER SEEDING: 63 WAVELENGTH INTERVAL: 2.12-2.14 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	7.412 a
C	6.680 b

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.27-2.29 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	3.041 a
C	2.767 b

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 2.14-2.16 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	8.035 a
C	7.917 a

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 11

(continued)

DAYS AFTER SEEDING: 81 WAVELENGTH INTERVAL: 1.81-1.83 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	8.103 a
A	5.003 b

DAYS AFTER SEEDING: 87 WAVELENGTH INTERVAL: 1.63-1.65 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C	22.698 a
A	20.962 b

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.58-1.60 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A	16.168 a
C	13.108 b

---

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 15

SUMMARY OF SIGNIFICANT DIFFERENCES IN REFLECTANCE DETERMINED BY DUNCAN'S TEST AT THE 5% SIGNIFICANCE LEVEL (Experiment 1)

DAYS AFTER SEEDING	RELATIONSHIP OF RELATIVE REFLECTANCE BETWEEN TREATMENTS			
	METHOD 1	WAVELENGTH (um)	METHOD 2	WAVELENGTH (um)
38	---	2.22	---	1.80
43	A>C;B>C	2.22	A>C;B>C	2.22
47	---	1.55	C>B;A>B	2.29
55	A>C;B>C	1.74	A>C;B>C	2.13
60	---	1.74	A>B>C	2.13
66	---	1.74	---	2.13
70	---	1.71	A>C	2.21
75	---	2.22	---	1.81
79	C>B	2.22	C>A;B>A	1.82
86	C>A	1.97	C>B;C>A	1.64
90	C>A;C>B	1.79	C>B;C>A	1.64
94	C>A;C>B	1.79	C>B;C>A	1.64
97	C>A;B>A	1.79	C>A;B>A	1.64

Treatments A, B and C were dried to 16, 12 and 8 % soil water content respectively before being rewatered.

4.2.2 RESULTS OF METHOD 3

Only three plots were used in this set of analyses, two replicates of treatment A (plots A1 and A2) and one replicate of treatment C (plot C1). Plate reflectance was ratioed down and subtracted from the raw curves, then the curves were multiplied by a calculated ratio (w).

4.2.2.1 RESULTS OF ANOVA AND DUNCAN'S TEST

ANOVA and Duncan's test for Method 3 are recorded in Tables A5 and 12 respectively.

On 75, 87 and 94 days after seeding, all plots had similar relative reflectance values. On 46 days after seeding, all plots had different reflectance values, with treatment C having the highest. On 51, 63 and 70 days after seeding, all plots differed significantly, with treatment C falling between the two plots of treatment A. On 56 days after seeding, all plots differed significantly, but this time treatment C had the lowest reflectance values. On 81 days after seeding, treatment C differed from the two plots of treatment A, with treatment C having the lower reflectance.

4.2.2.2 CORRELATION COEFFICIENTS

The best correlation coefficients (determined on data from 63 days after seeding through to the end of the experiment) are recorded in Table 14. (Due to the limited number of data points, correlation coefficients are very high and therefore confidence limits were not assigned.)

63 DAYS AFTER SEEDING - flag/boot/heading

Correlation was fairly good at this stage (Figure 11). r was negative from 1.40 through 1.58 um, 1.86 through 2.08 um, and 2.34 through 2.40 um. At both water absorption bands, r was negative, being -.729 at 1.43 um and -.725 at 1.95 um. r was highest at 1.57 um with a value of -.883.

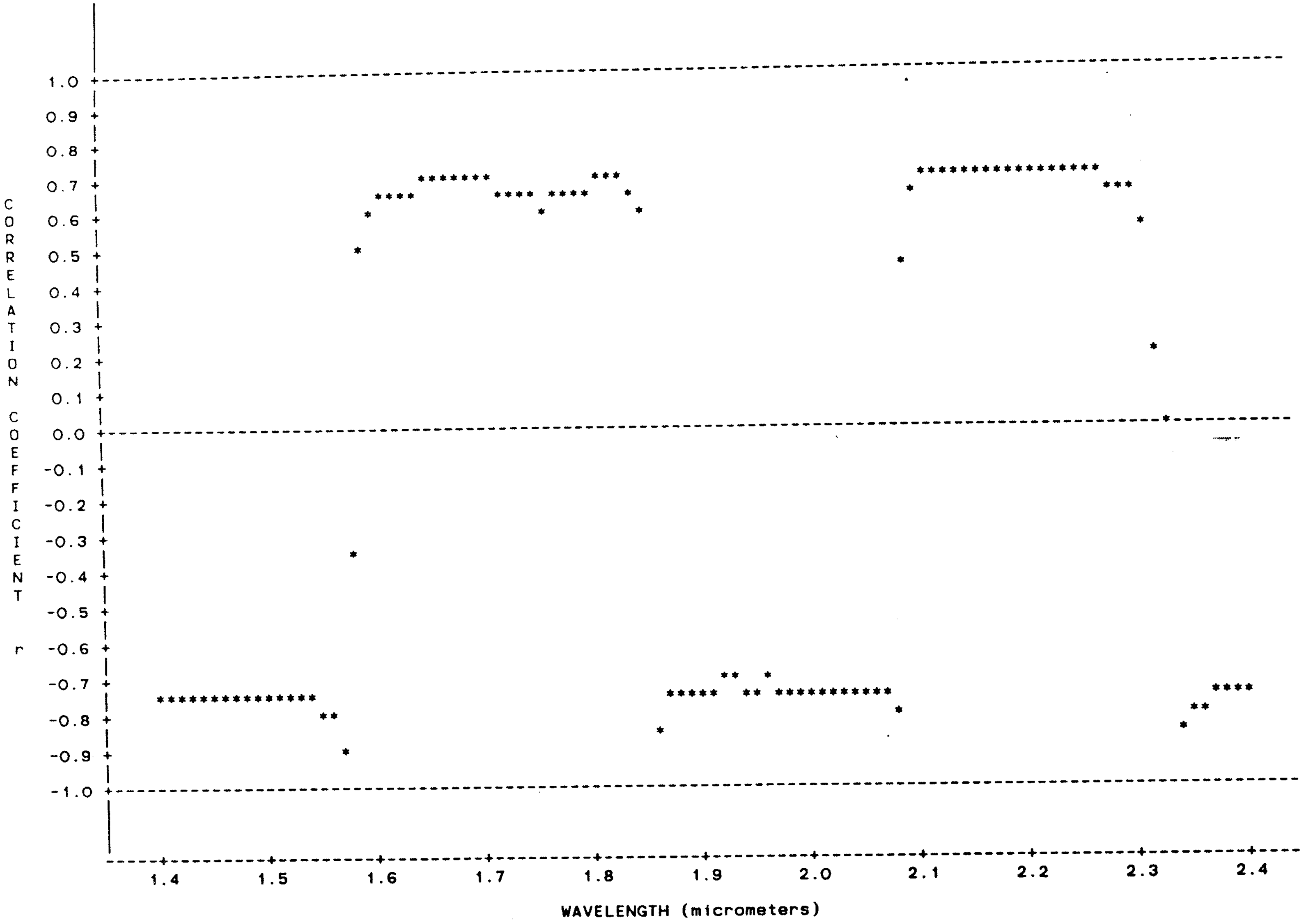


Figure 11: Plot of correlation coefficients between relative reflectance and water potential versus wavelength at the flag/boot/heading stage (Method 3).

70 DAYS AFTER SEEDING - anthesis

At anthesis, correlation was weak at most wavelengths but strong at 1.86 and 2.13 um, where r attained values of -.939 and -.996 respectively (Figure 12). r was negative at all wavelengths except 2.34, 2.38 and 2.39 um.

In the area of the water absorption bands, correlation was weak. r was -.088 at 1.43 um and -.087 at 1.95 um.

75 DAYS AFTER SEEDING - 5 days after anthesis

At this date correlation was strong at many wavelengths (Figure 13). The correlation coefficients were negative at all wavelengths except at 2.22 um.

At both water absorption bands, r was fairly good (r=-.833 at 1.43 um and r=-.838 at 1.95 um). The best correlation coefficient was -.970 at 2.21 um.

81 DAYS AFTER SEEDING - 11 days after anthesis

Correlation was very strong at this date (Figure 14). At 11 out of 101 data points, r was +.997 or higher. r was negative at 1.83 um only.

In both water absorption bands, r was less than +.997 (r= +.982 and +.988 at 1.43 and 1.95 um, respectively).

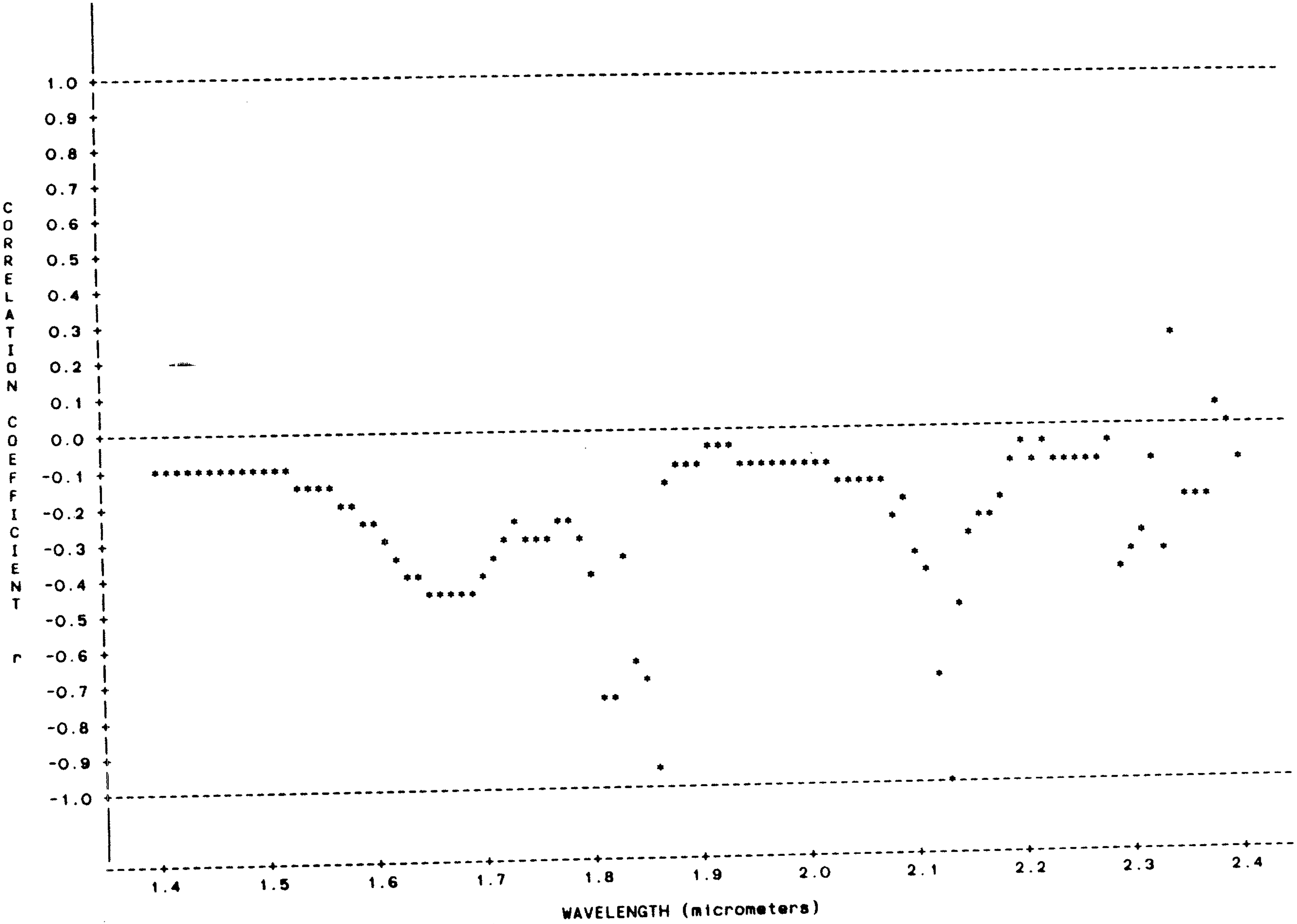


Figure 12: Plot of correlation coefficients between relative reflectance and water potential versus wavelength at anthesis (Method 3).

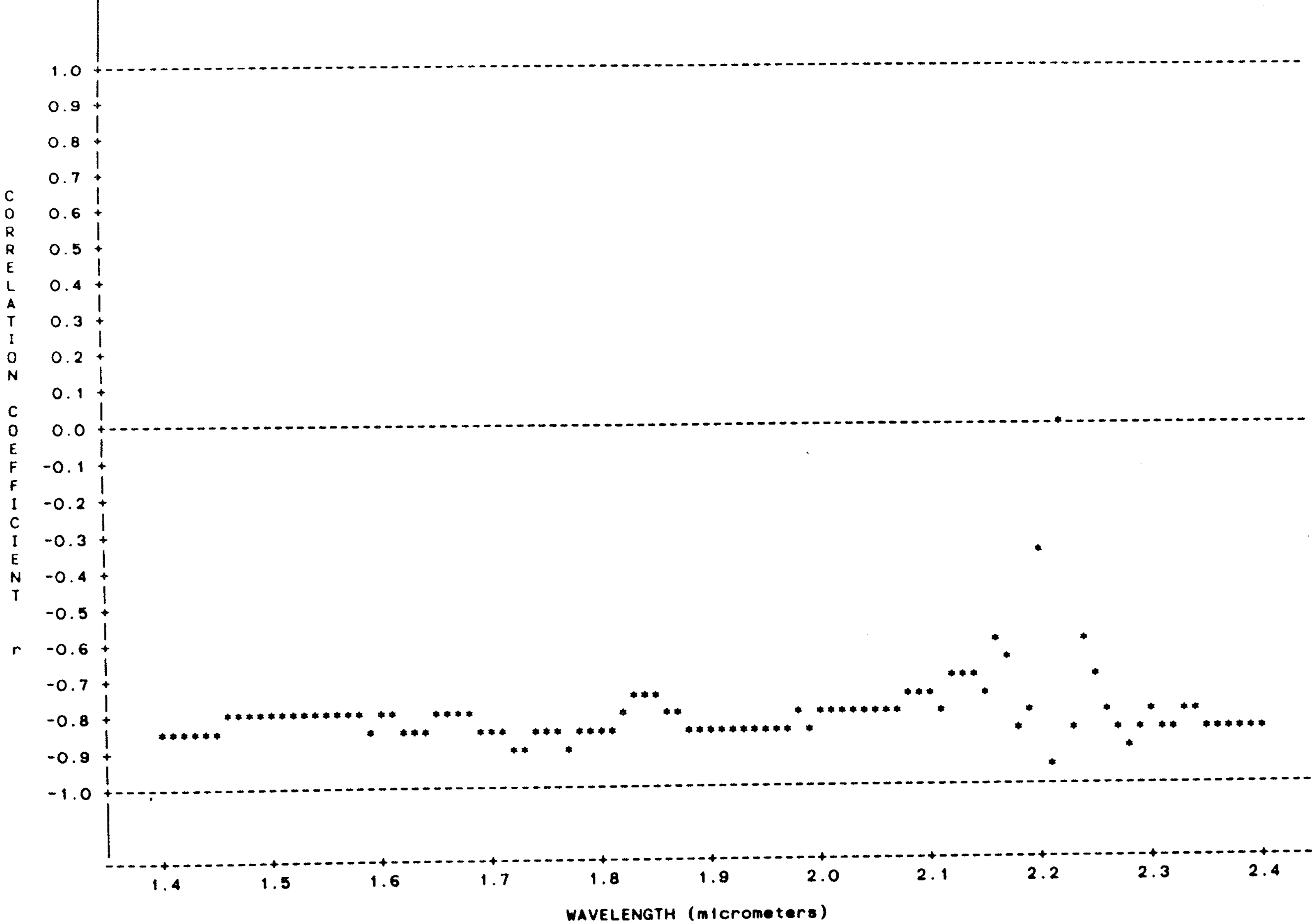


Figure 13: Plot of correlation coefficients between relative reflectance and water potential versus wavelength five days after anthesis (Method 3).

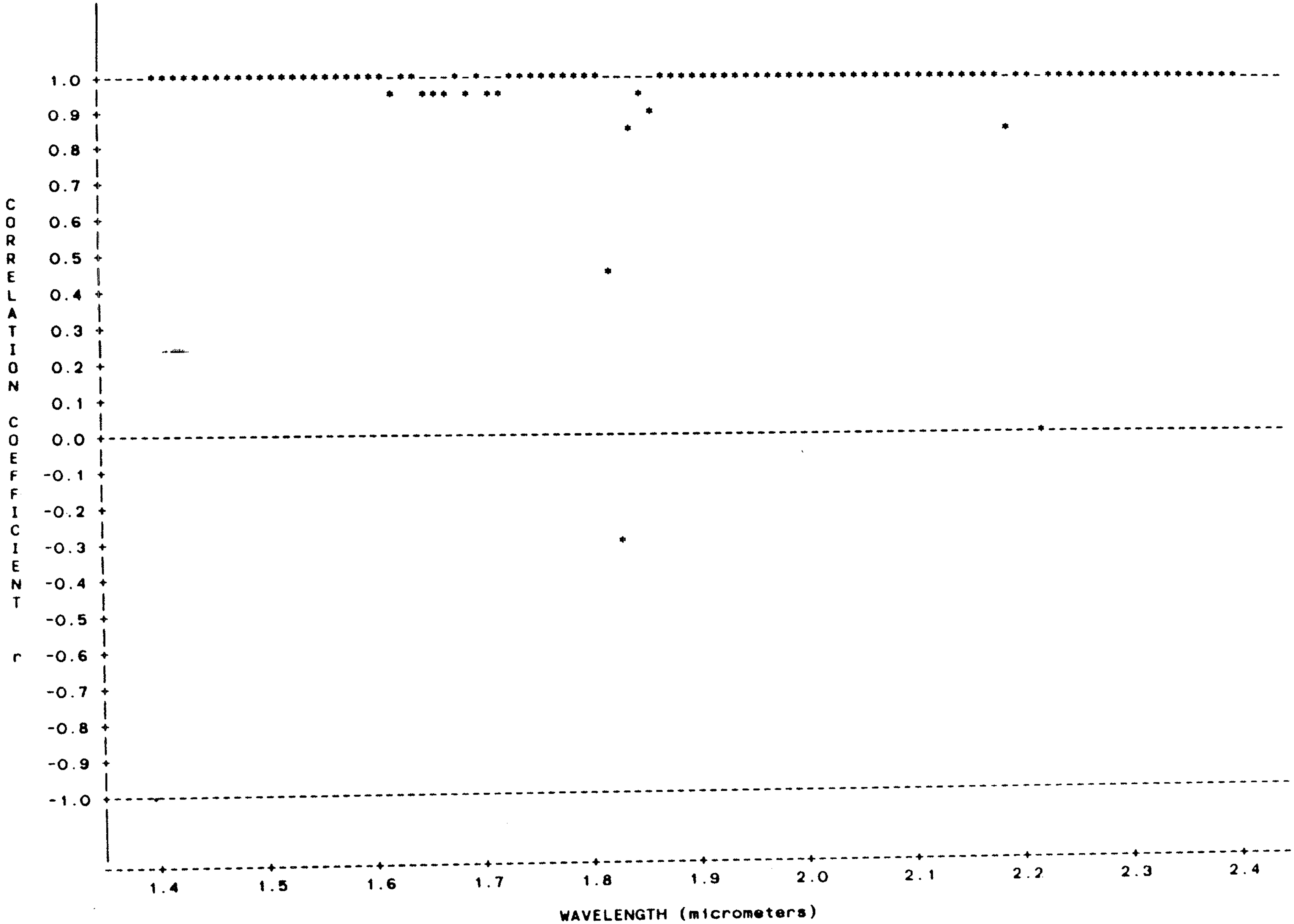


Figure 14: Plot of correlation coefficients between relative reflectance and water potential versus wavelength eleven days after anthesis (Method 3).

87 DAYS AFTER SEEDING - milk stage

Correlation was poor at every wavelength on this date, the best values of r being -.350 at 1.82 and -.331 at 2.21 um (Figure 15). In the area of the water absorption bands, correlation was weak; r was -.293 at 1.43 um and -.265 at 1.95 um. r was negative at all wavelengths except at 1.83 um.

94 DAYS AFTER SEEDING - soft dough stage

At this date, correlation coefficients were quite variable (Figure 16). r was negative from 1.40 through 1.55 um, 1.87 through 2.20 um and 2.22 through 2.40 um. Correlation was poor at both of the water absorption bands, the r value being only -.150 at 1.43 um and -.163 at 1.95 um.

The best correlation coefficient value was +.998 at 1.84 um. r was +.900 at 1.66 and +.924 at 1.67 um.

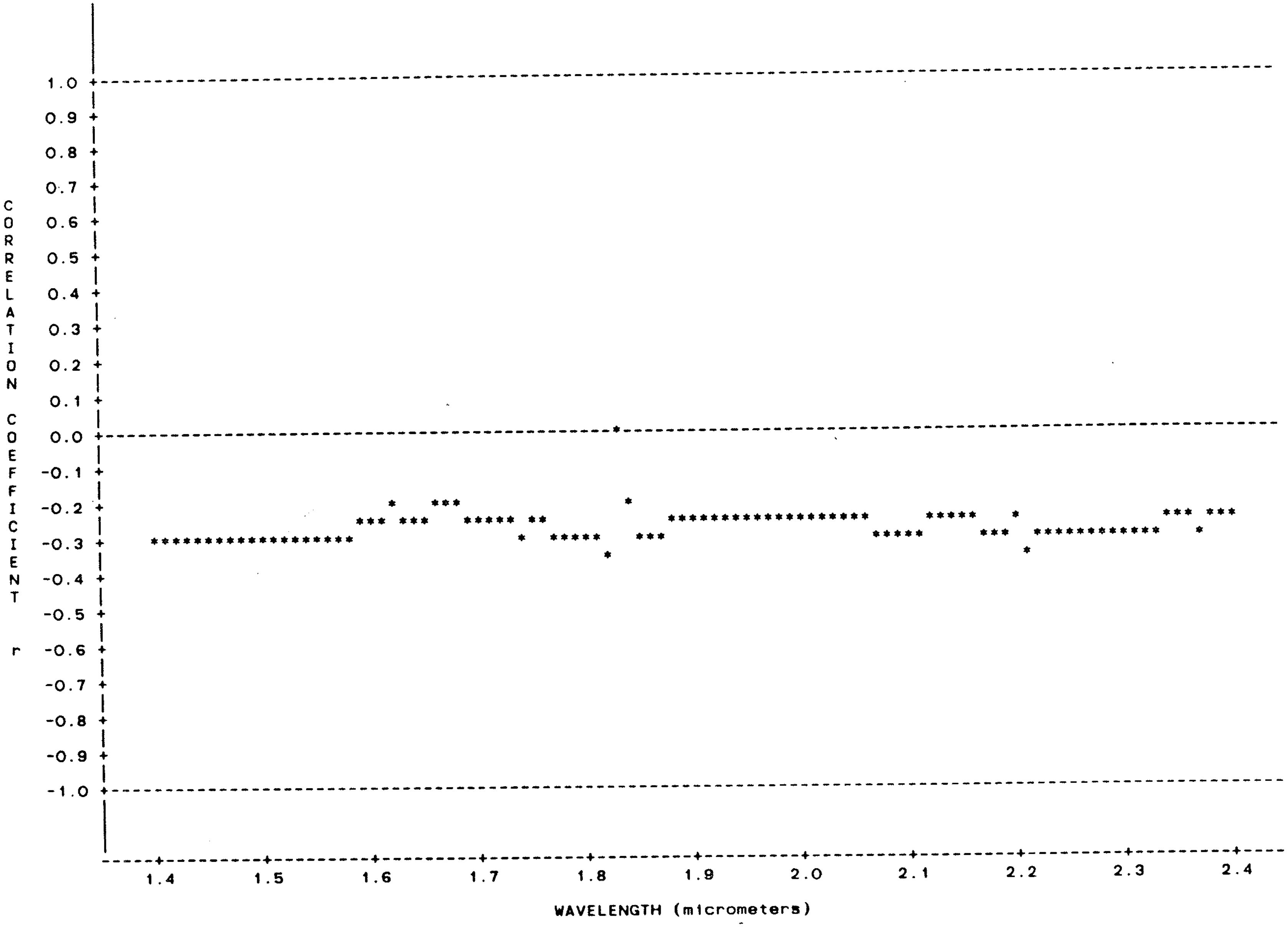


Figure 15: Plot of correlation coefficients between relative reflectance and water potential versus wavelength at the milk stage (Method 3).

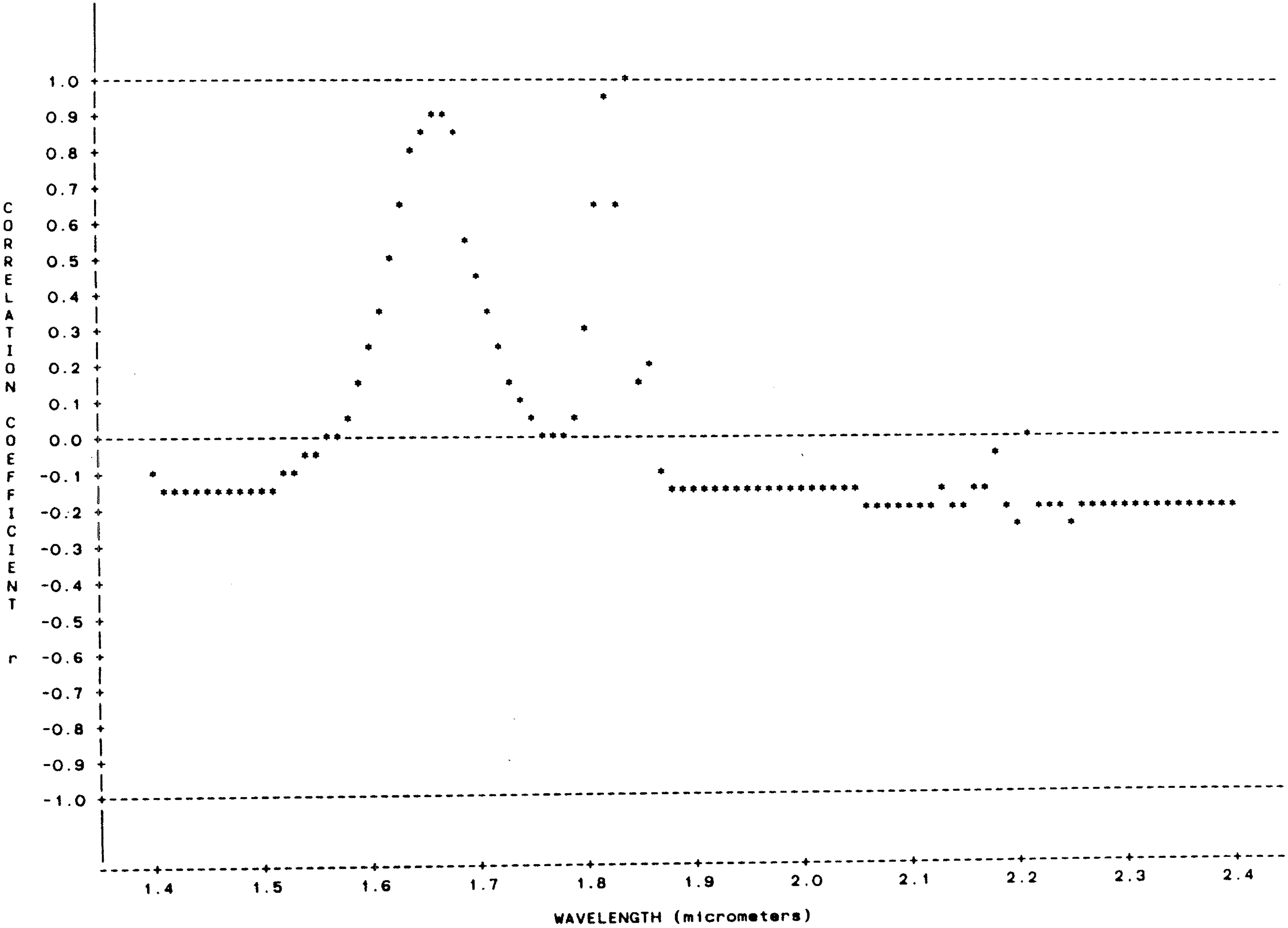


Figure 16: Plot of correlation coefficients between relative reflectance and water potential versus wavelength at the soft dough stage (Method 3).

TABLE 12

DUNCAN'S TEST FOR EXPERIMENT 2, STANDARDIZING RESULTS BY MEANS OF THE REFLECTANCE PLATE (METHOD 3)

DAYS AFTER SEEDING: 46 WAVELENGTH INTERVAL: 1.56-1.58 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C1	12.832 a
A1	11.798 b
A2	9.531 c

DAYS AFTER SEEDING: 51 WAVELENGTH INTERVAL: 1.56-1.58 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A2	18.698 a
C1	16.624 b
A1	10.553 c

DAYS AFTER SEEDING: 56 WAVELENGTH INTERVAL: 1.56-1.58 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A1	12.658 a
A2	12.131 b
C1	11.366 c

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 12

(continued)

DAYS AFTER SEEDING: 63 WAVELENGTH INTERVAL: 1.56-1.58 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A1	20.515 a
C1	10.943 b
A2	4.540 c

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.12-2.14 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A1	4.391 a
C1	1.686 b
A2	.041 c

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 2.20-2.22 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A2	16.233 a
C1	16.161 a
A1	16.133 a

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 12

(continued)

DAYS AFTER SEEDING: 81 WAVELENGTH INTERVAL: 1.50-1.52 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A1	20.559 a
A2	19.945 a
C1	.078 b

DAYS AFTER SEEDING: 87 WAVELENGTH INTERVAL: 1.81-1.83 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A2	17.798 a
C1	17.195 a
A1	13.486 a

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.83-1.85 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A2	11.346 a
A1	10.298 a
C1	8.698 a

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

4.2.3 RESULTS OF METHOD 4

In this method, only three plots were used and the least stressed treatment's mean relative reflectance was ratioed down to serve as the standard.

4.2.3.1 RESULTS OF ANOVA AND DUNCAN'S TEST

Results from ANOVA and Duncan's test are found in Tables A6 and 13 respectively.

On 70, 75, 81 and 87 days after seeding, all plots were similar in relative reflectance values. On 51 days after seeding, all plots were significantly different, with plot C1 having reflectance values intermediate to the two plots of treatment A. On 56 days after seeding, all plots were different, but this time plot C1 had significantly higher reflectance values than plots A1 and A2. On 46 days after seeding, plot A2 had significantly lower reflectance values than the other two plots. On 63 days after seeding, plots C1 and A2 differed significantly, plot C1 having the highest values. On 94 days after seeding, plots A1 and A2 differed significantly from plot C1, with plot C1 having the lower reflectance.

4.2.3.2 CORRELATION COEFFICIENTS

Correlations were first determined 63 days after seeding and were continued until the experiment was ended. The best correlation coefficients are given in Table 14.

63 DAYS AFTER SEEDING - flag/boot/heading

Correlation was fairly good at a few wavelengths (Figure 17). The best value of r was -.985 at 1.49 um. r was negative from 1.40 through 1.54 um. At the 1.43 um water absorption band r was -.728 and at the 1.95 um water absorption band, r was +.691.

70 DAYS AFTER SEEDING - anthesis

Correlation coefficients ranged from +.993 at 1.89 um and +.998 at 2.28 um, to -.995 at 2.14 um and -.996 at 2.16 um (Figure 18). r was negative from 1.40 through 1.71 um, 1.74 through 1.85 um, 1.94 through 1.97 um, 1.99 through 2.06 um, 2.10 through 2.14 um and 2.16 through 2.18 um. Individual negative points occurred at 1.88, 1.90, 2.08, 2.21, 2.25, 2.29 and 2.30 um. r values jumped from positive to negative values quite frequently. Correlation was poor at one water absorption band (r was -.163 at 1.43 um) and good at the other water absorption band (r was -.949 at 1.95 um).

75 DAYS AFTER SEEDING - 5 days after anthesis

Correlation was quite good at this date (Figure 19). r reached -.985 at 2.21 um, -.954 at 1.73 um, -.938 at 1.77 um, and -.965 at 2.28 um. In the water absorption bands, correlation coefficients were fairly good but no better than at many other wavelengths. At 1.43 um, r was -.885 and at 1.95 um, r was -.857.

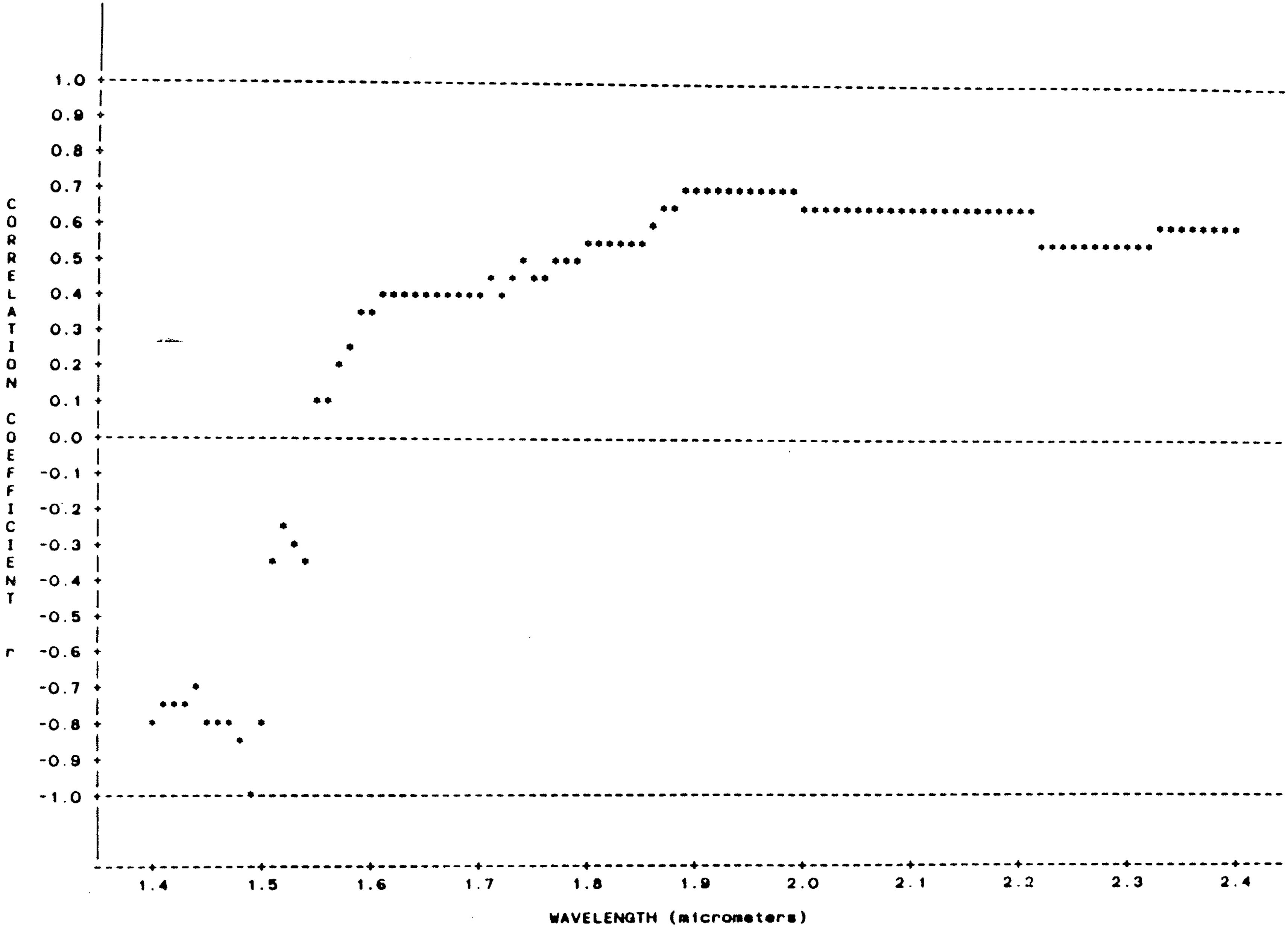


Figure 17: Plot of correlation coefficients between relative reflectance and water potential versus wavelength at the flag/boot/heading stage (Method 4).

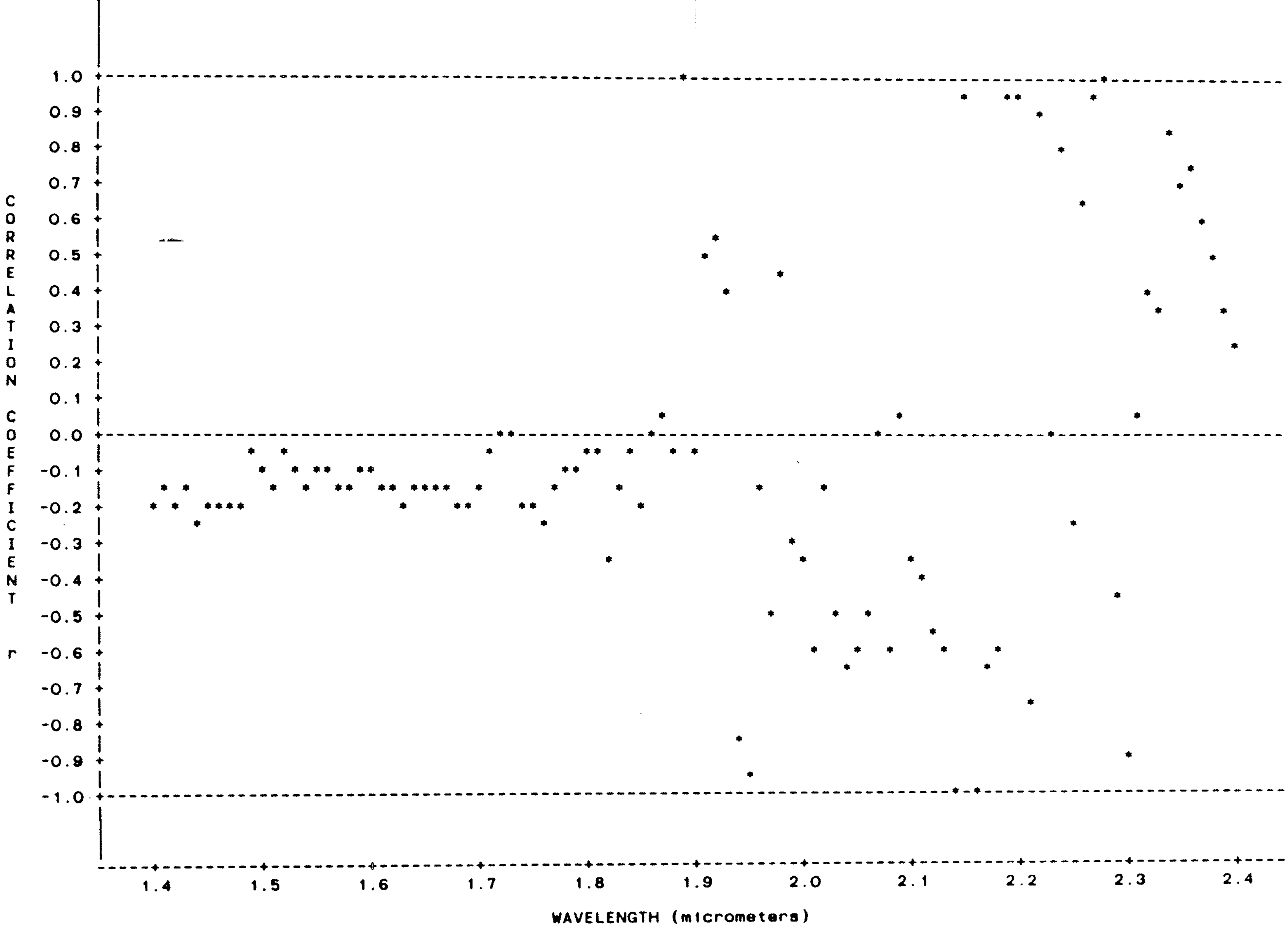


Figure 18: Plot of correlation coefficients between relative reflectance and water potential versus wavelength at anthesis (Method 4).

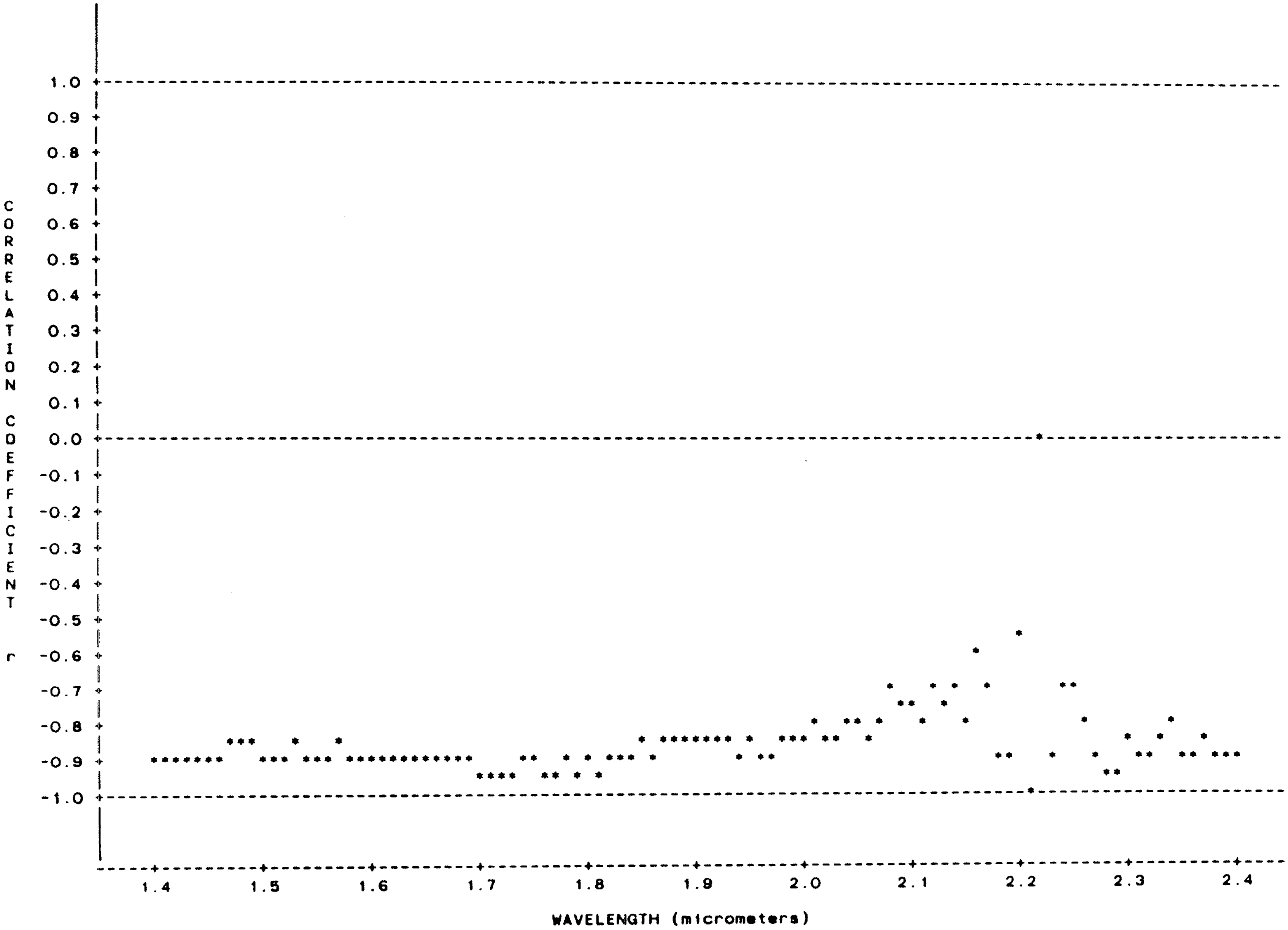


Figure 19: Plot of correlation coefficients between relative reflectance and water potential versus wavelength five days after anthesis (Method 4).

81 DAYS AFTER SEEDING - 11 days after anthesis

Correlation was poor at all wavelengths, the best r value being +.703 at 2.19 um (Figure 20). r was negative from 1.59 through 1.87 um and at 2.20 um. Correlation was poor at both water absorption bands, r being +.399 at 1.43 um and +.416 at 1.95 um.

87 DAYS AFTER SEEDING - milk stage

Correlation was strong at only a few wavelengths (Figure 21). At 1.82 um, r was -.996; at 1.60 um, r was +.732; and at 2.16 um, r was +.746. Correlation was negative from 1.40 through 1.59 um, 1.75 through 1.82 um, 1.84 through 2.11 um, and 2.26 through 2.40 um.

Correlation was not good in the water absorption bands; at 1.43 um, r was -.404 and at 1.95 um, r was -.347.

94 DAYS AFTER SEEDING - soft dough stage

Correlation at the soft dough stage was very good at several wavelengths (Figure 22). r was negative at 2.09, 2.10, 2.14, 2.15 and 2.19 um, and from 2.22 through 2.27 um, 2.29 through 2.36 um, and 2.38 through 2.40 um. r was +1.000 at 1.51 and 1.87 um, and +.999 at 1.78 and 1.84 um. r was -.998 at 2.31 um. In the water absorption bands, correlation was very good but not outstanding. At 1.43 um, r was +.957 and at 1.95 um, r was +.850.

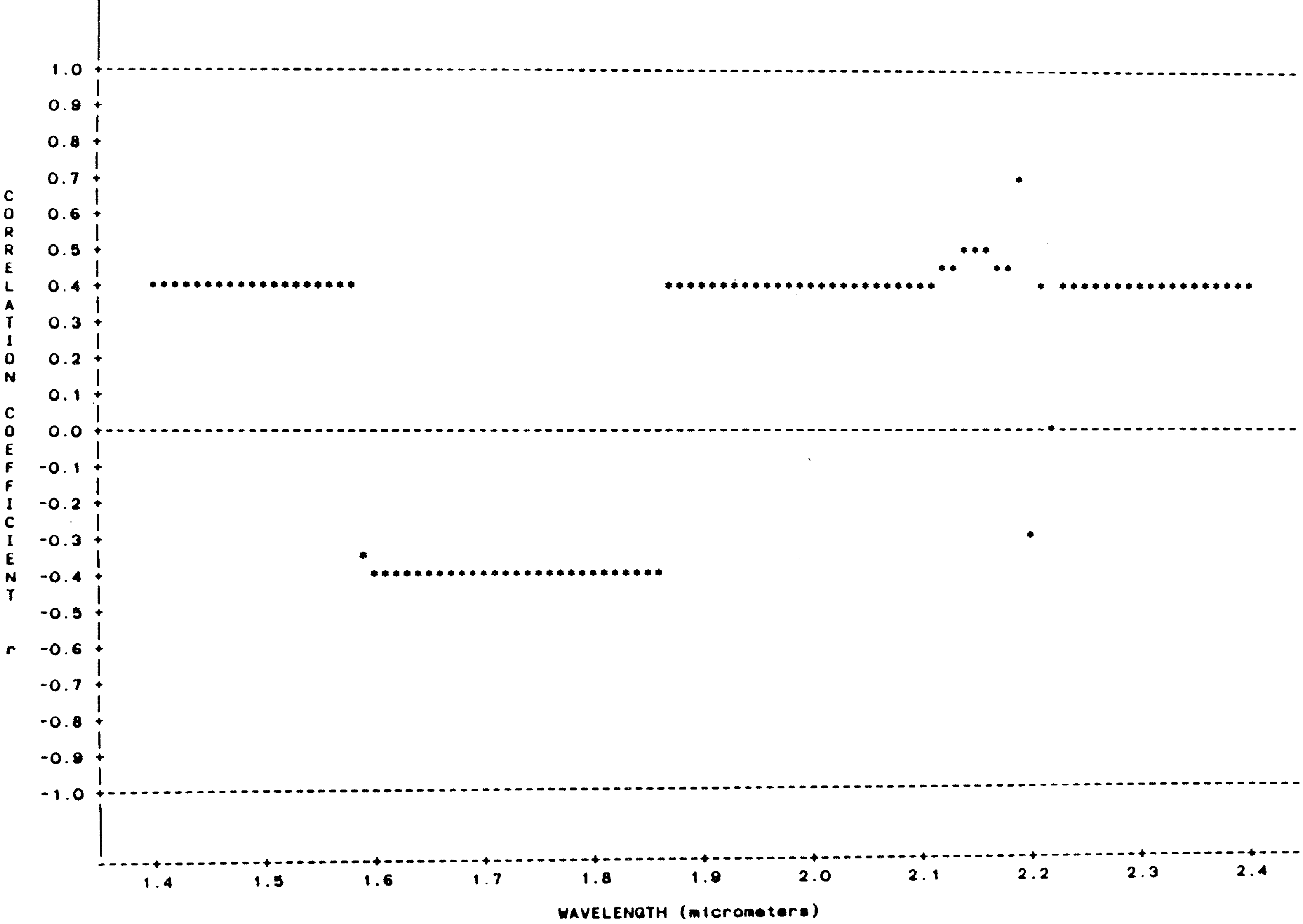


Figure 20: Plot of correlation coefficients between relative reflectance and water potential versus wavelength eleven days after anthesis (Method 4).

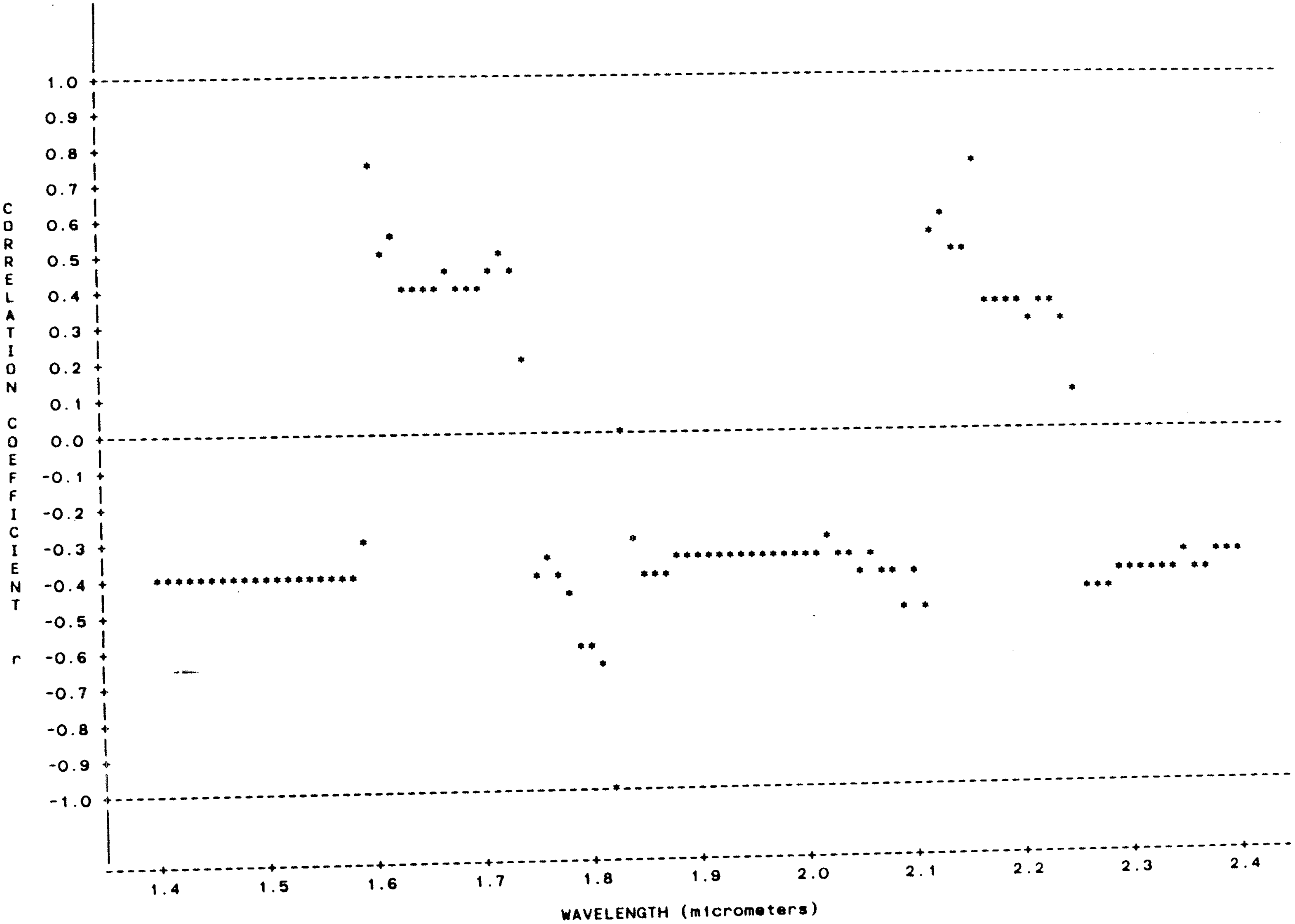


Figure 21: Plot of correlation coefficients between relative reflectance and water potential versus wavelength at the milk stage (Method 4).

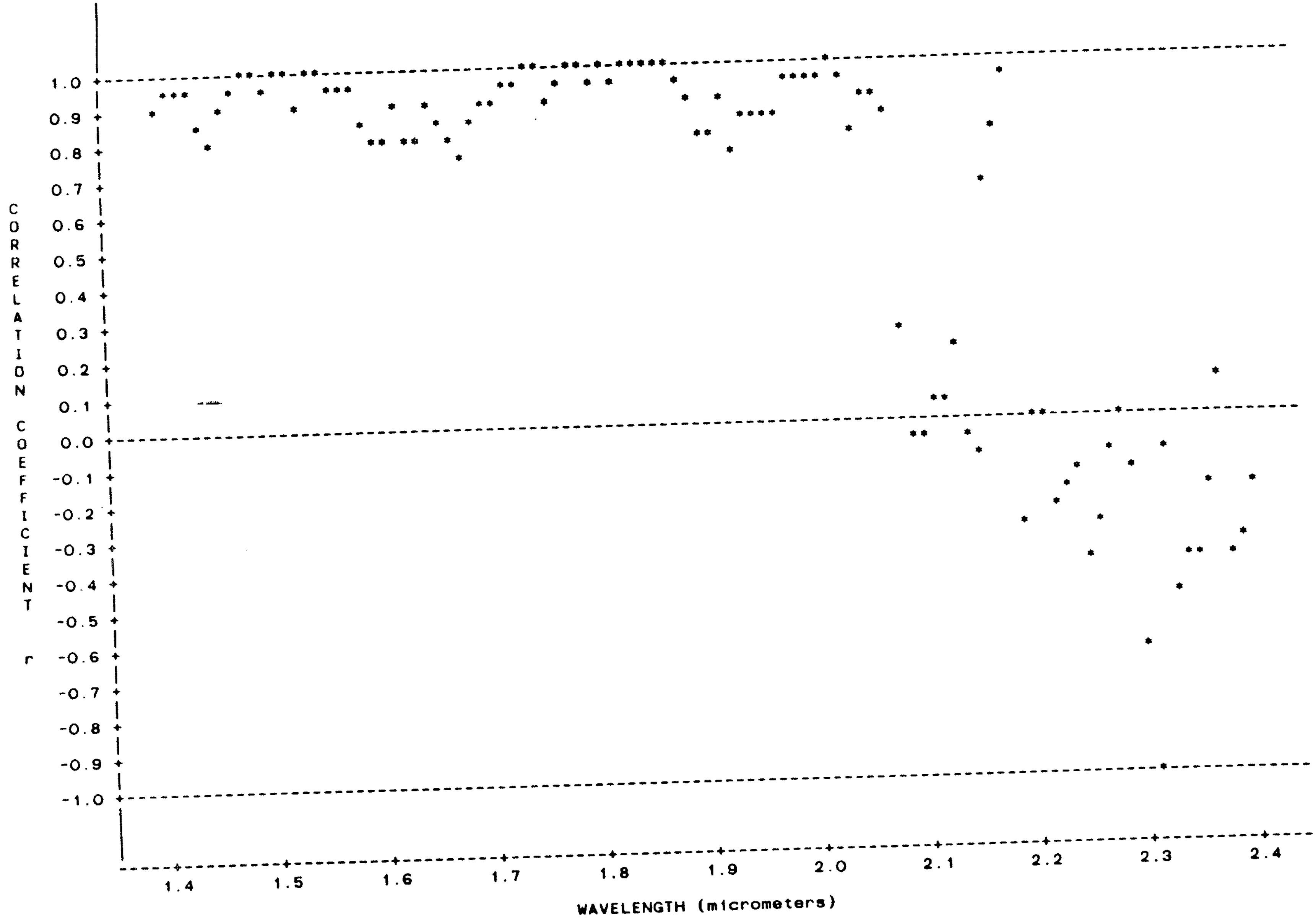


Figure 22: Plot of correlation coefficients between relative reflectance and water potential versus wavelength at the soft dough stage (Method 4).

TABLE 13

DUNCAN'S TEST FOR EXPERIMENT 2, STANDARDIZING RESULTS BY MEANS OF TREATMENT A (METHOD 4)

DAYS AFTER SEEDING: 46 WAVELENGTH INTERVAL: 1.48-1.50 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A1	3.975 a
C1	3.888 a
A2	3.171 b

DAYS AFTER SEEDING: 51 WAVELENGTH INTERVAL: 1.48-1.50 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A1	5.290 a
C1	4.732 b
A2	4.428 c

DAYS AFTER SEEDING: 56 WAVELENGTH INTERVAL: 1.48-1.50 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C1	8.443 a
A1	7.000 b
A2	5.839 c

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

[2] Reflectance values with the same letter do not differ at the 5 % level.

TABLE 13

(continued)

DAYS AFTER SEEDING: 63 WAVELENGTH INTERVAL: 1.48-1.50 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C1	8.471 a
A1	7.358 ab
A2	6.319 b

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.14-2.16 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C1	3.456 a
A2	3.411 a
A1	3.407 a

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 2.20-2.22 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A2	10.919 a
C1	10.841 a
A1	10.773 a

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

2 Reflectance values with the same letter do not differ at the 5 % level.

TABLE 13

(continued)

DAYS AFTER SEEDING: 81 WAVELENGTH INTERVAL: 2.18-2.20 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A1	12.493 a
A2	11.958 a
C1	11.724 a

DAYS AFTER SEEDING: 87 WAVELENGTH INTERVAL: 1.81-1.83 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
C1	16.954 a
A2	16.705 a
A1	16.299 a

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.83-1.85 um

Water Stress Treatment[1]	Mean Relative Reflectance[2]
A2	11.399 a
A1	11.039 a
C1	8.865 b

[1] Treatments A and C were dried to 16 and 8 % soil water content respectively before being rewatered.

2 Reflectance values with the same letter do not differ at the 5 % level.

4.2.4 DISCUSSION OF METHODS 3 AND 4

In these two sets of results, doubts are raised as to the ability to separate water stress treatments according to relative reflectance. In Method 3, Table 16 indicates all three plots differed significantly from each other at 46, 51, 56, 63 and 70 days after seeding. This was contrary to expectations because two of these plots were from the same treatment.

Duncan's test performed on the water potentials indicated differences between plots were significant only at 75 and 81 days after seeding. For 75 days after seeding (5 days after anthesis), plot A1 differed in water potential from plots A2 and C1. On this date, all plots had similar relative reflectance values.

For 81 days after seeding (11 days after anthesis), plots A2 and C1 differed in water potential. This was the only date that indicated plots A1 and A2 were similar in relative reflectance and that both A1 and A2 were different from C1.

In Method 3, correlation coefficients were best on 81 days after seeding, when r reached 1.000 (when rounded) at 1.64, 2.16, and 2.30 um.

On 94 days after seeding, correlation was best at 1.84 um where r was .998.

In Method 4, Duncan's test indicated differences between relative reflectance of plots at 46, 51, 56, 63, and 94 days after seeding. At 46 days after seeding, A2 was found to differ from A1 and C1. Both at 51

TABLE 14

SUMMARY OF THE BEST CORRELATIONS USING METHODS 3 AND 4 (EXPERIMENT 2)

DAYS AFTER SEEDING	USING REFLECTANCE PLATE		USING MEAN RELATIVE REFLECTANCE OF TREATMENT A	
(stage)	wavelength (um)	r[1]	wavelength (um)	r[1]
63 (flag/boot/ heading stage)	1.57	-.883	1.49	-.985
70 (anthesis)	1.86	-.939	1.89	+.993
	2.13	-.996	2.14	-.995
			2.16	-.996
			2.28	+.998
75 (5 days after anthesis)	2.21	-.970	1.73	-.954
			1.77	-.938
			2.21	-.985
			2.28	-.965
81 (11 days after anthesis)	1.63,2.25	+.998	2.19	+.703
	1.64,2.23	1.000		
	2.23,2.24	+.999		
	2.26,2.31	+.998		
	2.29,2.30	+.999		
	2.32	+.997		
87 (milk stage)	1.82	-.350	1.60	+.732
	2.21	-.331	1.82	-.996
			2.16	+.746
94 (soft dough stage)	1.66	+.900	1.51,1.87	+1.000
	1.67	+.924	1.74,1.75	+.988
	1.84	+.998	1.78,1.84	+.999
			1.79	+.996
			1.83	+.991
			2.31	-.998

[1] r has been rounded off and therefore values of 1.000 are observed.

and 56 days after seeding, all plots differed from each other. At 63 days after seeding, C1 differed from A2. At 94 days after seeding, C1 differed from A1 and A2. This latter date gives the type of results desired.

Correlation values were most significant at 63, 70, 87 and 94 days after seeding. The best value of r was found on 94 days after seeding, when r was 1.000 (when rounded) at 1.51 and 1.87 um.

In Methods 3 and 4, the water absorption bands were not special wavelengths at which correlation was above average. No emphasis could be put on them as indicators of degree of water stress.

From these last two sets of results, the tables indicate that although relative reflectance may be significantly different between treatments, it is not necessarily related to stress treatment. This was only found on one date (94 days after seeding, for both Methods 3 and 4) when plots A1 and A2 did not differ, whereas plot C1 did.

Method 4 in general gives better correlations than Method 3. On 81 days after seeding, however, Method 3 was much superior.

TABLE 16

SUMMARY OF SIGNIFICANT DIFFERENCES IN REFLECTANCE DETERMINED BY DUNCAN'S TEST AT THE 5 % SIGNIFICANCE LEVEL (Experiment 2)

DAYS AFTER SEEDING	METHOD 1	WAVELENGTH (um)	METHOD 2	WAVELENGTH (um)
46	A>C	2.22	C>A	1.69
51	C>A	1.56	---	2.29
56	C>A	1.92	---	1.84
63	---	1.74	A>C	2.13
70	A>C	2.34	A>C	2.28
75	C>A	1.71	---	2.15
81	A>C	2.35	C>A	1.82
87	C>A	1.96	C>A	1.64
94	---	1.74	A>C	1.59
DAYS AFTER SEEDING	METHOD 3	WAVELENGTH (um)	METHOD 4	WAVELENGTH (um)
46	C1>A1>A2	1.57	A1>A2;C1>A2	1.49
51	A2>C1>A1	1.57	A1>C1>A2	1.49
56	A1>A2>C1	1.57	C1>A1>A2	1.49
63	A1>C1>A2	1.57	C1>A2	1.49
70	A1>C1>A2	2.13	---	2.13
75	---	2.21	---	2.21
81	A>C	1.51	---	2.19
87	---	1.82	---	1.82
94	---	1.84	A>C	1.84

Plots A1 and A2 were dried to 16 % soil water content, and plot C1 was dried to 8 % soil water content.

4.3 RESULTS AND DISCUSSION OF TIME-SCAN EXPERIMENT

A well-watered plot was scanned four times consecutively. Examination of spectral curves indicate that the longer the lights radiated the crop, the higher the relative reflectance (Figure 23). The four parameters measured with a LI-COR porometer (Model LI-1600) included relative humidity, leaf temperature, stomatal diffusion resistance and transpiration rate. The three replicates of each parameter were averaged and are presented in Table 17.

Relative humidity increased once scans were initiated, then held fairly steady throughout the experiment.

Leaf temperature increased after the first scan then decreased throughout the remainder of the experiment.

For the set of data collected after the first scan, stomatal diffusion resistance was quite variable between replicates as was transpiration rate. Averaging the values of all three replicates, stomatal diffusion resistance increased after the first scan date then dropped drastically and remained there. Transpiration slightly increased from the initial measurement to after the first scan, then more than doubled by the end of the next consecutive scan. Prior to the fourth scan, it had decreased quite markedly.

Resistance will be low if stomates are open. After the second scan, a decreased leaf temperature, very reduced stomatal diffusion resistance and a much increased transpiration rate suggested stomata had opened. Water lost from leaves due to increased transpiration could explain the increased reflectance with time.

This experiment indicates that the length of time that lights were shining on the plot did affect relative reflectance. Whenever there was a delay between scans, spectral curves would have been affected.

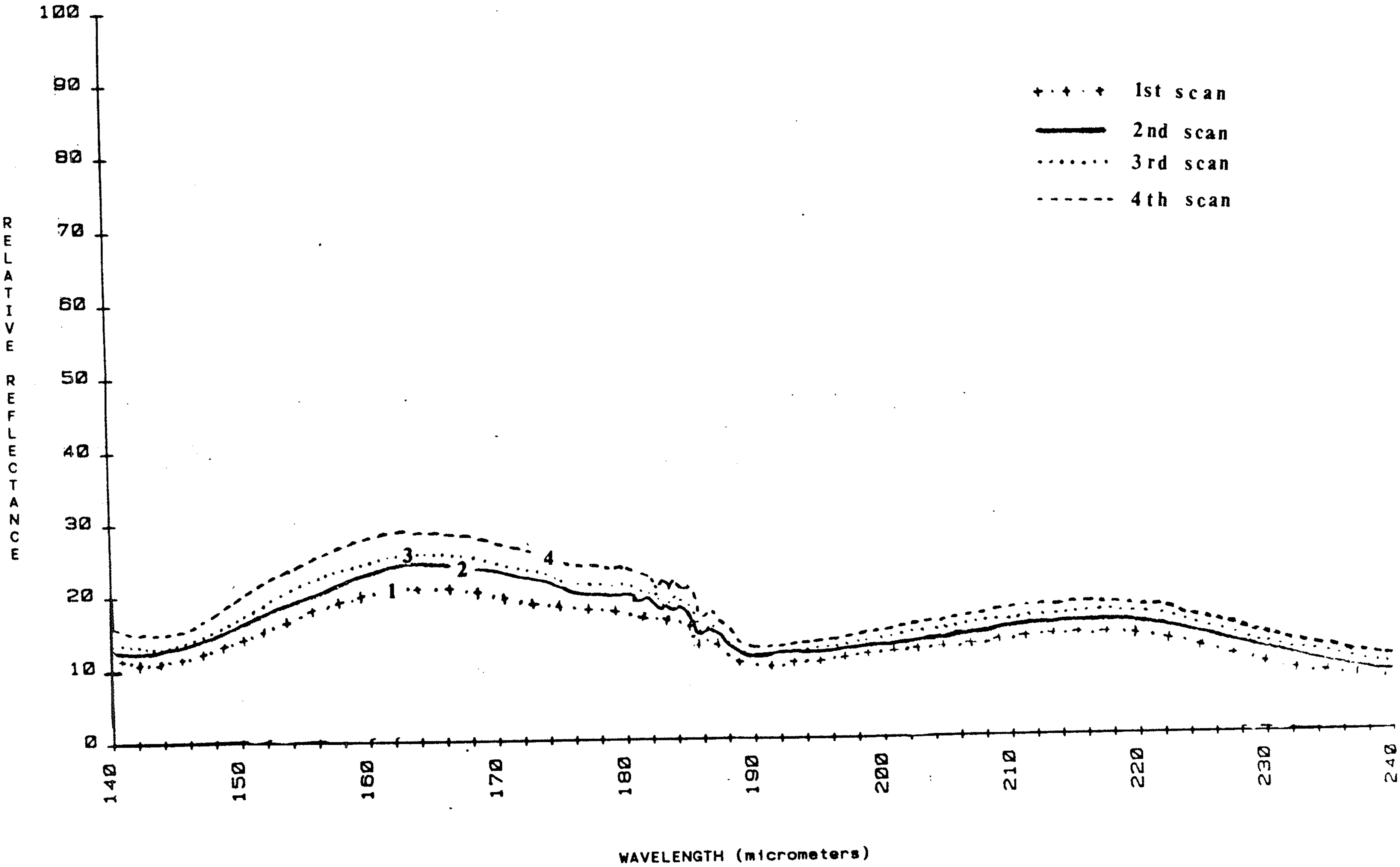


Figure 35: FOUR CONSECUTIVE SPECTRAL SCANS

TABLE 17

PARAMETERS MEASURED DURING TIME-SCAN EXPERIMENT

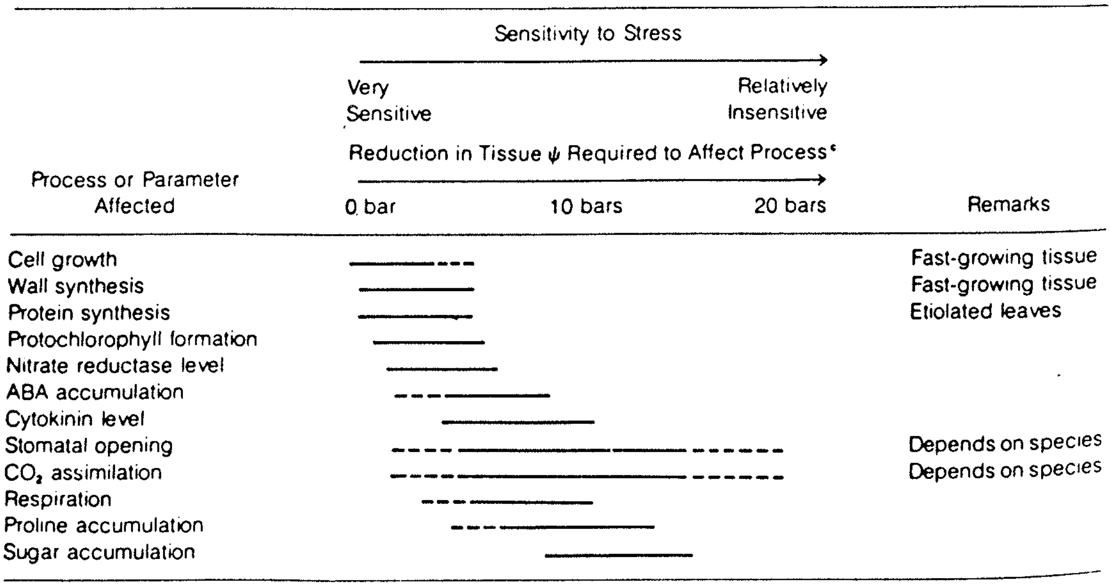
PARAMETER	PRIOR TO FIRST SCAN	PRIOR TO SECOND SCAN	PRIOR TO THIRD SCAN	PRIOR TO FOURTH SCAN
RELATIVE HUMIDITY (%)	19.89	26.01	26.14	25.88
LEAF TEMPERATURE (Celsius)	15.90	18.43	12.87	9.93
STOMATAL DIFFUSION RESISTANCE (cm/sec)	23.73	48.96	6.87	7.83
TRANSPIRATION RATE (ugm/cm²/sec)	.453	.569	1.206	.878

4.4 GENERAL DISCUSSION

When water stress is imposed, several physiological and morphological changes occur that could affect middle infrared reflectance. Hsiao (1973) rated these processes and parameters according to their sensitivity to stress (Table 18).

Table 18

Generalized Sensitivity to Water Stress of Plant Processes or Parameters[a,b]



Process or Parameter Affected	Remarks
Cell growth	Fast-growing tissue
Wall synthesis	Fast-growing tissue
Protein synthesis	Etiolated leaves
Protochlorophyll formation	
Nitrate reductase level	
ABA accumulation	
Cytokinin level	
Stomatal opening	Depends on species
CO_2 assimilation	Depends on species
Respiration	
Proline accumulation	
Sugar accumulation	

[a] From Hsiao, 1973.

[b] Length of the horizontal lines represents the range of stress levels within which a process first becomes affected. Dashed lines signify deductions based on more tenuous data.

[c] With ψ of well-watered plants under mild evaporative demand as the reference point.

Water stress is indicated by a decrease in water potential. There are three phases recognized as responses of osmotic potential to water stress (Morgan, 1980):

i) the number of solute molecules increases, and turgor is maintained.

ii) the number of solute molecules is maintained or reduced, and turgor drops.

iii) the number of solute molecules is maintained, and turgor will be zero.

The process most sensitive to reduced turgor pressure in cells is plant growth (cell expansion), coupled with a reduction in cell wall synthesis (Hsiao, 1973). At this same degree of sensitivity, protein synthesis may be inhibited (Hsiao, 1973).

As water stress progresses, certain enzymes suffer reduced activity, while others exhibit higher activity (Hsiao, 1973; Salisbury and Ross, 1978). At this level of stress, cell division is inhibited. In wheat, as in other mesophytes, abscisic acid moves into guard cells and turgor pressure decreases, causing stomatal closure to begin (Hsiao, 1973; Bidwell, 1974; Salisbury and Ross, 1978). With the closing of the stomata, transpiration and photosynthesis drop off.

It would appear logical that stress of this degree, when stomatal closure is occurring, would affect middle infrared reflectance. Relative reflectance would differ due to both chemical and morphological variations. From the chemical aspect, enzymes and amount of water in the leaf would vary according to degree of stress.

Physiological and morphological features affected by stress include cell growth, cell wall synthesis, cell division and closure of stomata; if turgor fell to the point that leaves wilted, differences in leaf orientation would also have affected relative reflectance.

The plants in our experiments were stressed from early tillering throughout grain-filling. The stage of plant development at which stress was imposed was important, as was the duration of stress. Plants can adapt if stressed early and can be preconditioned (Brown et al, 1976; Angus and Moncur, 1977; Rawson et al, 1977; Hsiao, 1973). However if the stress is removed, plants revert back to their past nature (Rawson et al, 1977; Brown et al, 1976).

In our experiments, cycles of stress were imparted. Soil water content fell to the designated drying point, the stress was relieved by rewatering and then the plots would be stressed again. When plants were rewatered, photosynthesis, leaf water potential and stomatal diffusion should have recovered rapidly (Frank et al, 1973). This suggests there should be fewer differences between treatments in our experiments than if treatments were maintained at stress levels.

Early in development until late tillering, stress would be expected to have a small effect because there would be such a large volume of soil per unit green leaf matter. That is, stress would develop more rapidly at heading than at tillering (Frank et al, 1973).

The stressed plants began to differ visibly from the less stressed plants as early as flag leaf stage. Two very evident adaptations to stress were hastening of maturity and reduced tiller production. This hastening of maturity indicated stress was mild (Angus and Moncur, 1977). If the plants had been severely stressed, they would have matured more slowly (Angus and Moncur, 1977).

As plants mature, changes (including differences in water content) occur. The most stressed treatment would be expected to have the highest MIR reflectance from after tillering throughout development because of reduction of water content, coupled with morphological adaptations to conserve water. We would expect differences in relative reflectance to persist through to senescence of the most stressed treatment. At this time, relative reflectance of all treatments should converge since all plants would be senescing to the same limit.

In our experiments, spectral curves were ratioed to account for differences in leaf area; if they had not been, as development continued and senescence occurred the least stressed treatment would have had higher reflectance (due to more plant matter).

Results of Experiment 1 do indicate a trend. In Method 1, prior to 55 days after seeding, water content of the various treatments did not differ. Even so, treatment A had higher relative reflectance than the other treatments until 55 days after seeding (flag/boot/heading stage). Perhaps in ratioing to account for differences in leaf area index, the spectral curves were distorted.

The treatments did not differ from then until 79 days after seeding (the soft dough stage). This was a time when differences in relative reflectance were expected. Moreover, for four out of five dates between 55 and 79 days after seeding, water content differed between treatments.

From the soft dough stage through to the end of the experiment, treatment C had higher relative reflectance than the other treatments. This was expected since water content differed between treatments in four out of five dates between 79 and 97 days after seeding.

In Method 2 (Experiment 1), either treatment A differed from the others or treatments did not differ until the soft dough stage. From the soft dough stage through to the end of the experiment, treatment C had higher relative reflectance. This method matches our predictions more closely than Method 1.

In Experiment 2, no treatment prevailed as having the higher relative reflectance values. This lack of consistency necessitates examining the normalization procedures performed on the data.

It is obvious that the data must be transformed in some manner, because the raw curves indicated just as much variation within treatments as between treatments. One of the assumptions made was that specular reflectance (represented by reflectance from the aluminum plate) was similar for each scan. Subtraction of the specular reflectance would be justified on this basis. However, because of changing leaf orientation and varying leaf area index, the specular reflectance might not be the same for each plot. The greater the leaf area index, the greater the specular reflectance.

Perhaps the plate reflectance should be ratioed for each plot (in the same manner as was done to the diffuse reflectance) before being subtracted. In this way, ratioing would account not only for differences in diffuse reflectance, but also for differences in specular reflectance.

When subtracting the average of treatment A (Methods 2 and 4), ratioing would not be justified because the average of treatment A would be considered an independent standard.

One of the important effects of water stress is that tiller production is inhibited and leaf area index is reduced. Ratioing these curves to account for differences in leaf area index could in essence be eliminating useful variability between treatments. However since the telescope's field of view was so small, each scan would not necessarily have a representative leaf area index. The flat-folding mirror was oriented so that as much leaf material as possible would be in view through the telescope. Even in the unstressed treatment, the mirror had to be positioned so that the telescope was not inadvertently focused on an area with a low leaf area index (such as between rows of plants).

The third leaf was consistently used in our experiments for obtaining water potential readings. Position of the leaf is important because progressively from lower to upper leaves, water potential, osmotic potential and relative leaf water content decrease and turgor pressure increases (Millar and Denmead, 1976). Stomatal closure, on the other hand, would be induced at about the same turgor pressure in leaves at all positions on the stem (Millar and Denmead, 1976) and therefore stomata would close sooner on lower leaves than upper leaves. Based on these facts, it may have been better to use the fifth leaf (at tillering) and flag leaf (from the time of its emergence through to grain-filling) for obtaining water potential readings. This may have given better indications of variations in water potential readings between treatments.

When spectral scans were performed, the studio lights directed at the plot on the viewing platform were bright, radiating a fair amount of heat. This would have caused stomatal opening so plants would have transpired more. Any delay in initiating scans would alter the relative reflectance curve, and thereby add variability. Based on data from the time scan, leaves of well-watered plants were determined to have a higher leaf temperature before scans than after. Losing water through enhanced transpiration would explain the increasing of reflectance in the water absorption bands as time proceeded. However, reflectance increased at every wavelength, not just in areas of water absorption. This conforms with Tucker's (1980) statement that the region between .70 and 2.5 um is essentially a liquid water absorption band with 3-order magnitude.

In Experiment 2, wavelengths at which there was best correlation between reflectance and water potential for a given date were examined. Just as water absorption bands that occur at 1.43 and 1.95 um can indicate water content, it was hoped that one or more wavelengths would stand out as indicators of water stress. This was not supported by our data.

Experiment 1 gave much better results than Experiment 2 as far as any consistency between dates is concerned (Tables 15 and 16). Both Methods 1 and 2 of Experiment 1 were fairly good.

In Experiment 2, a different scale was used. If this scale was inaccurate, all treatments might have been stressed less than initially planned (and the actual soil water contents would be unknown). This is suspected because, unlike in Experiment 1, treatments showed no difference in water content.

Another factor which may have affected Experiment 2 was the spraying of all plots five times to combat aphids. Each time the plots were sprayed, leaves were left spotted with insecticide. It was initially assumed that all plots would be affected equally. Perhaps this was not true.

Furthermore, the aphids were more populous on certain plots than on others, and therefore played a hand at which plots would be more stressed.

Chapter V

CONCLUSIONS

(1) Both water content and water potential can affect relative reflectance independently. For example, water content may not differ significantly between water stress treatments even though water potential does. Once water contents vary between treatments due to differences in maturity, changes in cell structure may interfere with determining effects of water potential on reflectance.

(2) In Experiment 1, a relationship existed between reflectance from the crop canopy and stage of physiological development (determined by both visible indications and water content). The more severe the stress, the quicker the crop matured and consequently the higher its reflectance curve.

In Method 1 (standardizing results by means of the reflectance plate), treatment A (mildly stressed) had higher relative reflectance than the more highly stressed treatments until flag/boot/heading stage (55 days after seeding). After this, treatments did not differ until the soft dough stage. From the soft dough stage through to the end of the experiment, treatment C (highly stressed) had the higher reflectance.

In Method 2 (standardizing results by means of the average relative reflectance of the least stressed treatment), either treatment A differed or all treatments were the same until the soft dough stage.

Throughout the remainder of development, treatment C consistently maintained the highest reflectance.

For both Methods 1 and 2 in Experiment 1, the best relations between water stress and relative reflectance were at tillering (43 days after seeding), flag/boot/heading stage (55 days after seeding), and soft dough stage (90 days after seeding).

(3) In Experiment 2, in which both water content and water potential were measured, four methods were applied:

i) in Method 1, six plots were used and results were standardized by means of the reflectance plate;

ii) in Method 2, six plots were used and the average relative reflectance of the least stressed treatment (treatment A) served as the standard;

iii) in Method 3, only three plots (those with direct water potential readings) were used, with the reflectance plate serving as the standard;

iv) in Method 4, the three plots with direct water potential readings were used and results were standardized by means of the average relative reflectance of the least stressed treatment.

In none of these methods did any one treatment predominate with a higher reflectance curve for any length of time.

For Experiment 2, the best correlations between water potential and relative reflectance were

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Chapter VI

APPENDIX

ANOVA TABLES FOR EXPERIMENTS 1 AND 2

TABLE A1

ANOVA FOR EXPERIMENT 1, STANDARDIZING RESULTS BY MEANS OF THE REFLECTANCE PLATE (METHOD 1)

DAYS AFTER SEEDING: 38 WAVELENGTH INTERVAL: 2.21-2.23 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.379	.190	.50	.6160
Wavelengths	2	.139	.069	.18	.8355
Error	22	8.420	.383		
Total	26	8.938			

DAYS AFTER SEEDING: 43 WAVELENGTH INTERVAL:2.21-2.23 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	4.171	2.086	5.87	.0104*
Wavelengths	2	.255	.127	.36	.7033
Error	19	6.752	.355		
Total	23	11.178			

DAYS AFTER SEEDING: 47 WAVELENGTH INTERVAL: 1.54-1.56 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	7.128	3.564	.76	.4793
Wavelengths	2	80.991	40.496	8.64	.0017**
Error	22	103.086	4.686		
Total	26	191.205			

TABLE A1

(continued)

DAYS AFTER SEEDING: 55 WAVELENGTH INTERVAL: 1.73-1.75 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	1155.033	577.517	3.20	.0605
Wavelengths	2	8.654	4.327	.02	.9764
Error	22	3976.215	180.737		
Total	26	5139.902			

DAYS AFTER SEEDING: 60 WAVELENGTH INTERVAL: 1.73-1.75 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	65.049	32.524	2.10	.1465
Wavelengths	2	9.111	4.556	.29	.7482
Error	22	340.927	15.497		
Total	26	415.087			

DAYS AFTER SEEDING: 66 WAVELENGTH INTERVAL: 1.73-1.75 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.939	.470	1.64	.2161
Wavelengths	2	10.613	5.306	18.58	.0001**
Error	22	6.282	.286		
Total	26	17.834			

TABLE A1

(continued)

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 1.70-1.72 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.937	.468	.08	.9207
Wavelengths	2	4.787	2.393	.42	.6605
Error	19	112.968	5.644		
Total	23	118.691			

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 2.21-2.23 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.003	.002	.16	.8558
Wavelengths	2	.891	.446	47.37	.0001**
Error	22	.207	.009		
Total	26	1.101			

DAYS AFTER SEEDING: 79 WAVELENGTH INTERVAL: 2.21-2.23 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.046	.023	2.42	.1123
Wavelengths	2	.205	.103	10.83	.0005**
Error	22	.208	.010		
Total	26	.459			

TABLE A1

(continued)

DAYS AFTER SEEDING: 86 WAVELENGTH INTERVAL: 1.96-1.98 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	49.834	24.917	2.71	.0889
Wavelengths	2	3.192	1.596	.17	.8420
Error	22	202.525	9.206		
Total	26	255.550			

DAYS AFTER SEEDING: 90 WAVELENGTH INTERVAL: 1.78-1.80 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	90.768	45.384	9.98	.0008**
Wavelengths	2	.121	.060	.01	.9868
Error	22	100.055	4.548		
Total	26	190.944			

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.78-1.80 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	13.600	6.800	23.12	.0001**
Wavelengths	2	.143	.072	.24	.7864
Error	21	6.177	.294		
Total	25	19.920			

TABLE A1

(continued)

DAYS AFTER SEEDING: 97 WAVELENGTH INTERVAL: 1.78-1.80 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	60.208	30.104	6.61	.0057**
Wavelengths	2	.029	.015	.00	.9968
Error	22	100.257	4.557		
Total	26	160.494			

TABLE A2

ANOVA FOR EXPERIMENT 1, STANDARDIZING RESULTS BY MEANS OF TREATMENT A (METHOD 2)

DAYS AFTER SEEDING: 38 WAVELENGTH INTERVAL: 1.79-1.81 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.108	.054	2.38	.1159
Wavelengths	2	4.240	2.120	93.39	.0001**
Error	22	.499	.023		
Total	26	4.847			

DAYS AFTER SEEDING: 43 WAVELENGTH INTERVAL:2.21-2.23 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	4.171	2.086	5.87	.0104*
Wavelengths	2	.255	.127	.36	.7033
Error	19	6.752	.355		
Total	23	11.178			

DAYS AFTER SEEDING: 47 WAVELENGTH INTERVAL: 2.28-2.30 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	5.207	2.603	5.27	.0135*
Wavelengths	2	10.442	5.221	10.56	.0006**
Error	22	10.873	.494		
Total	26	26.522			

TABLE A2

(continued)

DAYS AFTER SEEDING: 55 WAVELENGTH INTERVAL: 2.12-2.14 um

edU+2/6 nol nover	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	281.700	140.850	4.47	.0235*
Wavelengths	2	.923	.461	.01	.9855
Error	22	693.615	31.528		
Total	26	976.238			

DAYS AFTER SEEDING: 60 WAVELENGTH INTERVAL: 2.12-2.14 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	42.976	21.488	30.42	.0001**
Wavelengths	2	6.772	3.386	4.79	.0187*
Error	22	15.538	.706		
Total	26	65.286			

DAYS AFTER SEEDING: 66 WAVELENGTH INTERVAL: 2.12-2.14 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	3.479	1.740	.07	.9344
Wavelengths	2	7.397	3.698	.14	.8661
Error	22	562.410	25.564		
Total	26	573.286			

TABLE A2

(continued)

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.20-2.22 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.023	.011	2.71	.0923
Wavelengths	2	.400	.200	47.76	.0001**
Error	19	.080	.004		
Total	23	.503			

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 1.80-1.82 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	5.058	2.529	1.82	.1856
Wavelengths	2	1.281	.640	.46	.6368
Error	22	30.589	1.390		
Total	26	36.918			

DAYS AFTER SEEDING: 79 WAVELENGTH INTERVAL: 1.81-1.83 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	65.168	32.584	7.37	.0035**
Wavelengths	2	1.679	.840	.19	.8283
Error	22	97.207	4.419		
Total	26	164.054			

TABLE A2

(continued)

DAYS AFTER SEEDING: 86 WAVELENGTH INTERVAL: 1.63-1.65 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.209	.104	3.39	.0520
Wavelengths	2	.9620	.4810	15.63	.0001**
Error	22	.677	.031		
Total	26	1.848			

DAYS AFTER SEEDING: 90 WAVELENGTH INTERVAL: 1.63-1.65 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	79.327	39.664	9.83	.0009**
Wavelengths	2	1.029	.515	.13	.8809
Error	22	88.769	4.035		
Total	26	169.125			

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.63-1.65 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	20.690	10.345	18.54	.0001**
Wavelengths	2	.288	.144	.26	.7749
Error	22	12.276	.558		
Total	26	33.254			

TABLE A2

(continued)

DAYS AFTER SEEDING: 97 WAVELENGTH INTERVAL: 1.63-1.65 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	98.235	49.117	8.59	.0019**
Wavelengths	2	2.560	1.280	.22	.8013
Error	21	120.082	5.718		
Total	25	220.877			

TABLE A3

ANOVA FOR EXPERIMENT 2, USING SIX PLOTS AND STANDARDIZING RESULTS BY MEANS OF THE REFLECTANCE PLATE (METHOD 1)

DAYS AFTER SEEDING: 46 WAVELENGTH INTERVAL: 2.21-2.23 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	1.665	1.665	32.71	.0001**
Wavelengths	2	2.343	1.172	23.02	.0001**
Error	14	.713	.051		
Total	17	4.721			

DAYS AFTER SEEDING: 51 WAVELENGTH INTERVAL: 1.55-1.57 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	80.500	80.500	9.28	.0045**
Wavelengths	2	440.543	220.272	8.46	.0001**
Error	14	295.015	8.677		
Total	17	816.058			

DAYS AFTER SEEDING: 56 WAVELENGTH INTERVAL: 1.91-1.93 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	3.294	3.294	10.27	.0064**
Wavelengths	2	1.372	.686	2.14	.1546
Error	14	4.489	.321		
Total	17	9.155			

TABLE A3

(continued)

DAYS AFTER SEEDING: 63 WAVELENGTH INTERVAL: 1.73-1.75 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	228.089	228.089	2.42	.1424
Wavelengths	2	3.906	1.953	.02	.9795
Error	14	1321.279	94.377		
Total	17	1553.274			

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.33-2.35 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	8.624	8.624	8.68	.0106*
Wavelengths	2	.091	.046	.05	.9555
Error	14	13.915	.994		
Total	17	22.630			

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 1.70-1.72 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	2328.27	2328.271	14.661	.0018**
Wavelengths	2	450.309	225.155	1.42	.2751
Error	14	2224.072	158.862		
Total	17	5002.652			

TABLE A3

(continued)

DAYS AFTER SEEDING: 81 WAVELENGTH INTERVAL: 2.34-2.36 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	11574.851	11574.851	13.17	.0027**
Wavelengths	2	19.785	9.893	.01	.9888
Error	14	12301.771	878.698		
Total	17	23896.407			

DAYS AFTER SEEDING: 87 WAVELENGTH INTERVAL: 1.95-1.97 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	1016.249	1016.249	16.40	.10012**
Wavelengths	2	102.677	51.339	.83	.4571
Error	14	867.634	61.974		
Total	17	1986.560			

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.73-1.75 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	95.551	95.551	.99	.3357
Wavelengths	2	4.180	2.090	.02	.9785
Error	14	1345.945	96.139		
Total	17	1445.676			

TABLE A4

ANOVA FOR EXPERIMENT 2, USING SIX PLOTS AND STANDARDIZING RESULTS BY MEANS OF TREATMENT A (METHOD 2)

DAYS AFTER SEEDING: 46 WAVELENGTH INTERVAL: 1.68-1.70 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	9.162	9.162	24.83	.0002**
Wavelengths	2	.046	.023	.06	.9398
Error	14	5.166	.369		
Total	17	14.374			

DAYS AFTER SEEDING: 51 WAVELENGTH INTERVAL: 2.28-2.30 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	.344	.344	3.24	.0935
Wavelengths	2	.070	.035	.33	.7234
Error	14	1.489	.106		
Total	17	1.903			

DAYS AFTER SEEDING: 56 WAVELENGTH INTERVAL: 1.83-1.85 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	.076	.076	.35	.5637
Wavelengths	2	.030	.015	.07	.9324
Error	14	3.031	.216		
Total	17	3.137			

TABLE A4

(continued)

DAYS AFTER SEEDING: 63 WAVELENGTH INTERVAL: 2.12-2.14 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	2.408	2.408	8.53	.0112*
Wavelengths	2	.427	.214	.76	.4882
Error	14	3.954	.282		
Total	17	6.789			

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.27-2.29 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	.339	.339	6.65	.0218*
Wavelengths	2	.026	.013	.26	.7758
Error	14	1.078	.051		
Total	17	1.443			

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 2.14-2.16 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	.064	.064	.19	.6730
Wavelengths	2	.139	.070	.20	.8188
Error	14	4.789	.342		
Total	17	4.992			

TABLE A4

(continued)

DAYS AFTER SEEDING: 81 WAVELENGTH INTERVAL: 1.81-1.83 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	43.244	43.244	12.76	.0031**
Wavelengths	2	1.072	.541	.16	.8552
Error	14	47.452	3.389		
Total	17	91.768			

DAYS AFTER SEEDING: 87 WAVELENGTH INTERVAL: 1.63-1.65 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	13.560	13.560	5.13	.0399*
Wavelengths	2	.783	.392	.15	.8636
Error	14	37.000	2.643		
Total	17	51.343			

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.58-1.60 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	1	42.145	42.145	13.41	.0026**
Wavelengths	2	3.448	1.724	.55	.5896
Error	14	43.987	3.142		
Total	17	89.580			

TABLE A5

ANOVA FOR EXPERIMENT 2, USING THREE PLOTS AND STANDARDIZING RESULTS BY MEANS OF THE REFLECTANCE PLATE (METHOD 3)

DAYS AFTER SEEDING: 46 WAVELENGTH INTERVAL: 1.56-1.58 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	17.098	8.549	1385.51	.0001**
Wavelengths	2	4.894	2.447	396.60	.0001**
Error	4	.025	.006		
Total	8	22.017			

DAYS AFTER SEEDING: 51 WAVELENGTH INTERVAL: 1.56-1.58 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	107.491	53.746	119.12	.0003**
Wavelengths	2	10.415	5.208	11.54	.0218*
Error	4	1.805	.451		
Total	8	119.711			

DAYS AFTER SEEDING: 56 WAVELENGTH INTERVAL: 1.56-1.58 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	2.534	1.267	95.01	.0004**
Wavelengths	2	3.484	1.742	130.60	.0002**
Error	4	.053	.013		
Total	8	6.071			

TABLE A5

(continued)

DAYS AFTER SEEDING: 63 WAVELENGTH INTERVAL: 1.56-1.58 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	387.798	193.899	14484.55	.0001**
Wavelengths	2	3.459	1.730	129.20	.0002**
Error	4	.054	.013		
Total	8	391.311			

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.12-2.14 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	24.262	12.131	8252.55	.0001**
Wavelengths	2	.418	.209	142.18	.0002**
Error	4	.006	.002		
Total	8	24.686			

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 2.20-2.22 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.016	.008	2.13	.2351
Wavelengths	2	.477	.239	63.33	.0009**
Error	4	.015	.008		
Total	8	.508			

TABLE A5

(continued)

DAYS AFTER SEEDING: 81 WAVELENGTH INTERVAL: 1.50-1.52 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	814.509	407.255	178.79	.0001**
Wavelengths	2	21.466	10.733	4.71	.0888
Error	4	9.111	2.278		
Total	8	845.086			

DAYS AFTER SEEDING: 87 WAVELENGTH INTERVAL: 1.81-1.83 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	32.717	16.359	2.77	.1756
Wavelengths	2	13.560	6.780	1.15	.4033
Error	4	23.599	5.900		
Total	8	69.876			

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.83-1.85 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	10.668	5.334	.57	.6063
Wavelengths	2	57.993	28.997	3.09	.1543
Error	4	37.522	9.381		
Total	8	106.183			

TABLE A6

ANOVA FOR EXPERIMENT 2, USING THREE PLOTS AND STANDARDIZING RESULTS BY MEANS OF TREATMENT A (METHOD 4)

DAYS AFTER SEEDING: 46 WAVELENGTH INTERVAL: 1.48-1.50 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	1.169	.590	115.76	.0003**
Wavelengths	2	.280	.140	27.69	.0045**
Error	4	.020	.010		
Total	8	1.469			

DAYS AFTER SEEDING: 51 WAVELENGTH INTERVAL: 1.48-1.50 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	10.209	5.105	1851.63	.0001**
Wavelengths	2	2.235	1.118	405.31	.0001**
Error	4	.011	.003		
Total	8	12.455			

DAYS AFTER SEEDING: 56 WAVELENGTH INTERVAL: 1.48-1.50 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	1.146	.573	108.67	.0003**
Wavelengths	2	.574	.287	54.43	.0013**
Error	4	.021	.005		
Total	8	1.741			

TABLE A6

(continued)

DAYS AFTER SEEDING: 63 WAVELENGTH INTERVAL: 1.48-1.50 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	6.947	3.474	5.22	.0766
Wavelengths	2	7.579	3.790	5.70	.0675
Error	4	2.659	.665		
Total	8	17.185			

DAYS AFTER SEEDING: 70 WAVELENGTH INTERVAL: 2.14-2.16 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.004	.002	1.02	.4374
Wavelengths	2	.006	.003	1.32	.3636
Error	4	.008	.002		
Total	8	.018			

DAYS AFTER SEEDING: 75 WAVELENGTH INTERVAL: 2.20-2.22 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.032	.016	2.59	.1902
Wavelengths	2	.152	.076	12.24	.0197*
Error	4	.025	.006		
Total	8	.209			

TABLE A6

(continued)

DAYS AFTER SEEDING: 81 WAVELENGTH INTERVAL: 2.18-2.20 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.931	.466	.19	.8356
Wavelengths	2	5.323	2.662	1.07	.4230
Error	4	9.903	2.476		
Total	8	16.157			

DAYS AFTER SEEDING: 87 WAVELENGTH INTERVAL: 1.81-1.83 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	.656	.328	1.61	.3064
Wavelengths	2	.808	.404	1.99	.2516
Error	4	.813	.203		
Total	8	2.277			

DAYS AFTER SEEDING: 94 WAVELENGTH INTERVAL: 1.83-1.85 um

SOURCE	DF	SS	MS	F value	Prob.>F
Water Stress Treatments	2	11.283	5.642	105.63	.0003**
Wavelengths	2	.429	.215	4.01	.1107
Error	4	.214	.053		
Total	8	11.926			