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Spectral response of sweet corn, squash, and beans to nitrogen, zinc and water treatments

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SPECTRAL RESPONSE OF SWEET CORN, SQUASH, AND BEANS TO NITROGEN, ZINC AND WATER TREATMENTS

by

Saud Abdulaziz Amer

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As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Saud Abdulaziz Amer

entitled Spectral Response of Sweet Corn, Squash, and Beans to Nitrogen, Zinc and Water Treatments

and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

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SIGNED: S. A. Doner

DEDICATION

To my wife, Najla, and my children: Muhanad, Moataz and Hadil, whom I love with all my heart.

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ABSTRACT

The study consisted of six experiments conducted to examine the spectral response of different varieties of corn (Zea mays), squash (Cucurbita pepo) and bean (Phaseolis vulgaris) under variable zinc (Zn), nitrogen (N) and water treatments. Five of these experiments were conducted in the greenhouse during 1988 and 1989. The sixth experiment was conducted in the field during the summer of 1989.

Ground-based, remotely sensed data were collected over plant canopies during the growing period, using an Exotech Model 100 AX hand-held radiometer. The Exotech offers filter sets which match the thematic mapper (TM) bands 1 through 4 (0.45 - 0.52, 0.52 - 0.60, 0.63 - 0.69, and 0.76 - 0.90 μm).

Canopy spectral reflectance and derived vegetation indices showed their ability to significantly discriminate among varieties and variable treatments. Soil adjusted vegetation index (SAVI) mimics the normalized difference vegetation index (NDVI) and transformation normalized difference vegetation index (TNDVI) and exhibited all the characteristics of the NDVI curve when there were no soil influences (a single soil type). Red and near infrared (NIR) reflectance factors exhibited ability in monitoring crop growth and development. The TNDVI showed its superiority in detecting variations and in correlating with ground truth data (biomass cover percent). However, the study showed that remotely sensed data were sensitive to variations (varieties and treatments), but the data did not differentiate between them, unless supported with ground truth data.

INTRODUCTION

Fertilizer use in a crop production system is an economic investment. Insufficient applications of fertilizers are costly in terms of lost yields and over application results in unwarranted production costs.

Plants have long been known to differ in their susceptibility and tolerance to a nutrient and to water stress. Among the micronutrients, zinc has attained a great deal of agricultural prominence because of its widespread deficiency and responses of crops to its application.

Zinc fertilization has significantly increased yields in some field crops. Corn is one of the most Zn deficiency sensitive field crop species. Several Zn sources have been used to correct Zn deficiency in crops with zinc sulfate being the most frequently used (Takkar and Singh, 1978; Shukla and Mukhi, 1980; Coffman and Miller, 1973; Singh and Banerjee, 1986).

Water and nitrogen stress often limit corn grain yields. Although the literature is rich with information on the effects of either water or N stress on corn growth, development and yield, relatively little information is available concerning the combined interactive effects of these stresses. Nitrogen fertilizer is found to increase water-use efficiency on N-deficient soils when water is adequate, but less is known of the effects of high rates of N when water is limiting (Carlson et al., 1959; Olson, et al., 1964).

The optimal management of agricultural production requires increasingly more advanced approaches for monitoring growth development and stress. Fortunately, the rapid growth of the aerospace industry has made state-of-the-art hand held radiometers available for these purposes.

One of the broad objectives of remote sensing is to estimate areas planted to specific crops and to predict corp production by interpreting remotely sensed data over time. The factors considered include discrimination of vegetation, stress affecting crop growth or vigor, and stage of corp development.

Photosynthetically active, healthy tissues strongly reflect near infrared (NIR) light while absorbing most of the energy int he red portion of the spectrum for use in the photosynthetic process. A careful examination of the behavior of the red and NIR portion of the electromagnetic spectrum along with the indices derived from them may help to infer variations in agronomic treatments such as irrigation and fertilization.

If early detection of tonal differences of stressed corps can be obtained by analysis of spectral reflectance measurements, a valuable tool and cost-effective method that can save time and effort will be available to assess stress. On the other hand, this technique allows investigators to closely monitor development through observations made on a frequent basis, by-passing the often destructive and tedious approaches used to quantify those parameters in the past.

The normalized difference vegetation index (NDVI) is perhaps the most widely used index for green vegetation assessment. More recently, the NDVI and its transformation (TNDVI) have been shown to have a direct and highly correlated relationship with reflected photosynthetically active radiation. In addition, the integration of NDVI over a certain period of time has been successfully related to biomass integrated over the same period of time.

The present study examines the NDVI and its transformation (TNDVI), the integrated NDVI, and the soil-adjusted vegetation index (SAVI) in relation to crop condition (stress) and discrimination among varieties in field and greenhouse experiments. The objective of this study was to assess the suitability of ground-based remotely sensed data in detecting crop stress and distinguishing among varieties.

LITERATURE REVIEW

Zinc in Plant Growth

Zinc (Zn) deficiency and responses of crops to its application have been widespread around the world (Thorne, 1957; Ranhawa and Takkar, 1975). Field experiments were conducted on Zn-deficient alkali soils in India to determine the effect of Zn fertilization on the Zn nutrition of rice (Oryza sativa L.) (Takkar and Singh, 1978). The authors noticed that available soil Zn significantly increased from deficient to sufficient levels when Zn was applied. Their control plots exhibited poor growth and characteristic symptoms of Zn deficiency. On the other hand, Zn concentration in grain and straw increased with increasing rates of Zn application. Brown and Bell (1969) and Bruetch and Estes (1976) reported genotypic differences in the uptake of several nutrient in corn (Zea mays). But differential susceptibility of corn cultivars to Zn deficiency has rarely been found to correlate with Zn content or rate of Zn absorption (Ambler and Brown, 1969; Median and Nicholas, 1957; Safaya and Singh, 1977; Carroll and Longeragan, 1969). Safaya and Gupta (1979) studied the relationship between differential susceptibility to Zn deficiency and nutrient composition of 13 cultivars of corn grown on Zn deficient loamy sand soil of pH 8.5 in a greenhouse. It was observed that differential susceptibility of corn cultivars to Zn deficiency was not related to their Zn absorption characteristics. In the same soil, Zn-deficient plants had higher concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), Iron (Fe), manganese (Mn) and copper (Cu) except Zn in their tissues. Also, P uptake was significantly higher in the shoot of Zn-deficient plants.

Shukla and Prasad (1974) conducted a greenhouse experiment to verify that Zn application would enhance germination percentage, plant growth, Zn and K concentration and K/Na ratio in maize (Zea mays) under alkali soil conditions. Zinc and sulfur (S) treatments enabled maize to survive and increased growth markedly. Dry matter yield, as well as plant height, were increased by the application of Zn alone or in combination with S. There was no germination of seed from the control treatment. On the other hand, although germination occurred, plant growth was extremely poor when only S was applied. In a greenhouse study of the relationships among Na, K, and Zn in corn nutrition, Skukla and Mukhi (1979) found that shoot yield was significantly affected by Zn, K, and Na. There was an increase in yield with application of Zn over no Zn-treated soil, when K or Na were not applied. When Zn was not applied, the application of K increased yield. Sodium decreased yield at all levels of Zn. The results also showed that Zn concentration in corn shoots increased considerably with increasing levels of Zn at all levels of K and Na. Shukla and Mukhi (1980) conducted another greenhouse experiment to evaluate the ameliorative role of Zn on corn growth under alkali soil conditions. Shoot dry matter production was markedly depressed under alkali soil condition, when Zn was not applied. The application of Zn to the alkali soil improved plant growth. The yield increased in Zn-treated alkali soils was suggested to be associated with enhanced uptake of Zn.

Coffman and Miller (1973) conducted a greenhouse experiment to determine the response of corn to applied Zn on 12 Maryland soils. A few cases of Zn deficiency were found. The dry matter yield of corn grown on 11 of the 12 soils under investigation did not increase significantly with the application of Zn. However, the deficient soil responded to an application of 1.25 ppm Zn, resulting in almost a 100% increase in yield and preventing the development of Zn deficiency symptoms. With the application of Zn on one of the 11 soils, there was a reduction in the yield of dry matter, even though symptoms of Zn toxicity were not observed when the plants had 118 ppm Zn. The analysis of the corn for Ca, Mg, K, and P did not reveal a reason for the reduced yields from the application of Zn. Under the conditions of this experiment, the authors found that the critical level of Zn in corn was about 12 ppm above which there was no further significant increase in dry matter yield. Pumphrey et al. (1963) reported Zn deficiency symptoms in corn which contained up to 13 ppm Zn in the first leaf below the primary ear node at silking time but 15 ppm or more Zn in the leaf was adequate for good growth. Singh and Banergee (1986) studied the effect of different levels of Zn application on growth and Zn content in various plant parts of maize in the greenhouse on Zn-deficient soil. Symptoms of Zn deficiency began when the plants in the control pots were about three weeks old. Significant increases in dry matter production were obtained with Zn addition up to a certain level. Zinc concentration in the individual index leaf blades and in the whole shoot increased with Zn application. The critical Zn concentration declined with time, therefore diagnosing Zn deficiency may be difficult because Zn levels in Zn deficient plants depend on the time of sampling. Verma and Minhas (1987) conducted a field experiment on soils of pH 5 to 7 to study the interaction effect of Zn and P in a wheat-maize cropping system. The study showed that soil application of 20 kg Zn per ha significantly increased the yield of maize over the control when soil was not limed and P was not applied. Under the same soil conditions, no lime and no P, the addition of 40 kg Zn did not affect maize yield significantly over 20 kg added Zn. On the other hand, when soil was limed and P was not applied, the addition of 40 kg Zn per ha also increased the maize yield significantly in comparison with 20 kg added Zn. When P was applied, there was a strong interaction, and application of 40 kg Zn per ha under limed condition did not produce a significant effect on maize yield over 20 kg of added Zn. Under unlimed condition, however, 40 kg added Zn reduced the maize yield significantly over the 20 kg added Zn. The P-Zn interaction has been studied by a number of workers (Bingham and Garber, 1960; Brown et al., 1970; Reddy et al., 1973). They suggested that P affects the absorption of Zn from soil by roots in some way other than the precipitation of an insoluble Zn-phosphate. However, the information on the residual effect of Zn-P interaction is very meager. Kayode (1985) conducted field experiments to determine the responses of yield, components of yield and nutrient content of maize to soil-applied Zn. Zinc significantly increased yield only in terms of ear weights. Soil-applied Zn significantly increased ear-leaf N and Zn, whereas P concentration was significantly decreased. Grain yield was positively correlated with ear-leaf Zn.

Zinc pools and their availability to maize-wheat rotation were studied by Brar et al. (1986). The results indicated that continuous cropping caused the depletion of Zn from various soil pools, mostly from weakly absorbed and acid-soluble Zn. The application of N and P enhanced the depletion of soil Zn, which was suggested to be due to the increased yield of maize and wheat. The study indicated that DTPA-extractable Zn is a poor predictor of Zn deficiency in some soils.

Judy et al. (1964) conducted field and laboratory studies with Zn fertilization of pea beans (Pisum sativum) corn and sugar beets (Beta vulgaris). Shelled corn yields failed to show a significant response to Zn. There was a trend toward lower yields on higher phosphorus plots. Zinc uptake was not significantly affected by Zn or P treatment. Keefer et al. (1972) conducted a greenhouse experiment to test the response of corn to time and rate of P and application of Zn-EDTA and $ZnSO_4$. Corn was grown on two soils, which differed in available Zn, available P, total Zn, organic matter, and pH. Dry matter yield and Zn concentration and content of plant parts were increased where either source of Zn was applied with P, regardless of time to soil I (low in available and total Zn, organic matter). The second soil which was higher in Zn and organic matter responded to $ZnSO_4$ application only when high rates of P were applied eight weeks before planting. Plants grown on the low Zn soil had higher Zn levels when Zn-EDTA was applied, showing the higher efficiency of Zn application in a soil with neutral pH values. The use of Zn-EDTA on the higher Zn soil with a pH value of 5.1 affected neither yields nor Zn concentration in the leaves. Either the instability of Zn-EDTA under acid conditions (converted to a form not readily available to plants) or the higher organic content of the soil prevented the efficient use of this source of Zn. Safaya (1976) studied the P-Zn interaction in relation to growth, nutrient content in plant parts, and the rates of absorption of P, Zn, Cu, Mn, and Fe per unit fresh weight of corn roots for two growth periods under greenhouse conditions. Plants exhibited visual symptoms of Zn deficiency when the level of applied P was the highest (75 ppm). Phosphate decreased tissue-Zn concentration and Zn flux through roots. Zinc deficient plants exhibited higher concentrations of P in their tissue. Phosphate flux was mostly reduced with the application of Zn. In the absence of Zn, increasing P rates of application of 25 to 75 ppm decreased the dry matter yield of both tops and roots. On the other hand, Zn in the absence of P, tended to decrease the root and top growth with time. The rate of Cu absorption was reduced by both P and Zn application as the plants aged. Manganese flux was initially stimulated by P, but drastically reduced by Zn with time. Also Fe concentration in plants decreased with Zn application.

Gupta and Gupta (1985) conducted pot experiments on a Zn-deficient sodic soil to evaluate the effect of Zn sources on yield and Zn, Cu, Mn and Fe nutrition of soybean (Glycine max.) Zinc sulfate and Zn-EDTA were applied at rate of 0, 5, and 10 ppm in this study. Application of 5 ppm $ZnSO_4 \cdot 7H_2O$ exhibited higher yield than that of Zn-EDTA. Zinc concentration increased with Zn application, more so when applied as Zn-EDTA. Uptake of Cu and Mn increased with Zn application.

The Mn content decreased with Zn application. The study also showed that Fe uptake and concentration were higher with Zn-EDTA treatments than those under $ZnSO_4 \cdot 7H_2O$ treatments. Singh (1986) conducted a greenhouse study to determine the critical levels of soil and plant Zn needed for proper growth of cluster bean (Cyamopsis tetragonoloba). Twenty-six non-calcareous soils ranging in DTPA-extractable Zn from 0.24 to 2.00 ppm were studied. The pH varied from 7.5 to 8.3 and EC from 0.04 to 0.97 dS/m. Three levels of Zn (0, 5, 10 ppm) as $ZnSO_4 \cdot 7H_2O$ were applied. The characteristic symptoms of Zn deficiency were visually noticed on plants in several soils 3 to 4 weeks after sowing. Application of 5 and 10 ppm Zn increased the dry matter yields of cluster bean plants significantly over no Zn treatment. There was no significant difference in the dry matter yield between 5 and 10 ppm treatments, indicating that 5 ppm Zn was probably sufficient for proper growth of cluster bean. The critical Zn concentration in soils and plants below which plant response to Zn application might be expected was found to be 0.54 and 15.4 ppm, respectively.

The relative effectiveness of Zn fertilizer sources on nutrition of beans has been tested by many investigators. Judy et al. (1964), studied Zn fertilization of pea beans. The treatments which did not receive Zn exhibited severe Zn deficiency which was indicated by deformation and dwarfing of leaves, fewer and shorter pods, and delayed maturity. The symptoms appeared as early as 3 to 4 weeks after emergence and persisted to maturity on some treatments. On the other hand, both yield and Zn uptake significantly increased with Zn application. Chelated Zn materials were more effective than the inorganic carriers. Levels of Zn as related to early growth and development of determinate soybeans were studied by Ohki (1977). Zinc deficiency reduced top and root dry weights, plant height, flower number, and branching, however, node development was not affected by Zn deficiency. Zinc deficiency symptoms appeared on young developing and recently matured leaves. When plants were supplied with a minimum rate of Zn (5 ppm), recently matured leaves exhibited severe rugose appearance. Interveinal chlorosis was scattered in small areas, but was not prominent over the entire surface. On the other hand, top growth and root dry weight increased with Zn addition. Gabal et al. (1985) studied the effect of foliar applications of Cu, Mn and Zn on common bean growth, flowering and seed yield. Copper, Mn and Zn did not affect plant height, number of leaves, internode length, or fresh and dry weight per plant at full blooming stage compared with the control. The authors suggest that this unfavorable effect may have resulted from the fact that sampling took place at the full bloom stage when most plant activities were directed towards flowering and fruit setting instead of vegetative growth. The chlorophyll content of leaves increased significantly with Cu, Mn or low doses of Zn (25 ppm Zn was the best dose) foliar spray. It was found that leaf chlorophyll-content decreased by increasing levels of Zn application (over 25 ppm Zn). Such findings agreed with results obtained by other workers (Edward and Mohamed, 1973). Plants sprayed with Cu, Mn or Zn flowered 3 to 7 days earlier than the control treatment. Moreover, spraying plants with 40 ppm Cu, 25 ppm Mn, or 25 to 50 ppm Zn had an enhancing effect on the number of flowers per plant. Foliar spray with 10 to 20 ppm Cu or 25 ppm Zn improved pod setting significantly over the control treatments. The results also showed that a foliar spray with 100 ppm of Mn or Zn increased dry seed yield significantly. Marsh and Waters (1985) conducted greenhouse and field studies to determine the influence of various Zn levels or growth, nodulation, and N_2 fixation of cowpea (Vigna ungui). The Zn levels used were 0.0, 0.6, 1.5, 2.5 and 5 ppm Zn as $ZnSO_4$. The results showed that a significant increase in nodule numbers, nodule dry weight, and N_2 fixation occurred when plants received higher Zn levels. Plant parts showed higher Zn accumulation with increased Zn application, with roots having the maximum accumulation. The yield response to added Zn was reflected primarily by an increase in seeds per pod and seed yield which were highest at the higher applied Zn levels. Thus, Zn nutrition is an important factor influencing the nodulation of N fixation processes, and it may affect both Rhizobium nutrition and dry-matter accumulation.

Nitrogen Fertilizer and Water In Corn Plant Growth

Improvement of fertilizer and water use efficiency is a continuous goal of agricultural researchers. However, research data relating fertilizer rates and soil test indices to total nutrient uptake and grain yield in irrigated areas are scarce. Using the correct amounts and proportions of fertilizers in a crop production system is an economic investment. Insufficient fertilization is costly in terms of lost yields, and over-application increases production costs and can cause environmental pollution.

In order to apply the correct amounts of fertilizers, it is necessary to know the crop response to applied fertilizer in relation to the nutrient supplying power of the soil.

Obreza and Rhoads (1988) conducted a field study at the University of Florida to determine the response of irrigated corn to soil-test indices and applied N, P, K, and Mg fertilizer. A double-cropping system consisting of corn followed by annual ryegrass (Lolium multiflorum) or soybeans (Glycine max L.) was established at the research farm. Indices of available nutrients were measured through Mehlich I soil test prior to each season for two consecutive years. The results showed that maximum grain yield was obtained from a minimum application of 168 kg ha^{-1} of N (as NH_4NO_3), 29 kg ha^{-1} of P (concentrated superphosphate), and 0 kg ha^{-1} Mg (as $MgSO_4$). For K, maximum yield occurred with minimum applications of 209 and 0 kg ha^{-1} in 1980 and 1981, respectively. In the study, corn failed to respond to N rates above 168 kg ha^{-1} in the second year which was due, according to the authors, to release of N from crop residues that built up in the double-cropping system. Calculated critical Mehlich I soil test levels were 9, 45, and 33 mg kg^{-1} for P, K, and Mg, respectively. Field studies were conducted over a 6-year period on the Texas Agricultural Experiment Station to determine the effects of fertilizer N and residual NO_3^--N on irrigated corn yield (Onken et al., 1985). Nutrient source used was ammonium nitrate. Soil samples were taken prior to fertilizer application each year at depths 0 to 0.15, 0.15 to 0.30, 0.30 to 0.60 and 0.60 to 0.90 m and analyzed for NO_3^--N. Grain yield was significantly influenced by applied N and residual soil NO_3^--N. Residual NO_3^--N measured to a depth of 0.15 m was found to be sufficient for evaluation of residual N effects on irrigated corn yield on that soil. The results also indicated that fertilizer use efficiency (FUE) was influenced by grain yield, fertilizer N rate, and amount of residual soil NO_3^--N. The greatest reduction in FUE was due to residual NO_3^--N. Anderson et al. (1984) conducted field experiments for two consecutive years to determine the effect of N fertilizer on dry matter and N accumulation, partitioning and remobilization in genotypes of corn which differ in prolificacy (ear number per plant). Two N rates were used, 56 and 224 kg ha^{-1} as ammonium nitrate. Leaf N decreased linearly during the grain filling period at both N rates. Total stalk N decreased curvilinearlly at both N rates with most of the decrease occurring in the first 30 days following silking. On the other hand, ear N accumulated at a linear rate for the first 30 days during grain fill and then proceeded at a slower rate. Grain yield per plant was associated with the number of ears per plant. The increase in N fertility rate tended to increase the number of ears per plant of the more prolific genotypes. Genotypes with a greater average ear number were more efficient in using accumulated N for producing grain and partitioned more of the total plant N and dry matter to grain production. Leaf dry weights did not change during grain fill at either of the N rates for all genotypes, which suggested no essential net remobilization of carbohydrates from the leaves. However, there was a significant decrease in stalk dry weight during the grain-fill period, which was suggested to be associated with a decrease in soluble carbohydrates.

A greenhouse experiment was conducted to study the effects of horizontally and vertically oriented compaction zones and N fertilizer placement on corn root growth patterns, soil water depletion and N fertilizer uptake (Garcia, 1988). The results showed that compaction treatments did not significantly affect total root growth, but N fertilization tended to decrease it. Root growth compensation was enhanced in zones of favorable nutrient supply and redirection of growth to zones of more favorable physical conditions. Nitrogen uptake was highly affected by N placement when compaction zones were present. It was also found that water extraction from a given zone was directly related to root density in that zone.

Rhoads and Stanley (1984) conducted field experiments to determine the relationships between yield of two hybrids of irrigated corn at two populations and total uptake of N, P, and K in the tissue. The results showed that grain yields were significantly correlated with N in tissue and total N uptake. Eck (1984) conducted field experiments to determine the plant nutrient needs for corn, the effects of timing and duration of drought stress periods, and the interacting effects of N levels and drought stress on N nutrition and production of corn. Fertilizer N rates used were 0, 70, 140, 210, 280 and 350 kg ha^{-1}. The results indicated that two and four weeks of plant water stress during vegetative growth reduced yield of adequately fertilized (210 kg N ha^{-1}) corn by 23 and 46%, respectively. Two weeks of water stress during late and early vegetative growth had similar effects on grain yields. The yields were reduced 1.2% for each day stress was imposed during grain filling. The results also showed that adequate N slightly increased corn grain yield under stress and greatly increased yield with full irrigation. A field study was conducted to evaluate the interactive effects of N and water stresses on water relations of field grown corn leaves (Bennett et al., 1986). The authors concluded that the high-N plants were affected less by the water stress than low-N plants as evidenced by the maintenance of leaf turgor potential, open stomata, and higher rates of individual leaf transpiration despite similar reduction in leaf water potential during periods of water stress.

Altenhofen and Bausch (1983) assessed yield reductions caused by moisture stress using signs of visual stress in corn. They concluded that visual water stress symptoms can be used to estimate yield losses and manage a limited water supply for corn. By knowing the relation of soil type and weather to stress signs and yield loss provides a simple line guide for managing areas of limited water supply throughout the growing season. Water management for the grain fill stage was dependent on conditions during the period of vegetative growth when maximum potential yield is being determined.

Canopy Spectral Reflectance As Related To Nutrients and Water Treatments

Nutrient supplies and water availability can affect plant appearance and performance, hence it determines the nature of light interaction with a plant canopy. This feature can be utilized in remote sensing to characterize and quantify such variabilities.

Reflectance is the ratio of reflected radiant energy by a body to that incident on it (Rabchevsky, 1984). When the wavelength interval is specified, it is called spectral reflectance. When the tonal differences of vegetation canopies are studied, the bidirectional reflectance factor (BRF) is usually used. The BRF is defined as the energy reflected from a target to that reflected by a reference, perfectly diffuse, completely reflecting surface (Silva, 1978). The target is assumed to be a lambertion surface (diffuse reflector). A barium sulfate-coated plate is usually used as a reference. Both the target and reference should be under the same irradiating and viewing conditions. However, in this study the term reflectance will refer to the BRF.

One of the broad objectives of remote sensing applications in agriculture is to provide accurate vegetation indices for the interpretation of spectral response measurements of plant/soil communities. Many indices, utilizing the transformation of remotely acquired reflectance data, by combining different spectral bands, have been developed. These indices have proven useful in detecting changes, monitoring crop health and performance, and enhancing spectral variations attributed to canopy response while minimizing the spectral influence of soil background. Such indices include the soil line concept and vegetation indices (Kauth and Thomas, 1976; Richardson and Wiegand, 1977; Jackson, 1983; Jackson and Ezra, 1985; Asrar et al., 1985).

Soil Line Concept

The soil line concept has been investigated by many workers. Richardson and Wiegand (1977) developed a soil line for Landsat multispectral scanner (MSS) data collected over Hidalgo County, Texas, and used it to calculate other two-dimensional (2-D) vegetation indices that normalize the effect of soil background on the vegetation spectra. Wiegand and Richardson (1982) developed another concept termed the "soil line index" (SLI). It is a 2-D vector distance from the origin of the soil line to the point of intersection of the perpendicular vegetation index (PVI) with the soil line. They reported that such an index along with other vegetation indices could be utilized for monitoring vegetation development while reducing the effect of soil background. Huete et al. (1985) demonstrated the substantial effects of soil background on vegetation spectra, especially with sparse plant cover. They inserted trays of soils varying in their spectral response beneath a growing cotton canopy. The results showed that variations in soil spectral response influenced the greenness measures for plant covers up to 75%. More recently, Huete (1988) developed a new index, the soil adjusted vegetation index (SAVI), by manipulating the normalized difference vegetation index (NDVI). The SAVI was found to reduce the soil contribution in greenness measures.

Vegetation Indices

Jackson et al. (1980) presented a definition for a spectral vegetation index as "a quantity obtained, directly or by rationing, differencing, or otherwise transforming spectral data to represent plant canopy characteristics such as leaf area index, biomass ..." Tucker (1979) and Jackson et al. (1980) discussed the most frequently used spectral vegetation indices. The near infrared (NIR) to red ratio was probably the first of such transformations to be used for estimating biomass of leaf area index (LAI) (Jordan, 1969). He used the ratio of the intensity of transmitted NIR radiation to that of the red radiation, sensed on the forest floor, to derive the LAI for forest canopies. Higher ratios were obtained when there was more green biomass.

The vegetation index (VI) was developed and discussed by Rouse et al. (1973), Deering et al. (1975), and Deering (1978). They used the Landsat NIR and red channels to form the difference ratio (the ratio of the difference between the NIR and red bands and their sum) and named this ratio the vegetation index. They also found that for scenes with low vegetation cover, the VI may become negative. These observations led to the development of transformed vegetation index (TVI), formed by taking the square root of (VI + 0.5). The 0.5 was added to avoid the negative values under the square root. Recently VI and TVI became known as the normalized difference vegetation index (NDVI) and the transformed normalized difference vegetation index (TNDVI), respectively.

Rouse et al. (1974) evaluated the NDVI and TNDVI, calculated from Landsat (multispectral scanner) MSS data, for monitoring rangelands and wheat crops. The NDVI and TNDVI closely followed crop development as ground cover, biomass, and leaf area indices increased. Tucker et al. (1979) collected red and NIR spectral data with a hand-held radiometer in an attempt to make qualitative and/or quantitative inferences about stage of growth and development of corn and soybean crops. The data were collected under a variety of irradiational conditions during the study period. Several radiance normalization techniques were applied to the spectral data. The individual red and NIR radiances were transformed into the NIR/red ratio, the NIR-red difference, the NIR + red sum, the NDVI of (NIR - red)/(NIR + red), and the transformed NDVI (TNDVI) of $\sqrt{NDVI + 0.5}$. The NDVI was closely associated with the early season when crop development was rapid. However, by late season, the NDVI was mostly responsive to fluctuation in green vegetation crop cover associated with the sequence of crop development and maturation. The authors were able to define five phenological stages of spectral crop development (SCD) for corn and soybean crops. The stages for both crops were : (1) the NDVI was negative for the bare soil before crop emergence and after emergence up to 20 to 30% cover; (2) the NDVI increased with increasing vegetative crop cover until bloom; (3) once vegetative crop cover was complete, NDVI reached a plateau. Stage three of SCD continued during bloom and until chlorosis was detected; (4) the period of crop maturation and dry-down, NDVI declined gradually. Leaves became chlorotic and were often lost from the plants; and (5) at this stage of SCD, the soybeans had lost all leaves and the corn had lost all green color, the NDVI resembled that measured at crop emergence (stage 1).

Landsat spectral reflectance data, on the other hand, have been evaluated by many investigators to detect water stress in vegetative canopies. Thompson

(1980) evaluated the applicability of Landsat digital data to detect moisture stress over part of the corn-soybean growing region in the United States. The remote sensing-based information was compared to a weekly ground-based index (crop moisture index). The author concluded that the remote sensing technique could be used to monitor the growing conditions within a region where corn and soybeans are the major crops.

Water stress in green plant canopies was monitored utilizing thematic mapper (TM) bands 3 (0.63 to 0.69 μm), 4 (0.76 to 0.90 μm), and 5 (1.55 to 1.75 μm) (Holben et al., 1983). The photographic IR region (TM4) was the most sensitive spectral band for foliar water stress detection when the water deficit was sufficient to cause wilting. TM3 was found less responsive to the level of foliar water stress. The mean values of TM5 reflectance data showed similar trends to TM4. The off-nadir viewing satellite may not be sensitive to the level of foliar water stress as the nadir viewing satellite when measuring dense canopies.

The NDVI and its transformation (TNDVI) are perhaps the most suitable and widely used indices for green vegetation and yield assessment, and agronomic characteristics of many crops (Tucker, 1977; Tucker, 1979; Pinter et al., 1981; Patel et al., 1985). Many attempts have been made to relate vegetative biomass to these spectral indices. Other investigators have shown a good correlation between NDVI-time-integral (NDVI-Days) and the end of season biomass (Holben et al., 1980).

Since then, some important developments in vegetation sensing have occurred. The most important is perhaps the use of the Advanced Very High Resolution Radiometer (AVHRR) data for land remote sensing.

The AVHRR sensor, on board the National Oceanographic and Atmospheric Administration (NOAA) polar-orbiting satellite, was originally designed for meteorological purposes. However, the system provides low-spatial-resolution high-radiometric-resolution multispectral data for the entire surface of the earth on a daily basis, in comparison to the 16 to 18 day cycle of the Landsat system. The multi-emporal nature of the data, which enabled researchers to address global and regional monitoring aspects of remote sensing, along with their low cost to the user and smaller volume have contributed to the increase in NDVI-based vegetation studies with remarkable results (Justice, 1986).

Some of these studies focused on green biomass productivity, green vegetation dynamics and production, and phenology of vegetation communities (Justice et al., 1986; Tucker, 1986; Tucker and Sellers, 1986; Townshend and Justice, 1986; Justice et al., 1986; Hielkema et al., 1986). Others have studied problems such as drought, grass-land monitoring, continental land cover mapping, tropical deforestation, and regional fire monitoring (Henricksen, 1986; Henricksen and Durkin, 1986; Justice and Hiernaux, 1986; Hiernaux and Justice, 1986; Prince and Astle, 1986; Prince and Tucker, 1986; Prince, 1990).

EXPERIMENTAL PROCEDURE

Six experiments were conducted to examine the spectral response of different varieties of corn (Zea mays), squash (Cucurbita pepo) and bean (Phaseolis vulgaris) plants to zinc (Zn), nitrogen (N), and water treatments. Five of these studies were conducted in the greenhouse at the University of Arizona Campus, Tucson, Arizona (32 28' N, 110 95' W, 1220 m above M.S.L.) from August 28, 1988 through March 5, 1989. The sixth experiment was conducted in the field during the summer of 1989 at the University of Arizona Maricopa Agricultural Center (MAC), 5 km east of Maricopa and 8 km north of the Casa Grande-Maricopa Highway in Pinal County, Arizona (32 53' N, 11 45' W, 358 m above M.S.L.).

Soil Characteristics

The soil selected for both field and greenhouse studies was Casa Grande (sandy loam), reclaimed. Casa Grande soils are fine-loamy, mixed, hyperthermic Typic Natrargids. These soils are deep, well drained, slowly permeable, and formed in old alluvium. On the MAC farm, the soil typically has a brown to reddish brown sandy loam (SL) surface horizon from 0 to 30 cm deep. The subsoil horizon from 30 to 60 cm is usually a reddish brown sandy clay loam which increases in calcium carbonate content with depth. Below this horizon at a depth of 60 to 100 cm is a horizon enriched with calcium carbonate (Calcic horizon), which also has a sandy clay loam (SCL) texture. The depth to the Calcic horizon varies from 25 to 100 cm in depth, but commonly occurs between 50 and 80 cm in depth. Some physical and chemical properties of the 0 to 30 cm layer of the soil are shown in Table 1.

Description of Greenhouse Study

Corn and Zinc Experiment

The soil collected from the MAC field 113 was air-dried, ground using an electrical grinder, and passed through a 2 mm sieve. Polyethylene pots of 16 cm diameter were filled with 2 kg of the sieved soil. The soil was Zn-deficient containing 0.19 ppm DTPA extractable Zn with corn and beans showing mild

Table 1. Some physical and chemical properties of the 0 to 30 cm layer of the Casa Grande soil. (Post et al., 1988).

Clay content	: 15%
Sand content	: 60%
Bulk density	: 1.5 g cm^{-3}
Total pore space	: 44%
Water-weight basis at	
-.1 bar	: 19%
-.33 bar	: 15%
-15 bar	: 8%
Organic matter	: 0.6%
Calcium Carbonate	: 4%
Cation Exchange Capacity	: 11 meq/100 g

deficiency symptoms in the field. Three cultivars of sweet corn, Zea mays Saccharata, (V1, Northern Extra Sweet; V2, Jubilee; and V3, Sweeti 82) were used. Zinc was mixed thoroughly in the soil before planting at 0, 5, 10 and 15 ppm as $ZnSO_4 \cdot 7H_2O$. Each treatment was replicated three times and received a basal application of N and P at 160 and 50 ppm, respectively, in the form of NH_4NO_3 and $Ca(H_2PO_4)_2 \cdot H_2O$. The plants were irrigated with distilled water as needed and allowed to grow for 41 days (28 Aug. through 8 Oct. 1988). Reflectance measurements were made about two weeks after planting as described below.

After 41 days, the above ground plant was harvested and separated into leaves (blades only) and stems. The plan samples were washed with deionized water and dried at 65°C. After day matter was determined, leaves only were ground in a stainless steel Wiley mill. Dried tissue samples were then digested in a mixture of nitric and perchloric acids using a block digester (Technicon BD-40). The Zn concentration in the digest was determined by atomic absorption spectrophotometry.

Reflectance Measurements

A portable Exotech Model 100 AX radiometer was used to measure the spectral response of the corn, squash and bean canopies. The Exotech radiometer measures the radiant flux of a target simultaneously in four wavebands. It has a 15° field of view (FOV) with bandpass intervals that match the thematic mapper (TM) bands 1 through 4 (0.45 - 0.52, 0.52 - 0.60, 0.63 - 0.69, and 0.76 - 0.90 μm).

The radiometer was held during all measurements in such a way as to obtain a radar view from a height of 50 cm above the plant canopy, which corresponds to a circular area of about 13 cm in diameter at 50 cm elevation. Spectral reflectance measurements were made at 3-day intervals. The three pots of each treatment were set on a black-painted wood frame and spectral response was measured. Five readings were taken per treatment. Readings from a standard barium sulfate-coated reference plate were obtained immediately before and after the target (canopy) readings. Data were logged in an Omni-data polycorder model 516. Measurements were taken during sunny, cloud-free days between 0900 and 1130 hours. The reflectance was then calculated by dividing the average of five target radiance measurements by the plate radiance, both corrected for dark-level instrument offset, and multiplied by the plate reflectance factor corrected for sun angle.

Spectral response measurements for all other experiments (greenhouse and field) were made by the same instruments and followed the above procedure.

Bean and Zinc Experiment

Polyethylene plots of 16 cm diameter were filled with 2 kg of sieved soil. Zinc was applied at 0, 5, 10 and 15 ppm as $ZnSO_4 \cdot 7H_2O$, and was mixed thoroughly in the soil before planting. Three varieties of beans, Vigna angularis (Adzuki, V1); Phaseolus acutifolius (Tepary, V2); and Phaseolus vulgaris (Anasazi, V3) were grown. Each treatment was replicated three times and received a basal application of N and P at rates of 100 and 50 ppm, respectively, in the form of NH_4NO_3 and

$Ca(H_2PO_4)_2H_2O$. The full does of P and 40 ppm of N were applied before planting and the remaining N was split into two 30 ppm applications. Eight seeds were sown in each pot on 23 October 1988. After emergence, plants were thinned to three per pot and irrigated with distilled water as needed. The plants were allowed to grow about four weeks after planting. The experiment was terminated due to Zn contamination of soil. However, the reflectance measurements were analyzed for distinguishing different varieties of the same crop.

Squash and Zinc Experiment

Zinc was applied at 0, 5, 10 and 15 ppm as $ZnSO_4 \cdot 7H_2O$ and was mixed thoroughly in the soil before planting. Three varieties of squash Cucurbita pepo (Corsair, V1; Tay Belle, V2; and Pavo, V3) were grown. Each treatment was replicated three times and received a basal application of N and P at rates of 110 and 50 ppm, respectively, in the form of NH_4NO_3 and $Ca(H_2PO_4)_2 \cdot H_2O$. The full dose of P and 40 ppm of N were applied before planting and the remaining N was split into two 35 ppm applications. Eight seeds were sown in each pot on 26 October 1988. After emergence, plants were thinned to three per pot and irrigated with distilled water as needed. The plants were allowed to grow about three weeks after planting. The squash and bean experiments were run concurrently and terminated at the same time due to Zn contamination of soil. The reflectance measurements were examined for distinguishing among the three varieties of squash.

Corn and Nitrogen Experiment

Three varieties of sweet corn (V1, Northern Extra Sweet; V2, Jubilee; and V3, Sweetie 82) were grown. Nitrogen was applied at 0, 150 and 300 ppm as NH_4NO_3. The N rates at 150 and 300 ppm were applied in four increments with approximately a two-week interval. Each application was dissolved in deionized water and added to the soil. Each treatment was replicated four times. The best three treatments were then used for data acquisition. The plants were irrigated with distilled water and allowed to grow for 100 days (26 November 1988 through 5 March 1989).

At the end of the experimental periods, the plants (above ground only) were harvested and separated into leaves, basal stalks, and the remaining part of the shoot. The plant samples were washed with deionized water and dried at 65°C. After recording their dry weights, leaves and basal stalks were ground separately in a stainless steel Wiley mill. Dried tissue samples of the leaves and basal stalks were then analyzed for chlorophyll (Johnson, 1973) and nitrate, respectively. The nitrate analysis was done by adding 200 ml of deionized water to 0.1 g sample of the ground basal stalk tissue in a 250 ml erlenymeyer flask and shaken for one hour. The solution was then filtered and the nitrate concentration was determined using Ion Chromatography (IC).

Spectral Response and Vegetation Cover Measurements

The radiant flux of the corn canopy was measured simultaneously in four wavebands using a portable Exotech Model 100 AX radiometer. Reflectance measurements were made as described for the corn and zinc experiment. They were started five weeks after planting and were made every three days during sunny, cloud-free days between 0900 and 1130 hours. Once a week, photographs were taken for each treatment immediately after the reflectance measurements to determine percent cover of biomass. Cover percentage was calculated using a dot grid sheet (64 dots per square inch).

Corn and Water Experiment

Three varieties of corn were seeded, on 29 November 1988, into 16 cm diameter pots containing 2 kg of soil as described previously.

Three water levels, W1, W2 and W3 were set at 80, 60 and 40%, respectively of the field capacity of the soil. Each treatment was replicated four times, and three treatments were then used for data acquisition. All treatments received applications of N at 300 ppm (split into three increments) in the form of NH_4NO_3. The plants were irrigated with distilled water and allowed to grow for 96 days (29 November 1988 through 28 February 1989). All pots were weighed daily over the entire period of the experiment, and the water loss (grams) through evapotranspiration was recorded. Water was added when 70 g was consumed in W1, 140 g was consumed in W2, and 210 g was consumed in W3. All treatments were then brought to 100% field capacity. The differential irrigation treatments were initiated seven weeks after planting.

At the end of the experimental period, the plant tops were harvested and separated into leaves (blades only) and stems. The plant samples were washed with deionized water and dried at 65°C. Dry weights were recorded and leaves were ground in a stainless steel Wiley mill. Dried tissue samples of the leaves were then used for chlorophyll analysis (Johnson, 1973).

Spectral Response and Vegetation Cover Measurements

Spectral response and vegetation cover measurements were made as described for the corn and N experiment.

Description of Field Study

The experiment was conducted with sweet corn (cv. 'Jubilee') during the spring of 1989 (22 February through 1 June 1989) at the University of Arizona Maricopa Agricultural Center.

Corn was grown under three levels of water: 40, 71, and 90 cm (W1, W2, and W3, respectively); and three levels of nitrogen: 0, 150, and 300 kg/ha (N1, N2 and N3, respectively) in the form of urea-ammonium nitrate solution 32 (44% urea, 32% NH_4NO_3, and 20% water). Each treatment was replicated three times in a randomized complete block. Treatments were divided into one meter plots with five plants per plot. Water treatments began on 11 April 1989, and nitrogen rates were applied on 12 April 1989. All water and N fertilizer treatments were applied through a buried drip system.

At the end of the experimental periods, the plant tops were harvested, dried at 65°C, and their dry matter recorded.

Spectral Response and Vegetation Cover Measurements

Spectral responses were measured weekly and four readings per plot were made. Photographs were taken after each reflectance measurement to calculate percent plant cover.

The procedure used to obtain reflectance measurement, described previously, was exactly followed for this experiment except that soil was the background rather than a black surface.

Statistical Procedure

The data were analyzed statistically by methods outlined in Lite and Hills. Separation of treatment means were performed using the least significant difference (LSD) test. The 5% level of significance was used in all instances. A randomized complete block (RCB) design with split plot analysis was used in all experiments.

RESULTS AND DISCUSSION

The results of the experiments conducted on sweet corn, beans and squash under different treatments will be discussed separately.

Corn and Zinc Experiment

Analysis of Spectral Data

The most common method of displaying the spectral response of biomass is simply a plot of percent reflectance vs. wavelength, or a spectral curve. Spectral curves for the three varieties (V1, V2 and V3) at four levels of Zn concentration (Zn_o, Zn_1, Zn_2 and Zn_3) were constructed at three stages during the growing season (beginning, middle and end of season). Figures 1 through 9 show the spectral response of each one of the three varieties under the four levels of Zn concentration at days (Julian) 259, 272 and 280 (18, 30 and 39 days after planting), respectively. It can be seen that it is difficult to quantify the effect of different levels of Zn concentration on the spectral response of corn plants.

A close examination of the spectral curves for each variety during the growing season shows no uniform pattern in response to the four levels of Zn concentration. The results also showed that the influence of different concentrations is more visible in the NIR region. For all varieties studied, the NIR reflectance increased with increasing green biomass over the growing period (day 259 to 280). If only IR bands were considered during this period (without knowledge of Zn applications), it could be concluded that four varieties were grown in the area. The

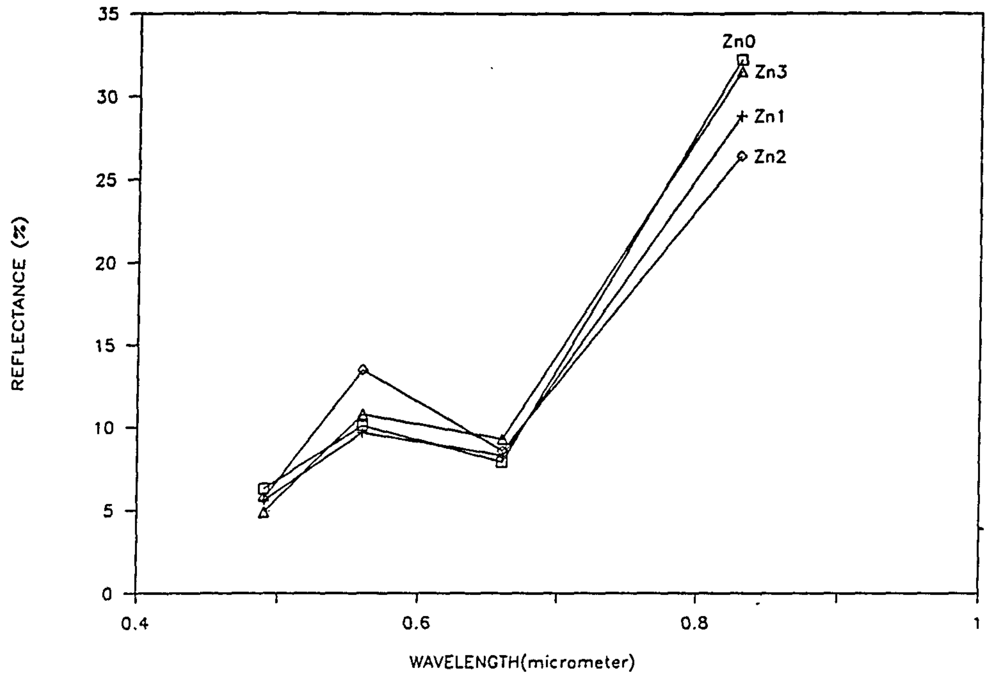

Figure 1. Spectral curve for variety one under four levels of Zn at day 259 (18 days after planting).

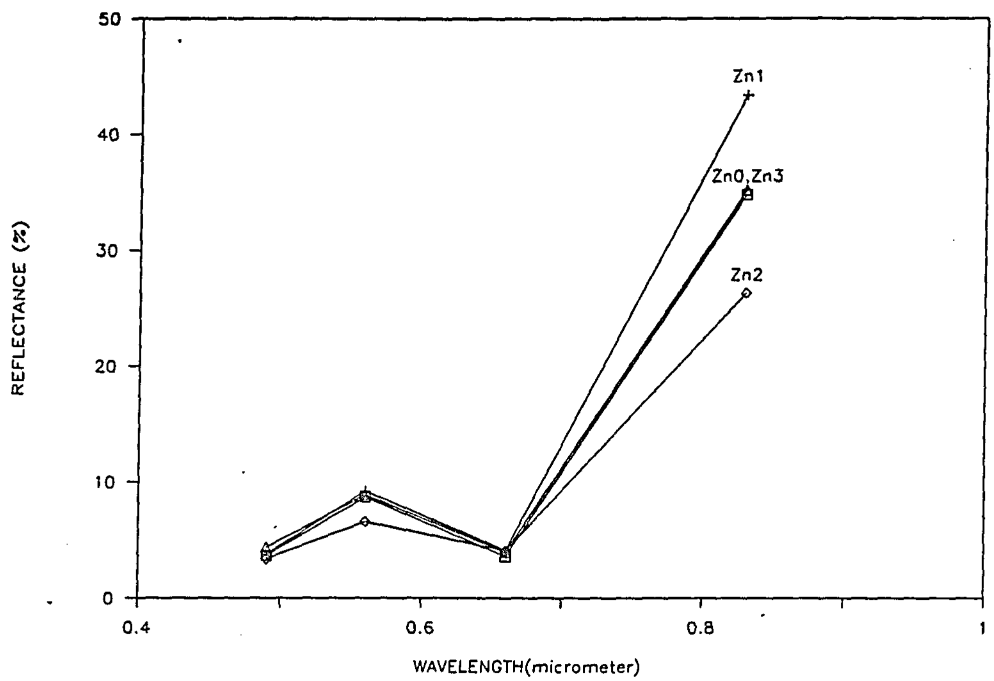

Figure 2. Spectral curve for variety one under four levels of Zn at day 272 (30 days after planting).

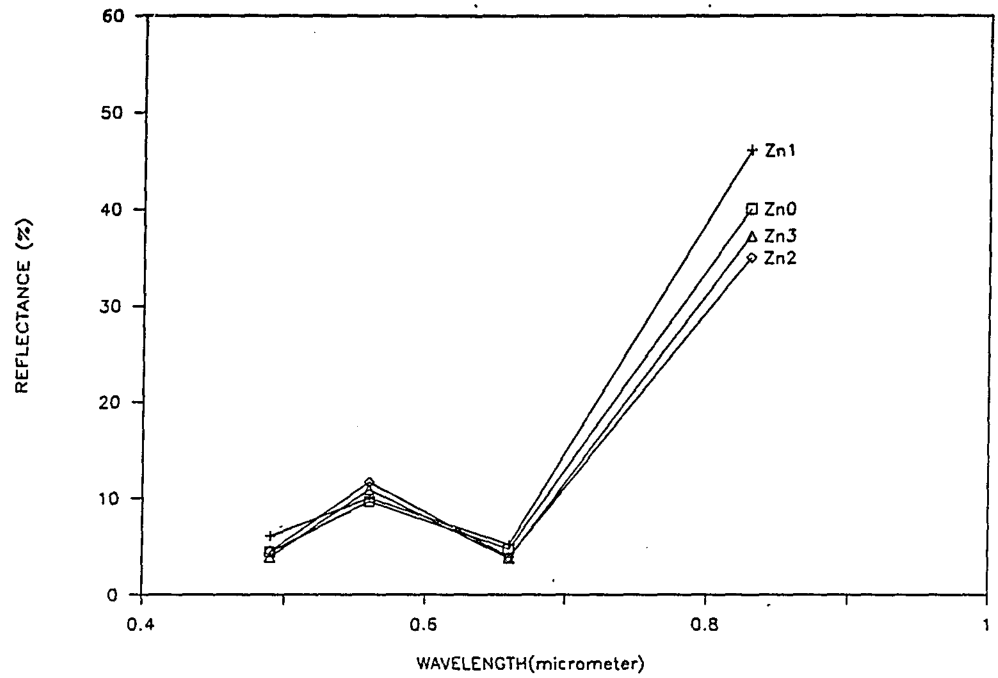

Figure 3. Spectral curve for variety one under four levels of Zn at day 280 (39 days after planting).

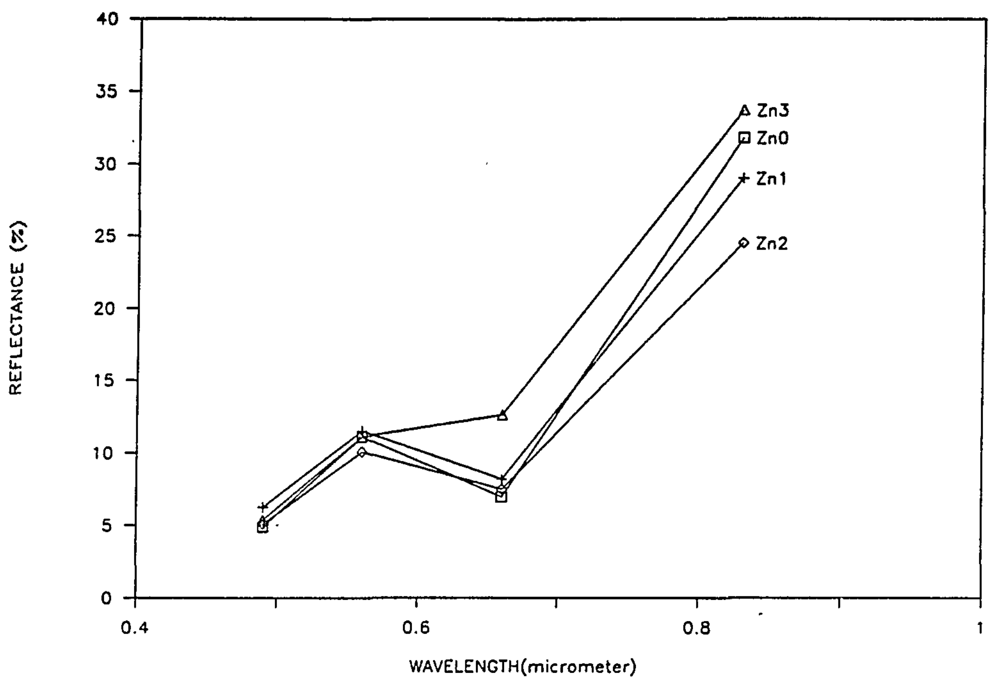

Figure 4. Spectral curve for variety two under four levels of Zn at day 259 (18 days after planting).

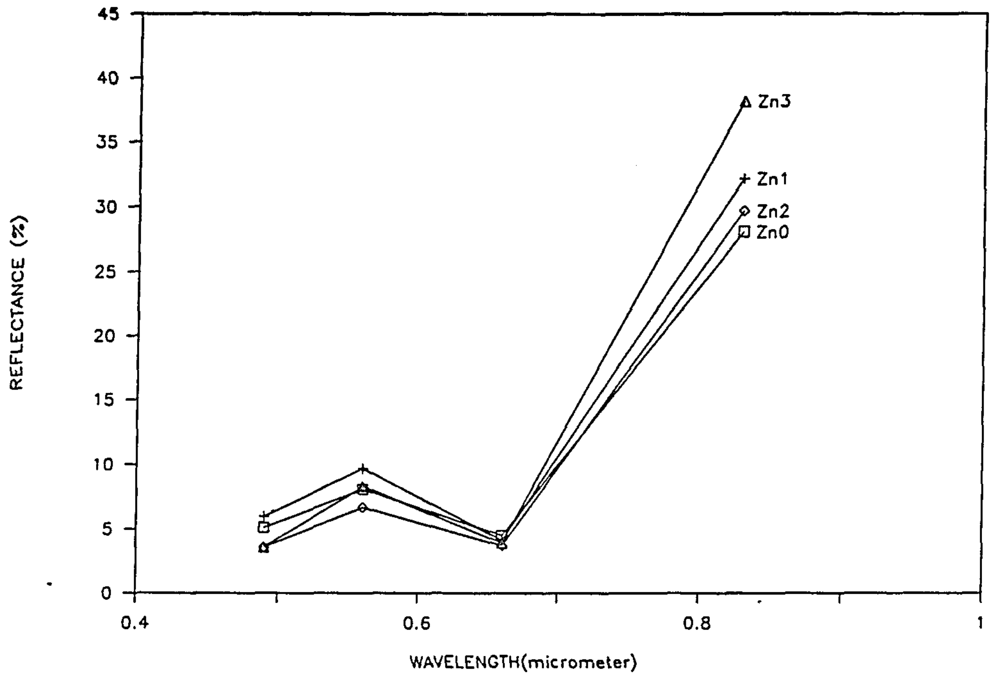

Figure 5. Spectral curve for variety two under four levels of Zn at day 272 (30 days after planting).

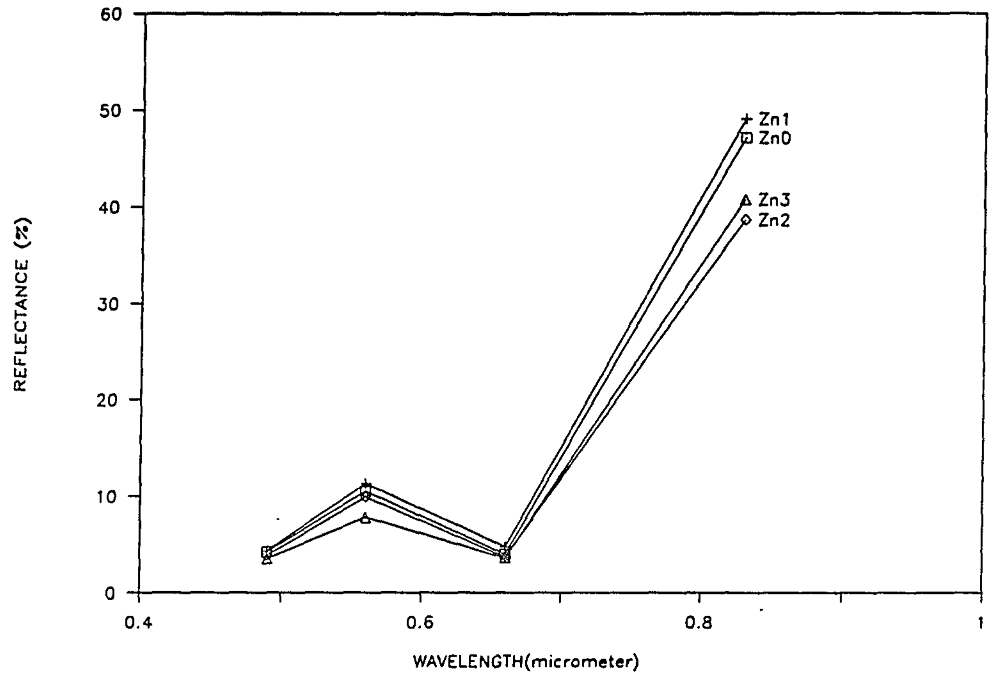

Figure 6. Spectral curve for variety two under four levels of Zn at day 280 (39 days after planting).

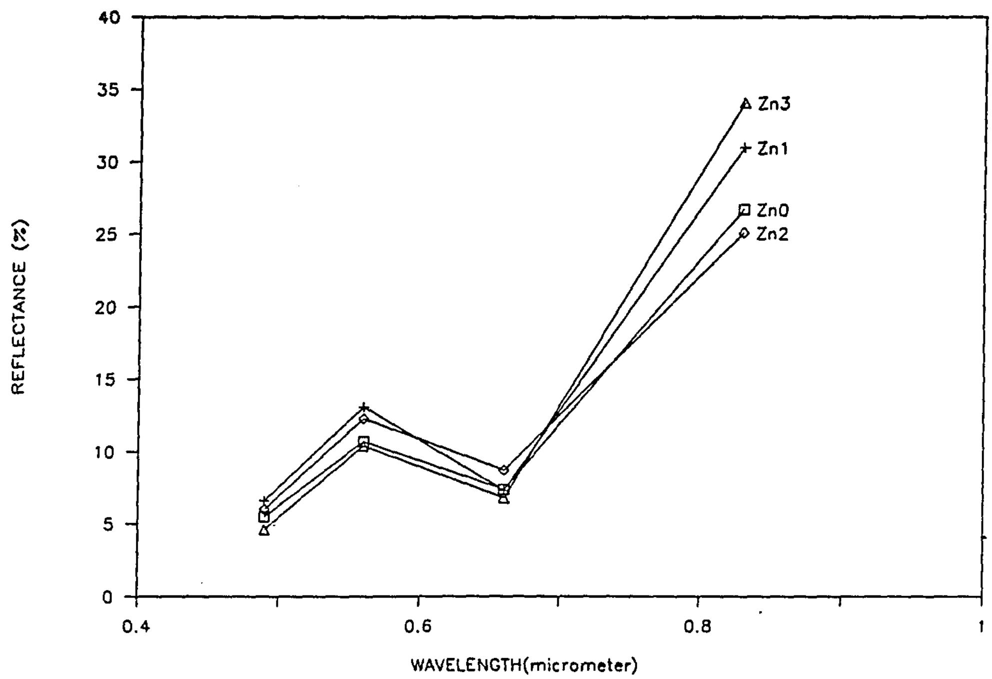

Figure 7. Spectral curve for variety three under four levels of Zn at day 259 (18 days after planting)

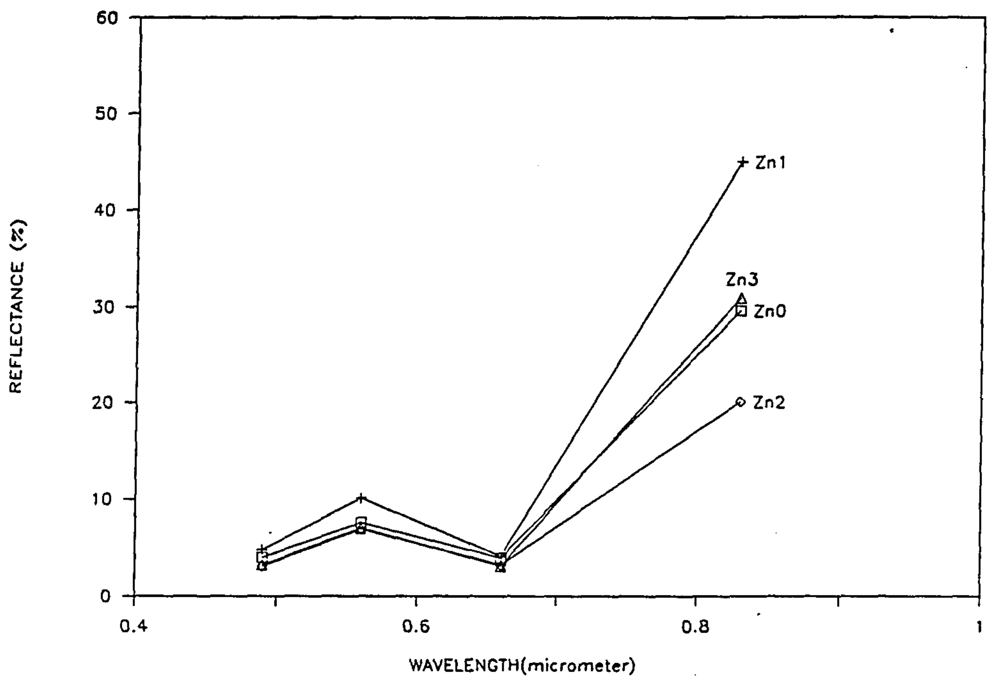

Figure 8. Spectral curve for variety three under four levels of Zn at day 272 (30 days after planting)

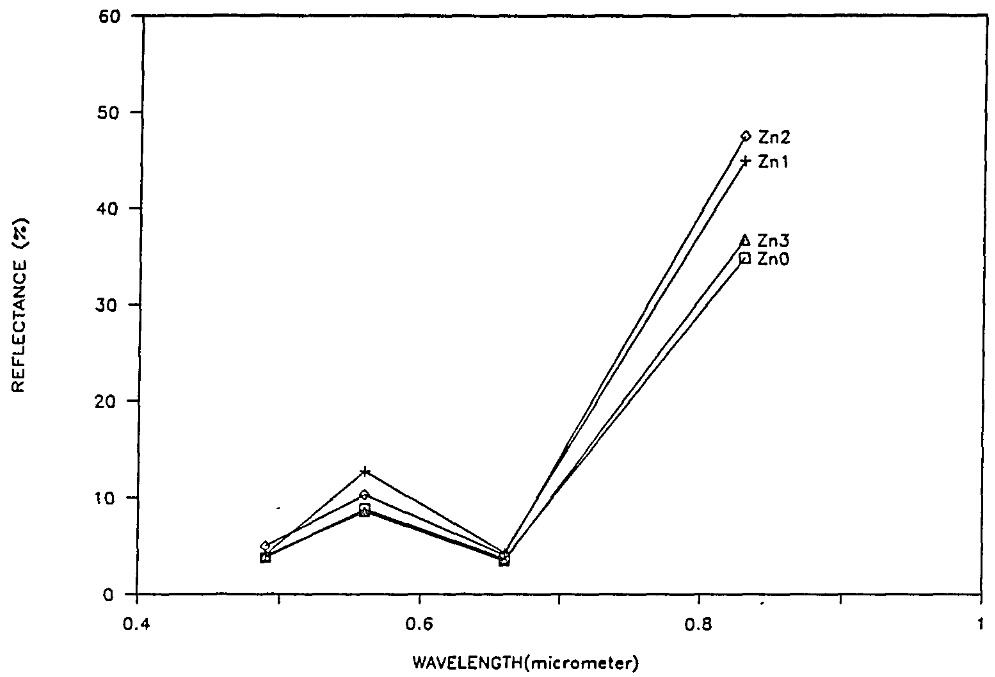

Figure 9. Spectral curve for variety three under four levels of Zn at day 280 (39 days after planting).

spectral response of the three varieties of corn grown under each of the four levels of Zn concentration at day 272 (30 days after planting season) is presented in Figures 10 through 13. The three varieties are distinguishable in the NIR portion of the spectrum at all levels of Zn. Similarly, if only NIR bands and Zn applications were to be considered for this study (without knowledge of different varieties grown), it could be concluded that three Zn applications were studied.

The normalized difference vegetation index (NDVI) and its transformation (TNDVI) have been extensively used for vegetation assessment in areas having green vegetation cover in the range from 20 to 80% (Jackson et al., 1983). For this study, the TNDVI was calculated as $\sqrt{NDVI + 0.5}$ and the NDVI was calculated as (NIR - R)/(NIR + R) using reflectance factors. Figures 14 through 17 represent the TNDVI calculations for the three varieties of corn under each level of Zn concentration. The TND values were essentially the same for all three varieties under each of the four levels of Zn. This may be attributed to the fact that the three varieties of corn responded similarly to all four levels of Zn concentration, which suggests similar spectral response in the red and NIR portion of the spectrum, from which the TNDVI was calculated. A t-test applied to that effect showed no significant difference among the means of the three varieties with respect to Zn concentration at the 0.05 level. However, a small gap among the spectral curves is visible and progressed along with the season.

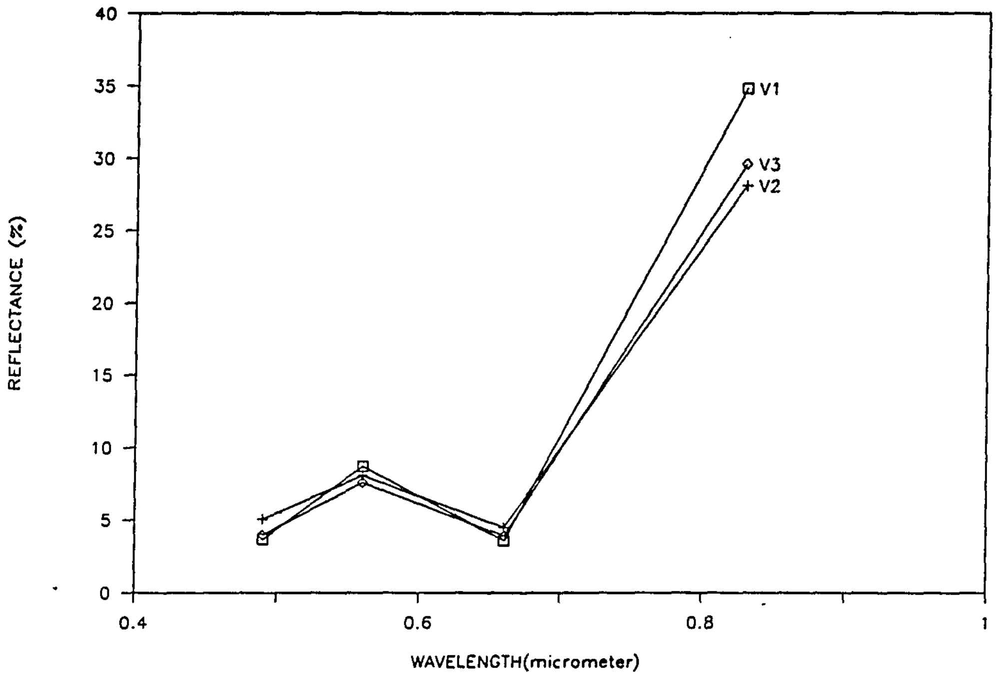

Figure 10. Spectral curve for the three varieties of corn under Zn0 at day 272 (30 days after planting).

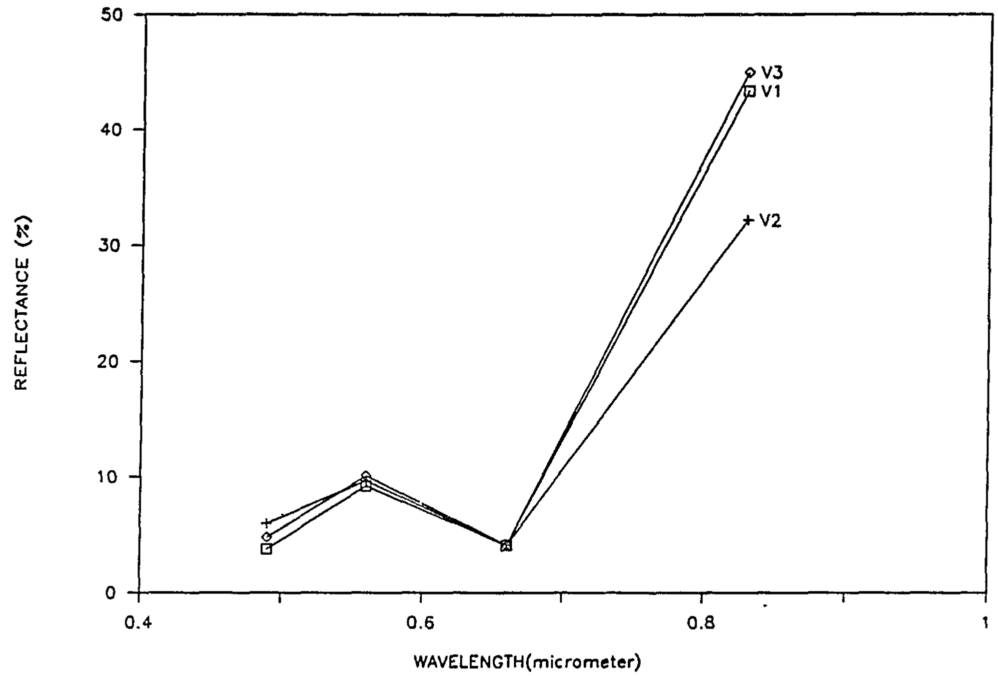

Figure 11. Spectral curve for the three varieties of corn under Zn1 at day 272 (30 days after planting).

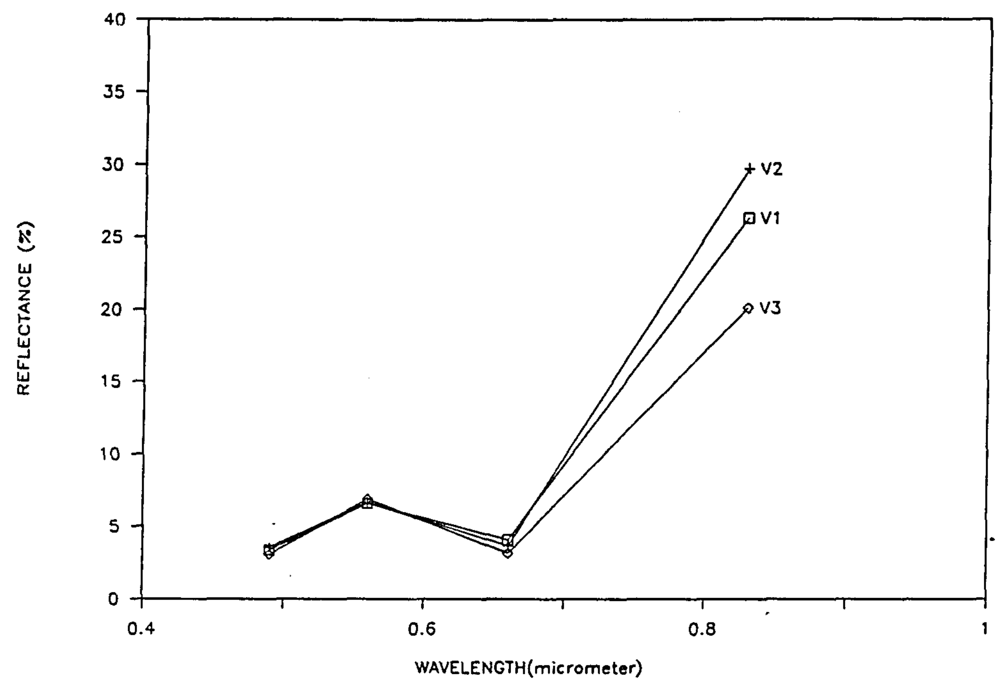

Figure 12. Spectral curve for the three varieties of corn under Zn2 at day 272 (30 days after planting).

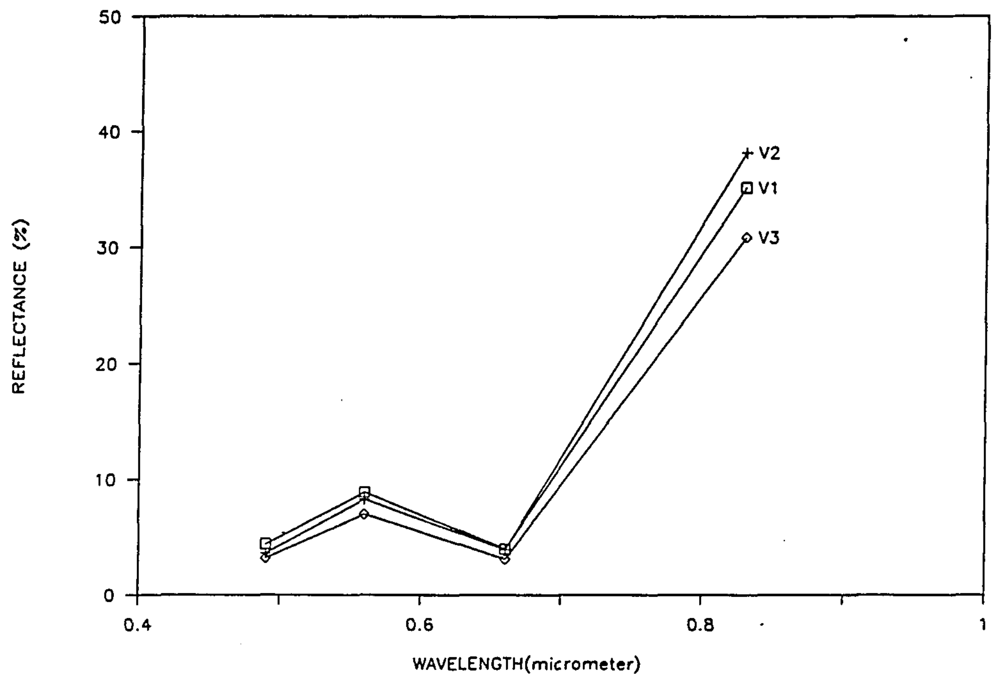

Figure 13. Spectral curve for the three varieties of corn under Zn3 at day 272 (30 days after planting).

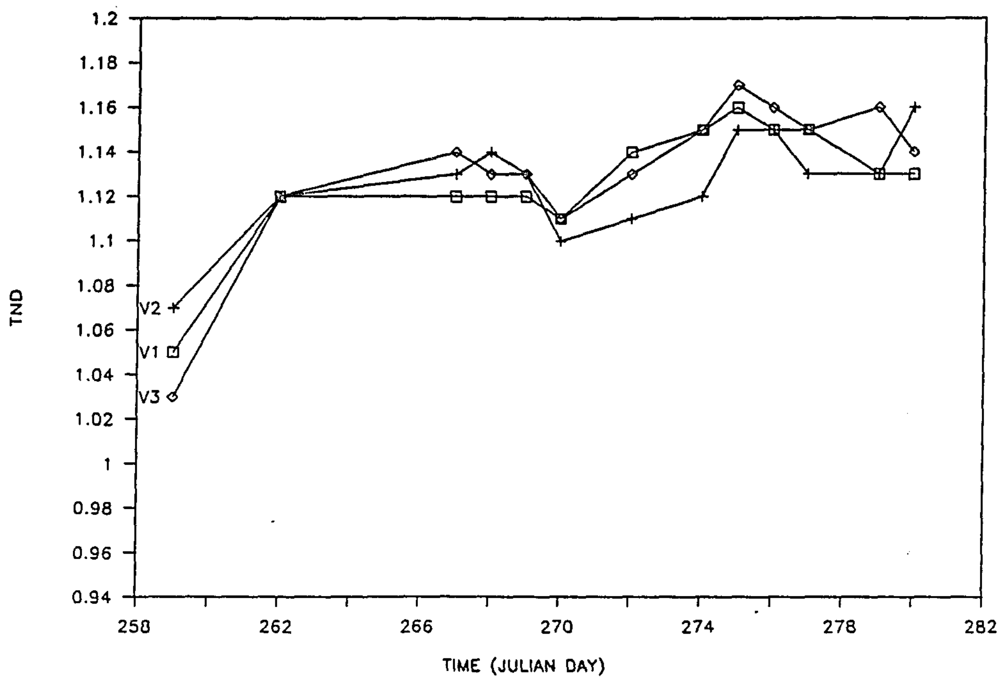

Figure 14. The transformed normalized difference as a function of time for the three varieties of corn under Zn0

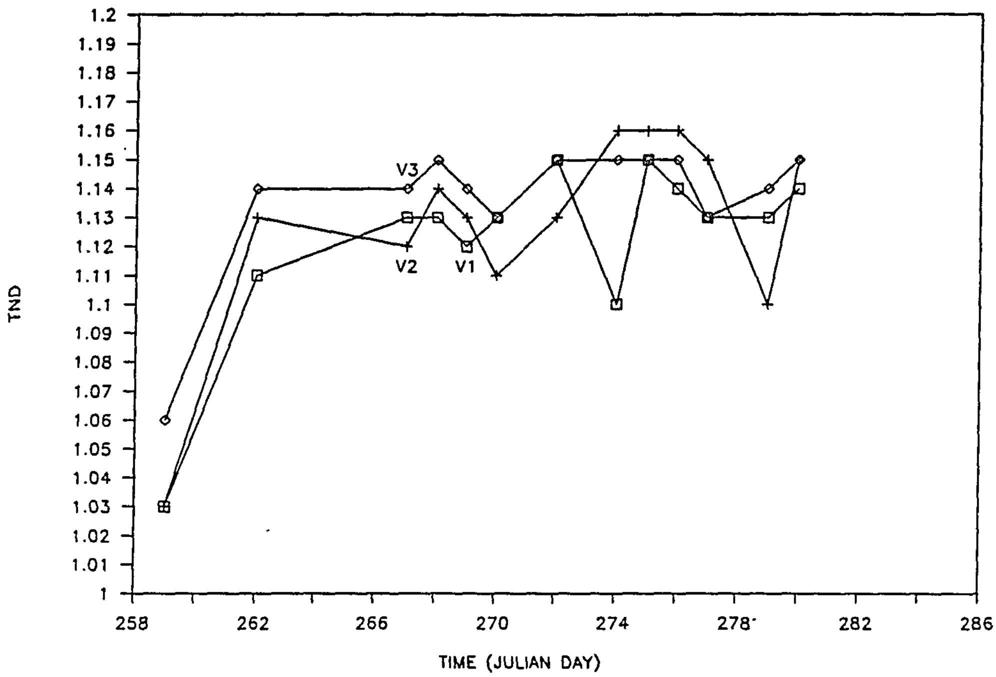

Figure 15. The transformed normalized difference as a function of time for the three varieties of corn under Zn1

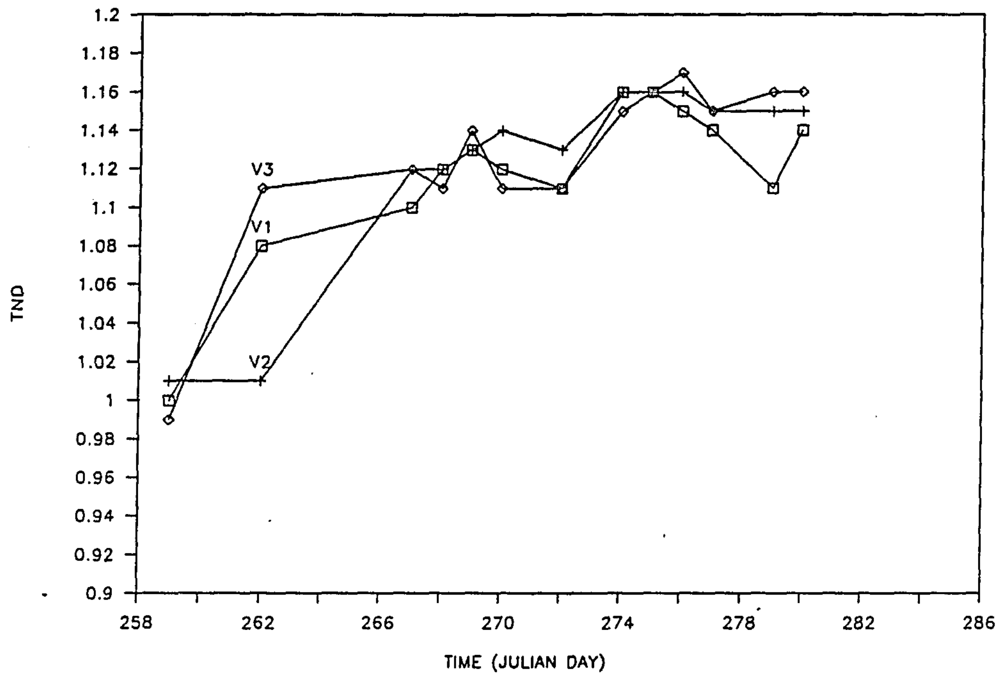

Figure 16. The transformed normalized difference as a function of time for the three varieties of corn under Zn2.

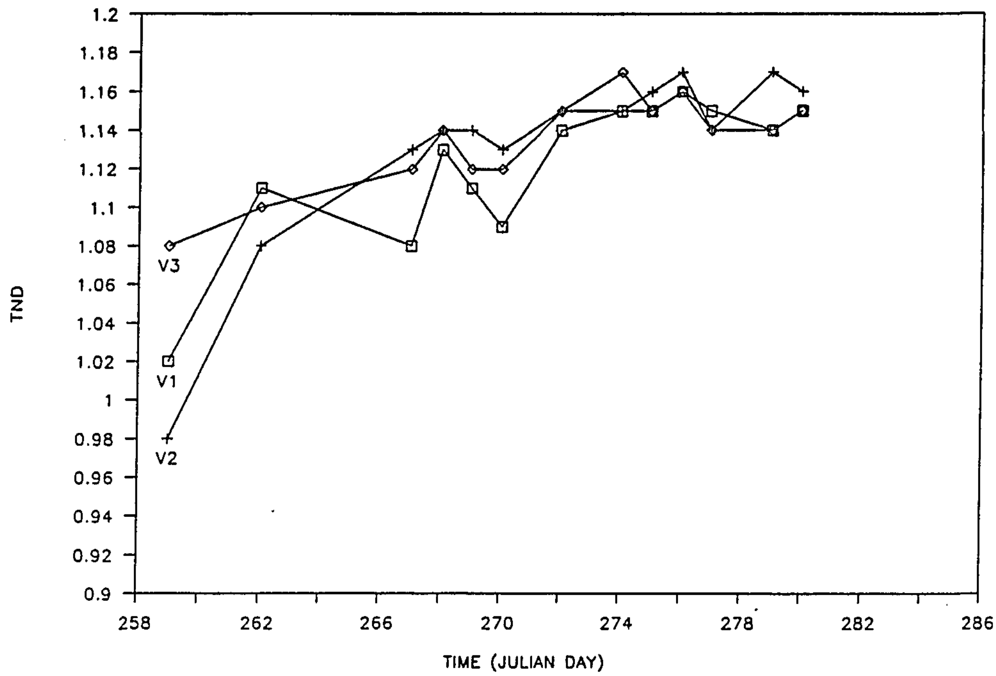

Figure 17. The transformed normalized difference as a function of time for the three varieties of corn under Zn3

Many studies have shown that there is a better correlation between an integrated NDVI over a certain period of time and biomass integrated over the same period than between single data values of both parameters (Goward et al., 1985). Figure 18 shows the positive relationship among the integrated TNDVI data for each of the three varieties and the end-of-season above-ground dry matter production at Zn_1. The same positive relationship was true for the other treatments. The integrated TNDVI data of variety one (V1) are plotted against the end-of-season above-ground dry matter at the four levels of zinc concentration (Fig. 19). The plot shows the expected positive relationship such that the higher the dry matter production, the higher the integrated TNDVI value. The integrated TNDVI value for variety one and zinc one (Zn_1V1) is rather high for its dry matter production compared with the other values. This may be due, at least in part, to the set up of the experiment. As mentioned earlier, the pots were moved from the table to the black board for each spectral measurement, which resulted in a different orientation of the pots each time the measurements were obtained. The same relationship was observed for the other treatments.

The Statistical Analysis

The analysis of variance is shown in Table 2. The data show that Zn applications significantly affected dry matter production at the 0.05 level. Significant differences among varieties with respect to dry matter production were not detected. The data also indicated that varieties responded similarly to Zn applications.

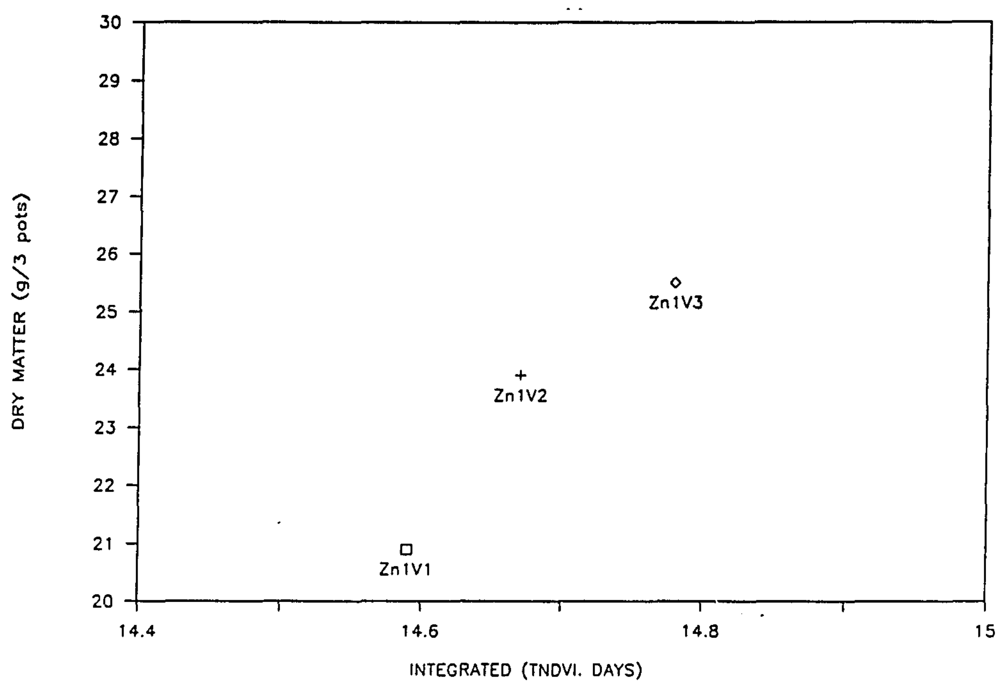

Figure 18. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for the three varieties of corn under Zn1.

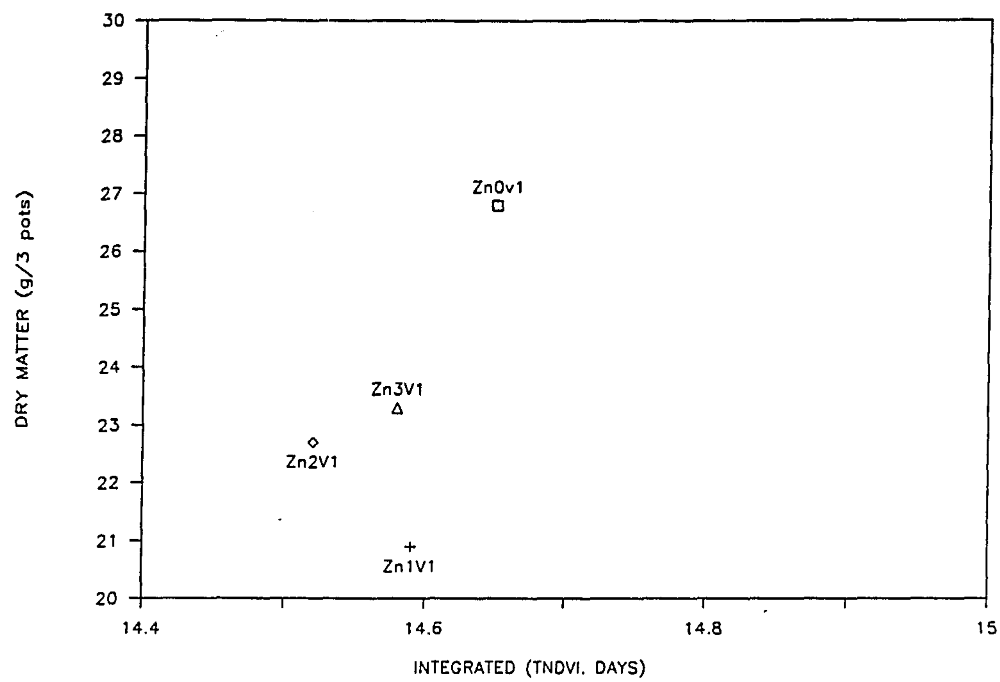

Figure 19. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for variety one of corn under Zn.

Table 2. Analysis of variance with dry matter production as a dependent variable.

Source	DS	SS	MS	P Value
Block	2	6.4039	3.2019	0.098
Variety	2	0.1489	0.0744	0.940
Block x Zinc	6	2.1894	0.3649	0.924
Zinc	3	12.516	4.1721	0.04**
Zinc x Variety	6	7.3044	1.2174	0.445

** Significant difference at 0.05 level.

Bean and Zinc Experiment

As mentioned earlier, the experiment was terminated about four weeks after planting due to Zn contamination of soil. However, the spectral data were used to assess the suitability of remote sensing techniques in distinguishing among varieties grown under different levels of Zn concentration. The spectral response of four thematic mapper bands of the three varieties of bean under each level of Zn concentration on day 324 (26 days after planting) is shown in Figures 20 through 23. The three varieties responded virtually the same under Zn_1, (Fig. 21); whereas the three varieties separated the most in the NIR portion of the spectrum under Zn_2 (Fig. 22). However, the spectral response pattern under all Zn levels was not consistent over the growing period. The complete spectral reflectance values over the growing period at four thematic paper bands are given in Appendix A. Figures

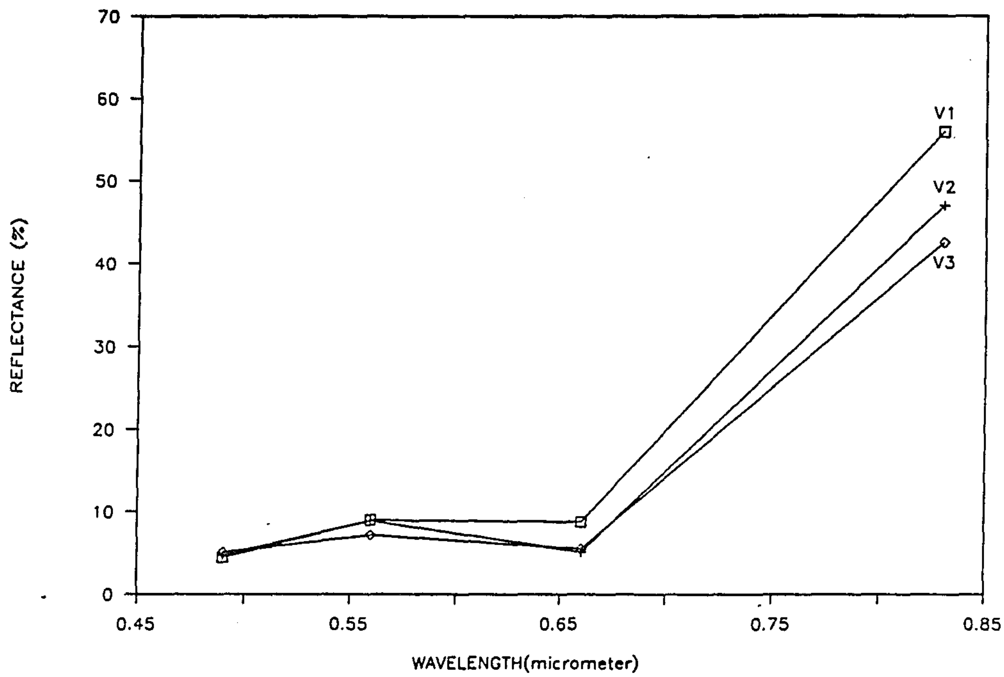

Figure 20. Spectral curve for the three varieties of bean under Zn0 on day 324 (26 days after planting).

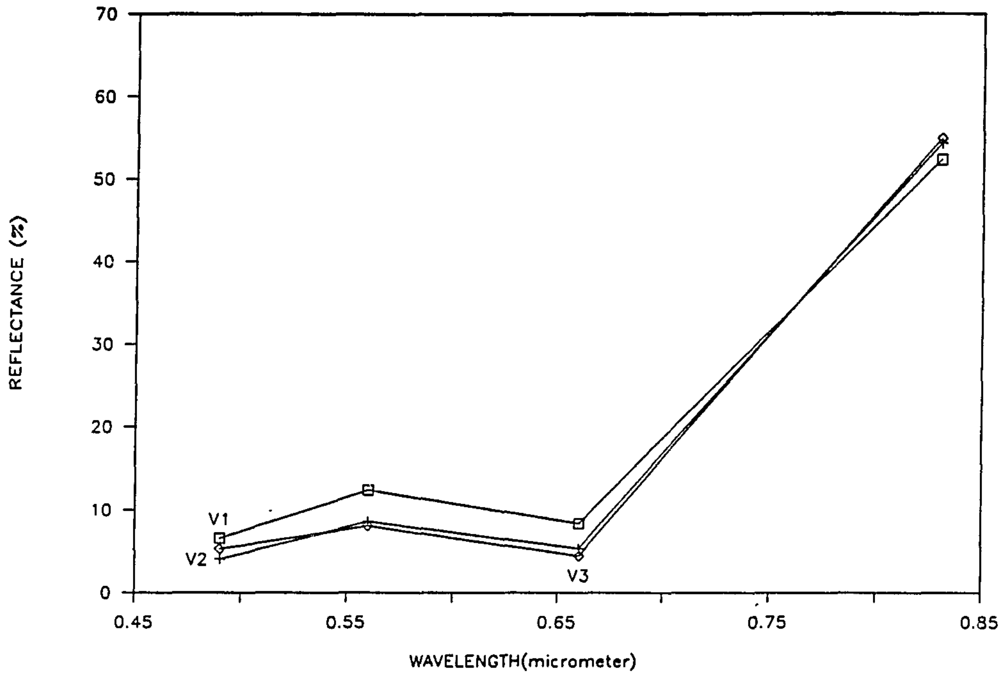

Figure 21. Spectral curve for the three varieties of bean under Zn1 on day 324 (26 days after planting).

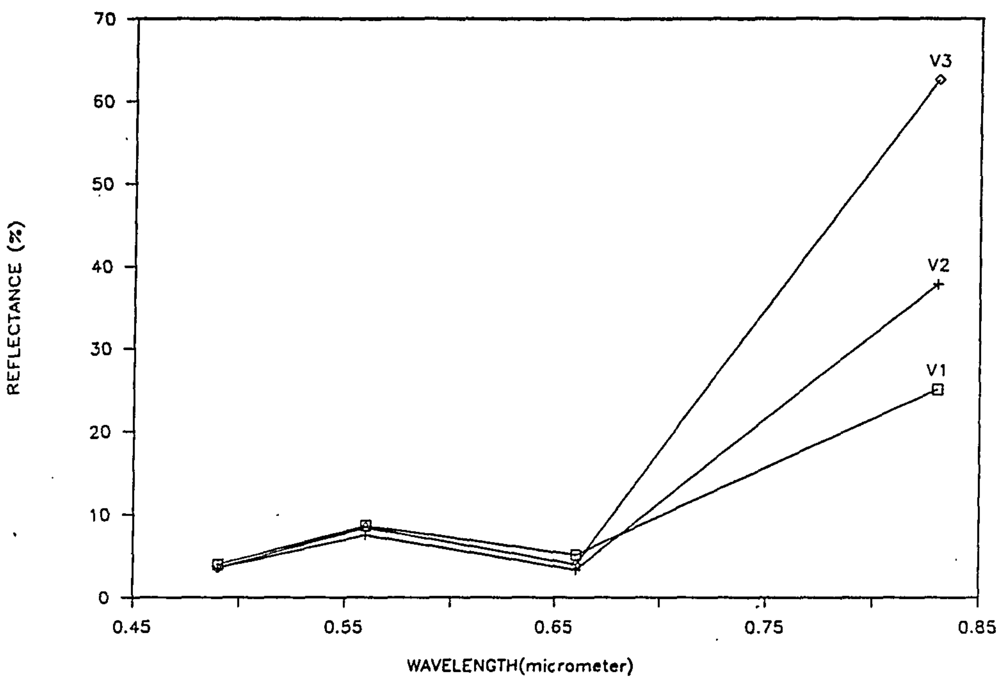

Figure 22. Spectral curve for the three varieties of bean under Zn2 on day 324 (26 days after planting).

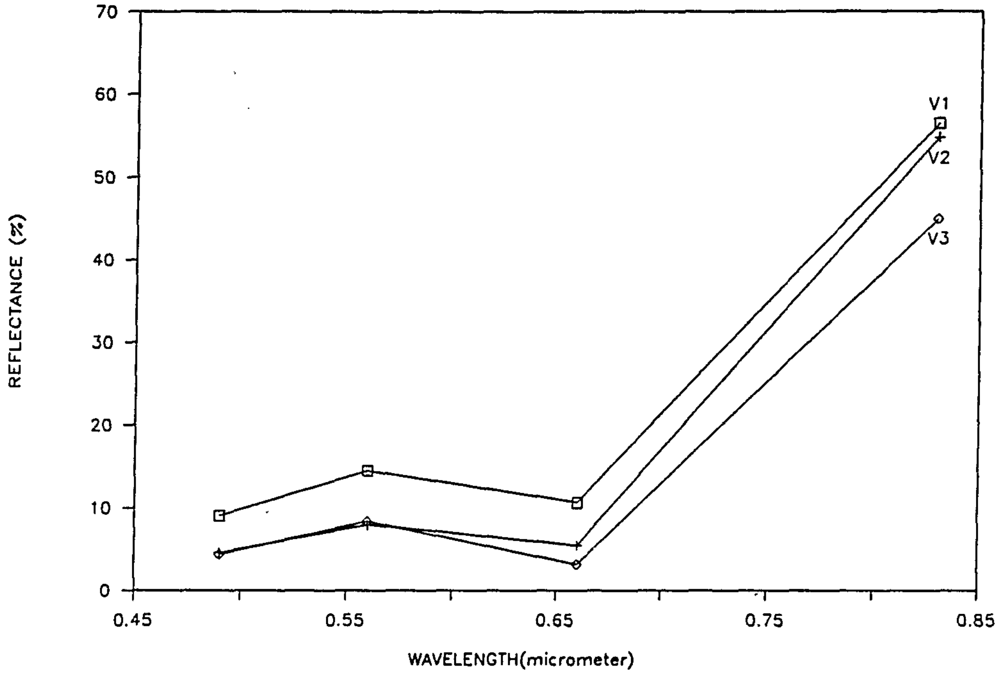

Figure 23. Spectral curve for the three varieties of bean under Zn3 on day 324 (26 days after planting).

24 through 26 show the spectral response of each variety under the four levels of Zn at day 324. Each variety responded differently to Zn concentrations. In addition, the spectral response is not uniform over the growing period (see data in Appendix A. The results indicated that the spectral data are sensitive to both varieties and Zn concentration. However, the technique will not differentiate between the two.

Squash and Zinc Experiment

As mentioned earlier, the experiment was terminated about three weeks after planting. The spectral response of the three varieties of squash under each Zn concentration at day 324 (26 days after planting) is shown in Figures 27 through 30. The three varieties responded differently to each Zn level. Spectral data of the three varieties separated the most in the NIR region of the spectrum under Zn_1 (Fig. 27), whereas, the same three varieties responded virtually the same under Zn_2 (Fig. 29). However, an interpretation of the spectral data without knowledge of different varieties grown could lead to the conclusion that three Zn applications were studied. On the other hand, Figures 31 through 33 show the spectral response of each one of the three varieties under the four levels of Zn concentration at day 324. Each variety responded differently to the four levels of Zn. The influence of different concentrations is more pronounced in the NIR region of the spectrum. Analysis of the spectral curves without knowledge of Zn applications could lead to the conclusion that more than one variety is being grown in the area.

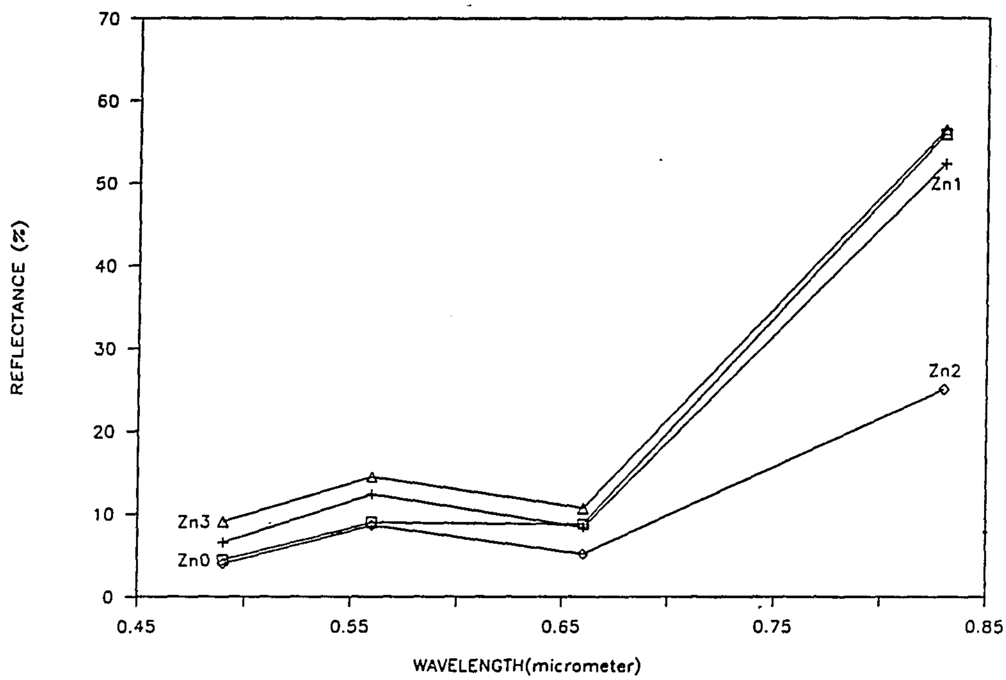

Figure 24. Spectral curve for variety one under four levels of Zn at day 324 (26 days after planting).

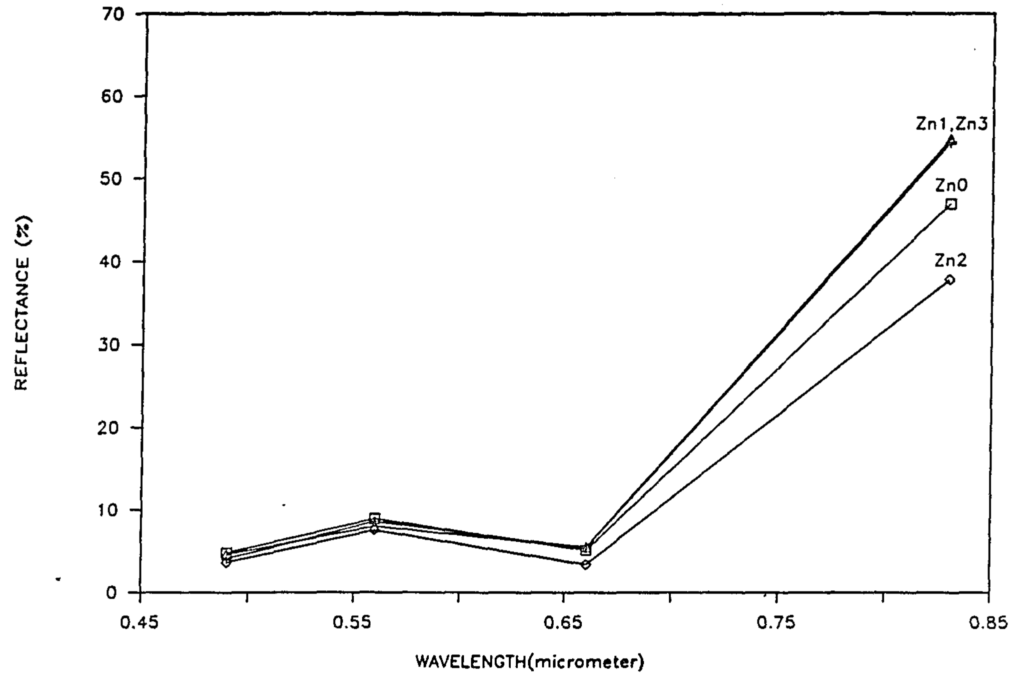

Figure 25. Spectral curve for variety two under four levels of Zn at day 324 (26 days after planting).

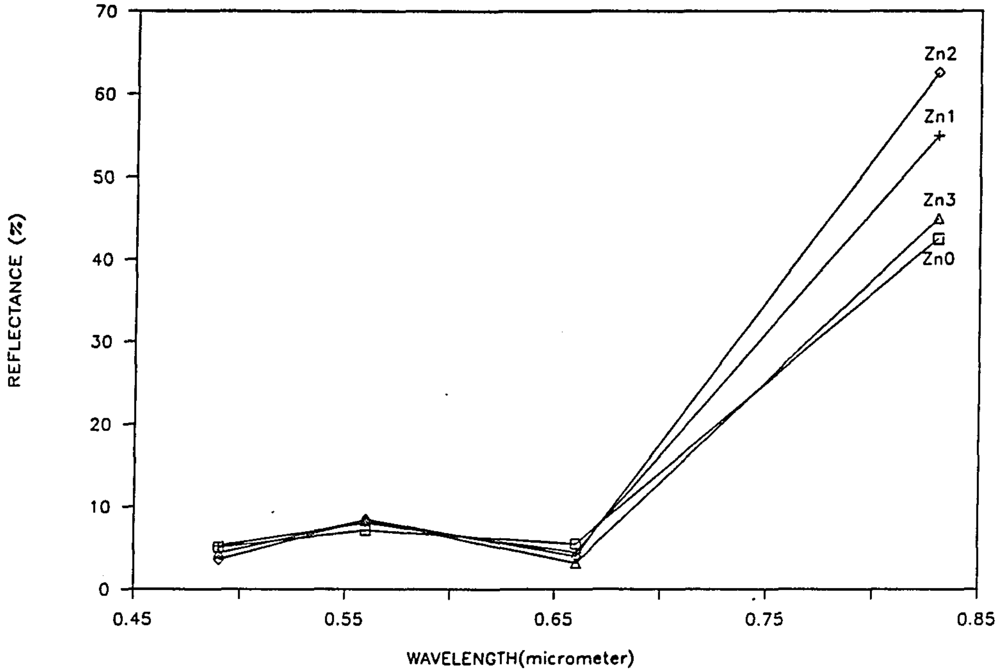

Figure 26. Spectral curve for variety three under four levels of Zn at day 324 (26 days after planting).

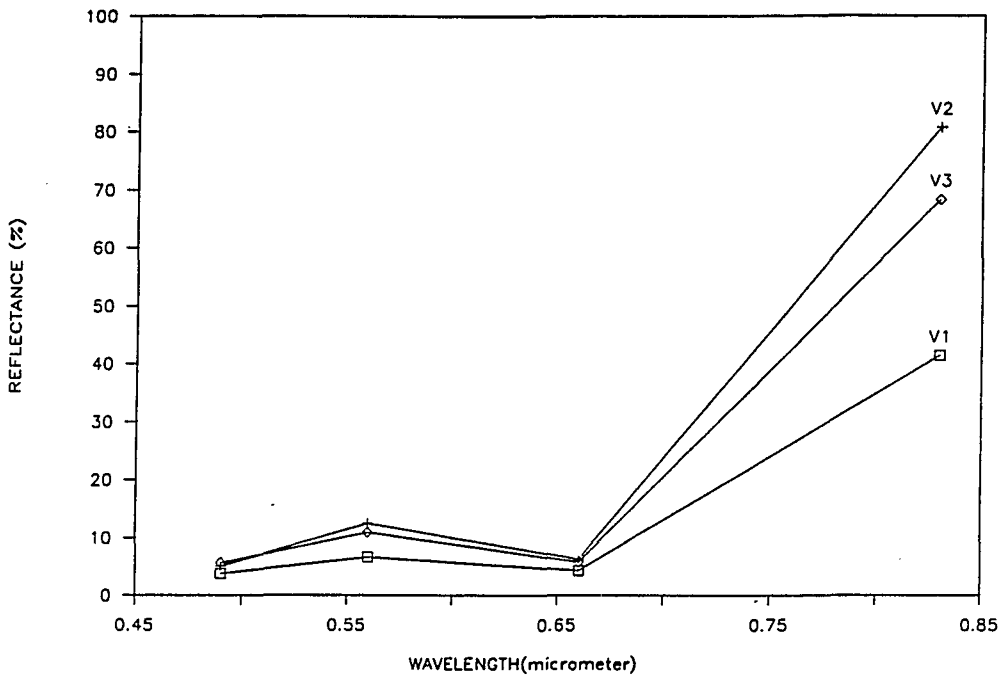

Figure 27. Spectral curve for the three varieties of squash under Zn0 at day 324 (26 days after planting).

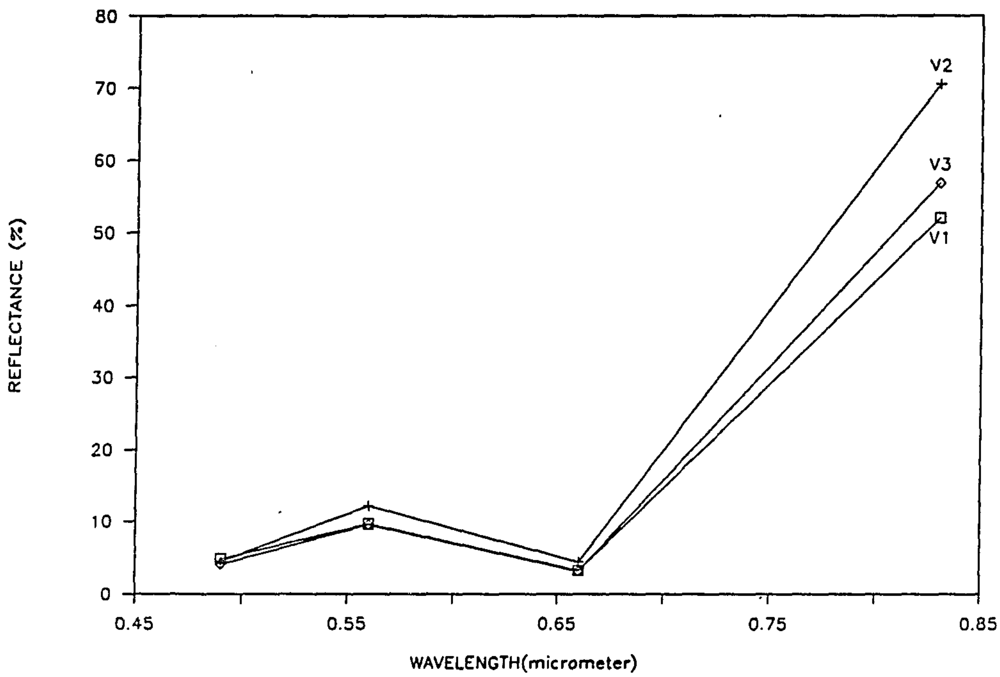

Figure 28. Spectral curve for the three varieties of squash under Zn1 at day 324 (26 days after planting).

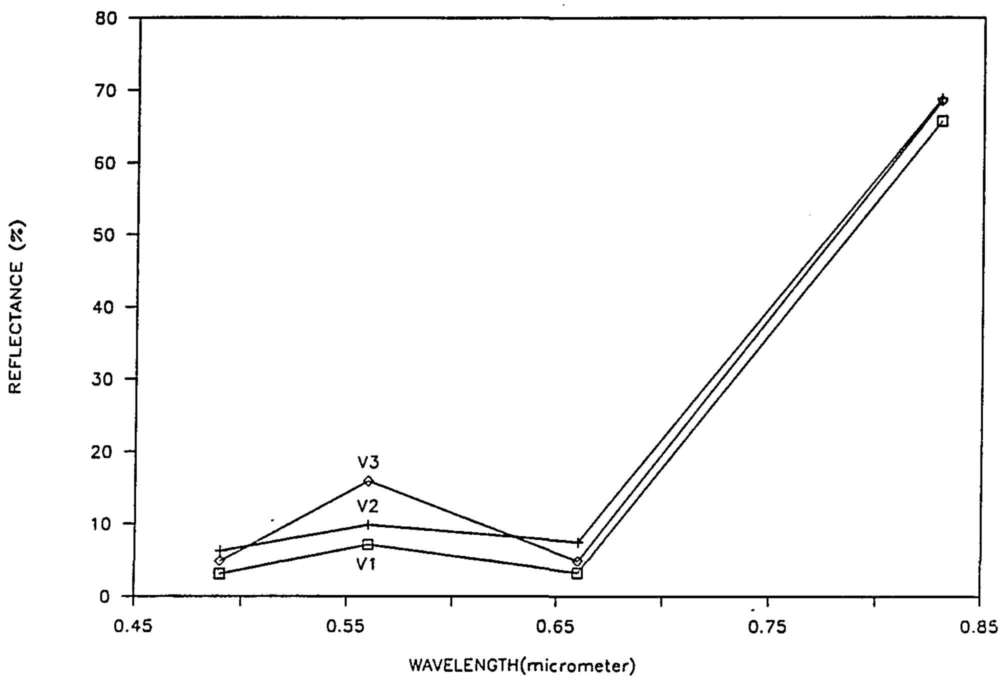

Figure 29. Spectral curve for the three varieties of squash under Zn2 at day 324 (26 days after planting).

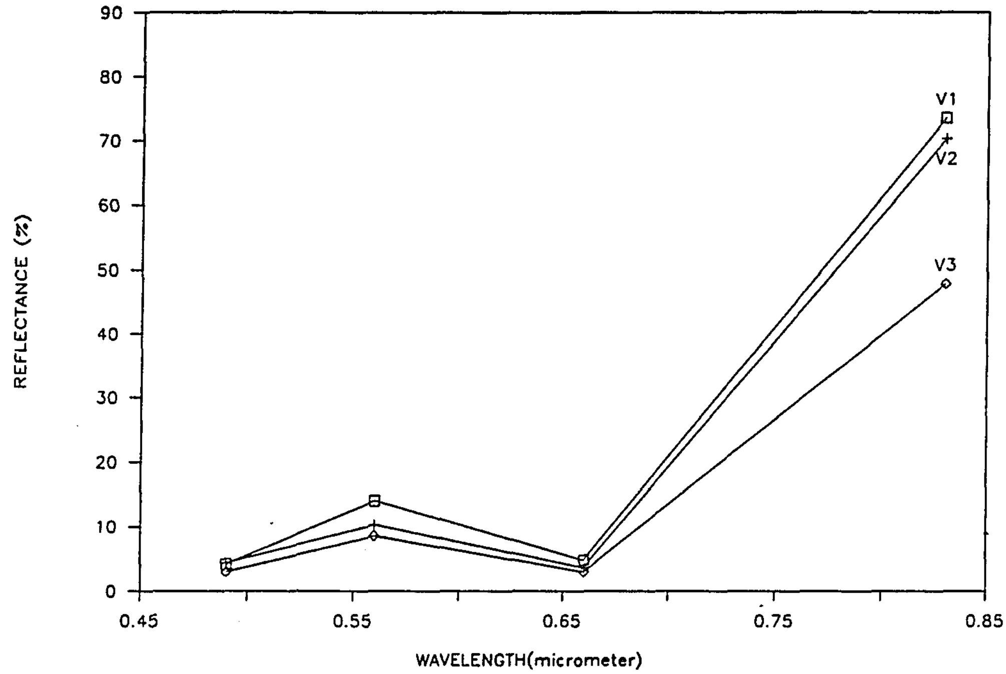

Figure 30. Spectral curve for the three varieties of squash under Zn3 at day 324 (26 days after planting).

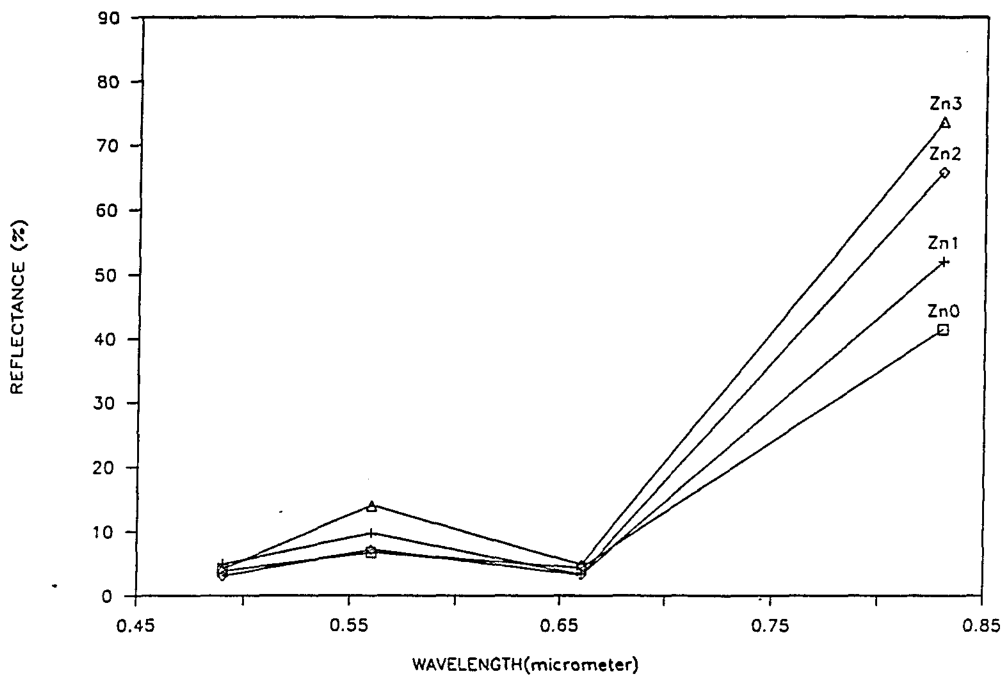

Figure 31. Spectral curve for variety one under four levels of Zn at day 324 (26 days after planting).

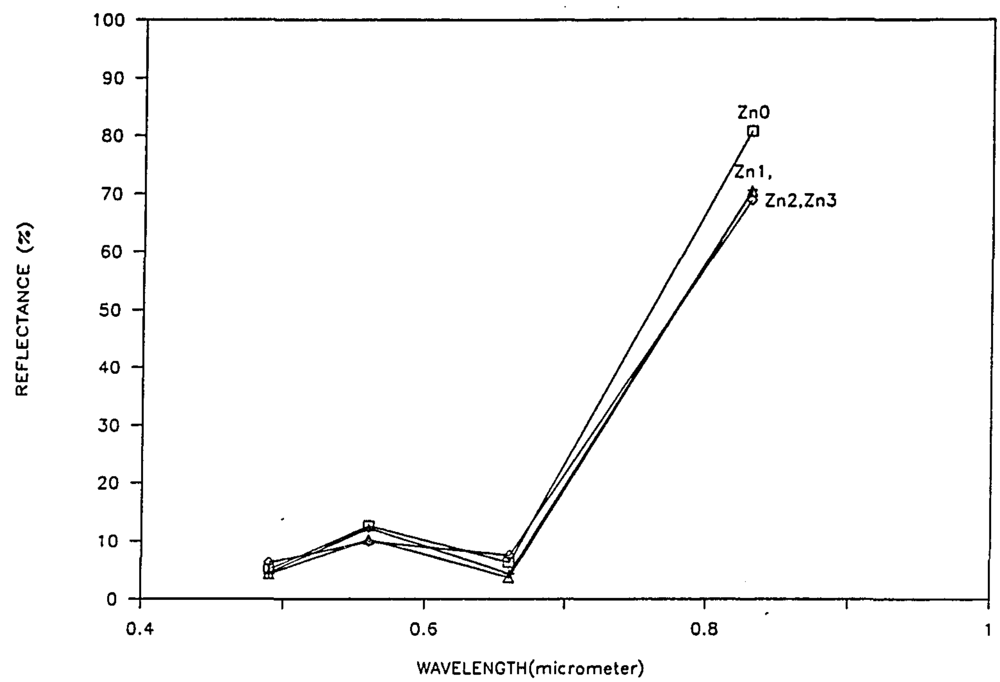

Figure 32. Spectral curve for variety two under four levels of Zn at day 324 (26 days after planting).

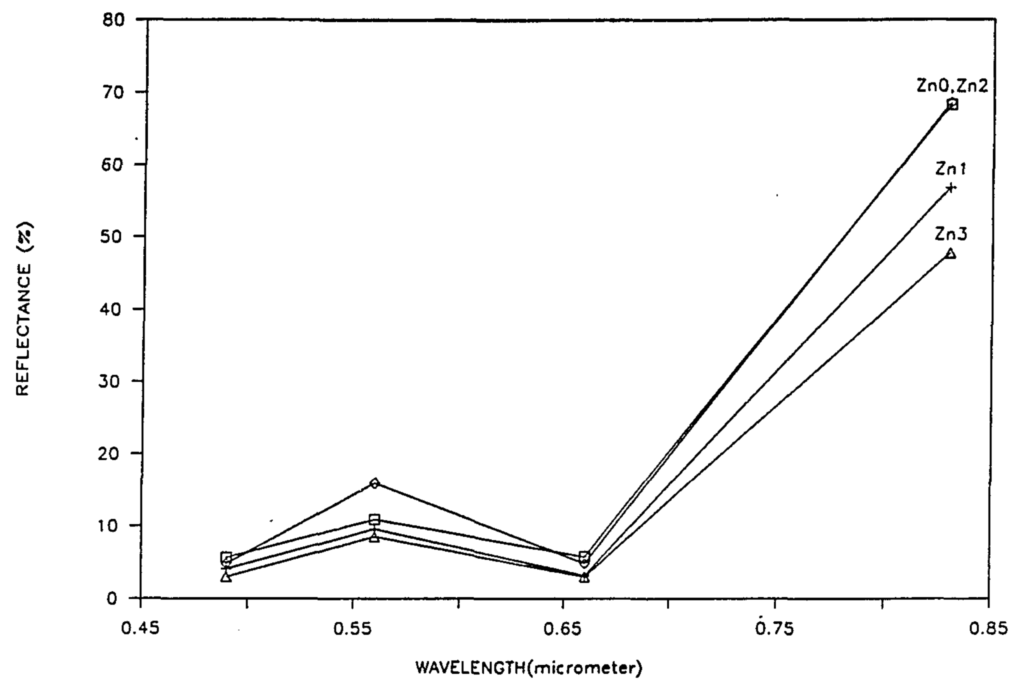

Figure 33. Spectral curve for variety three under four levels of Zn at day 324 (26 days after planting).

Corn and Nitrogen Experiment

Analysis of Spectral Data

Figure 34 depicts the spectral response of variety two under three N levels at day 34 (69 days after planting). The reflectance is relatively low throughout the visible (0.45-0.69 μm) wavelengths, increasing sharply in the NIR (0.76-0.90) band. The influence of different concentrations is more visible in the NIR region of the spectrum. A close examination of the data (Appendix A) during the growing period shows no uniform expected pattern in response to the three levels of N concentration. Plants are expected to establish a well-developed vegetative cover (increasing green-leaf biomass) with N applications, which results in higher NIR percent reflectance. The NIR signal is closely associated with leaf tissue such that the higher the green leaf biomass the higher the NIR reflectance factor. The data in Figure 34 showed that the highest N treatment (N2V2) exhibited the lowest NIR percent reflectance. This unexpected response pattern may be explained in part by the lack of favorable environmental factors for normal growth (i.e. temperature inside the greenhouse was lower than optimum) and/or the periodic movement of pots during the period of spectral measurements. Similar relationships were true for the other two varieties. However, if only spectral curves were to be considered during this period without knowledge of N applications, it could be concluded that three varieties of corn were grown in the area. The spectral response of the three varieties of corn grown under N_1 at day 34 (69 days after planting) is presented in Figure 35. The three varieties are distinguishable in the NIR portion of the

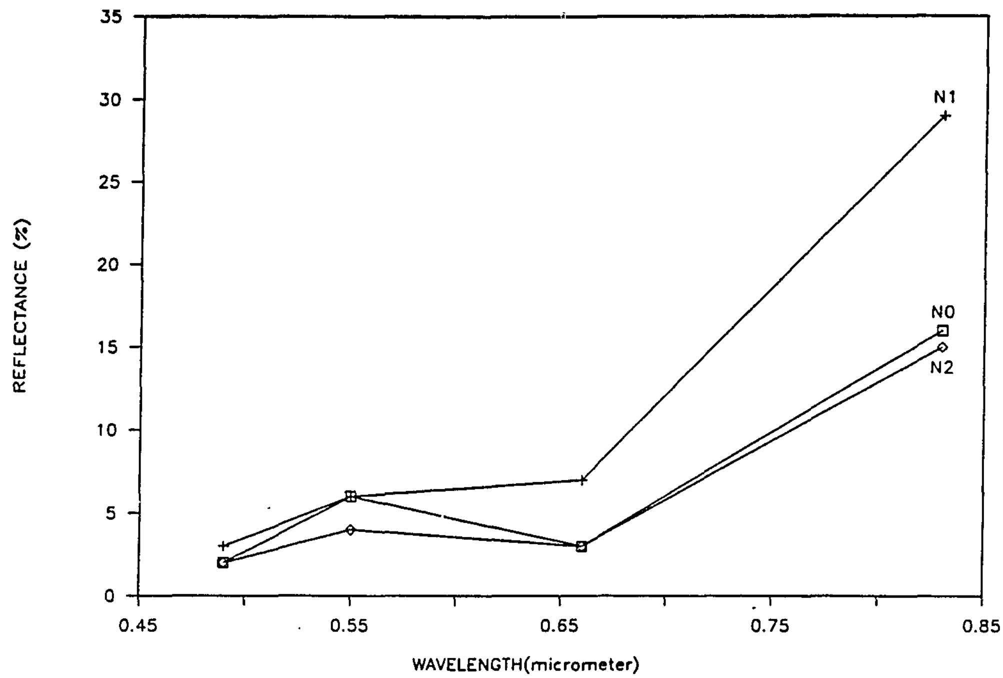

Figure 34. Spectral curve for variety two under three levels of N at day 34 (69 days after planting).

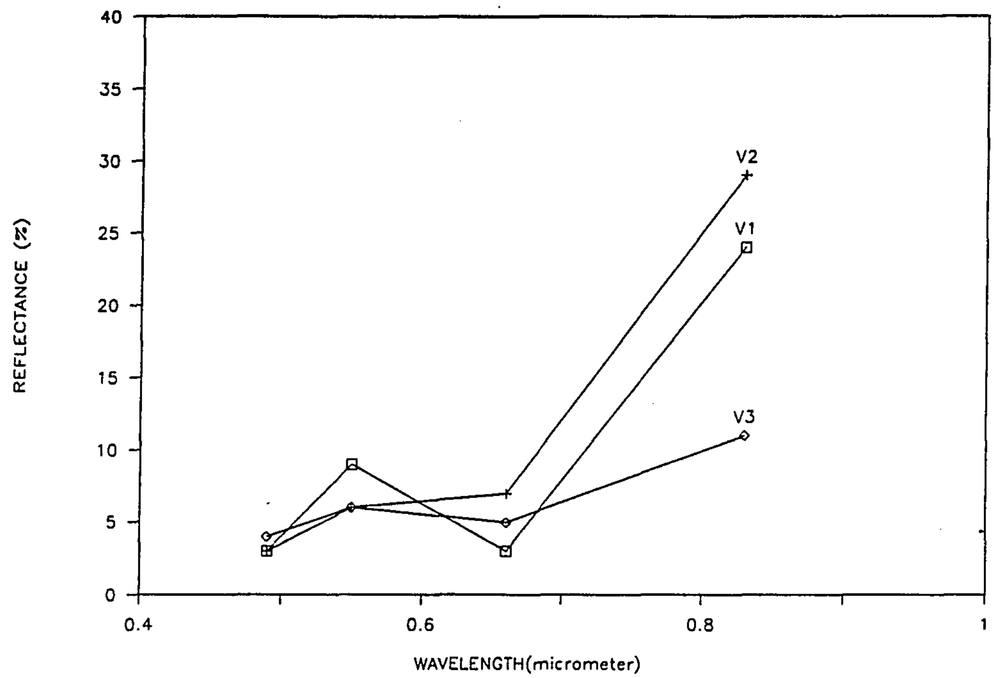

Figure 35. Spectral curve for the three varieties of corn under N1 at day 34 (69 days after planting).

spectrum. The same relationship held at the other two levels of N. Similarly, considering spectral curves only without knowledge of different varieties grown, it could be concluded that three N applications were studied. However, the results indicated that the spectral data are sensitive to both varieties and N concentrations, but they will not differentiate between the two.

Figures 36 through 38 present the transformed normalized difference vegetation index (TNDVI) calculations for the three varieties of corn under each level of N. The TNDVI values were essentially the same for all three varieties under each of the three levels of N. The low TNDVI value for N1V3 (Fig. 37) at day 42 (77 days after planting) is suspected to be due in part to the setup of the experiment, and/or to interference of an object other than plant canopy within the viewing area of the radiometer (the radiometer off-mounted when the measurements were taken). As mentioned in preceding sections, with respect to the setup, the pots were moved from the table to the black board for each spectral measurement, which resulted in a different orientation of the pots each time the measurements were obtained.

Remotely sensed data from vegetation often require a knowledge of the degree of ground cover for their interpretation. For example, assessment of stress conditions in vegetation can be confounded with ground cover variations. The percent biomass cover as a function of time is presented in Figures 39 through 41. A close examination of these figures show a gradual increase in the percent plant cover for varieties one and three in response to increased N application. Variety two developed more vegetative cover (higher biomass cover percent) under N1 (medium

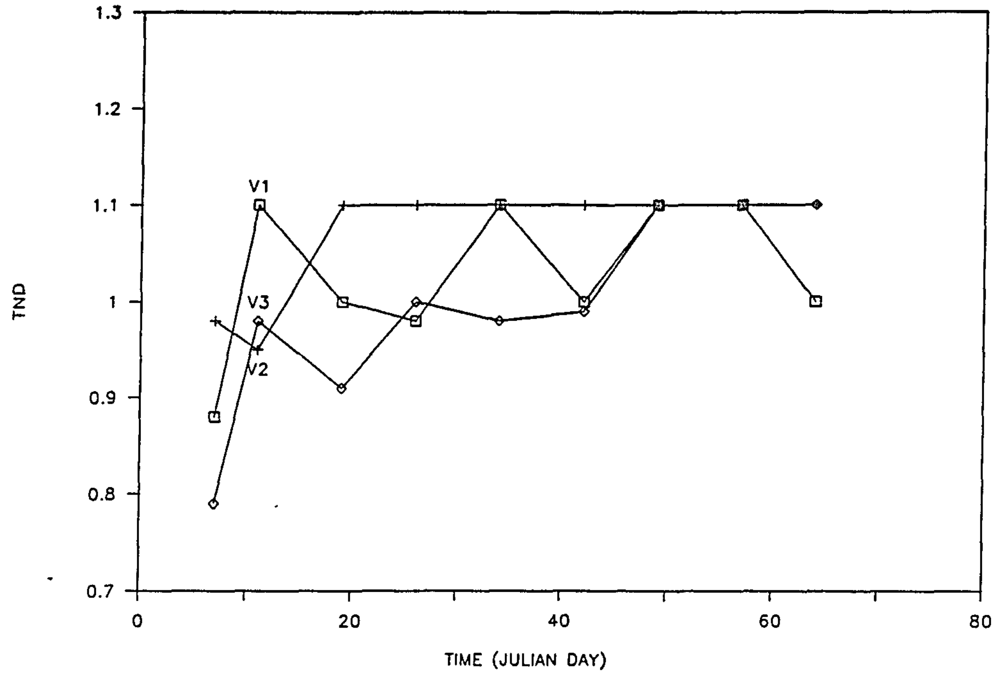

Figure 36. The transformed normalized difference as a function of time for the three varieties of corn under N0.

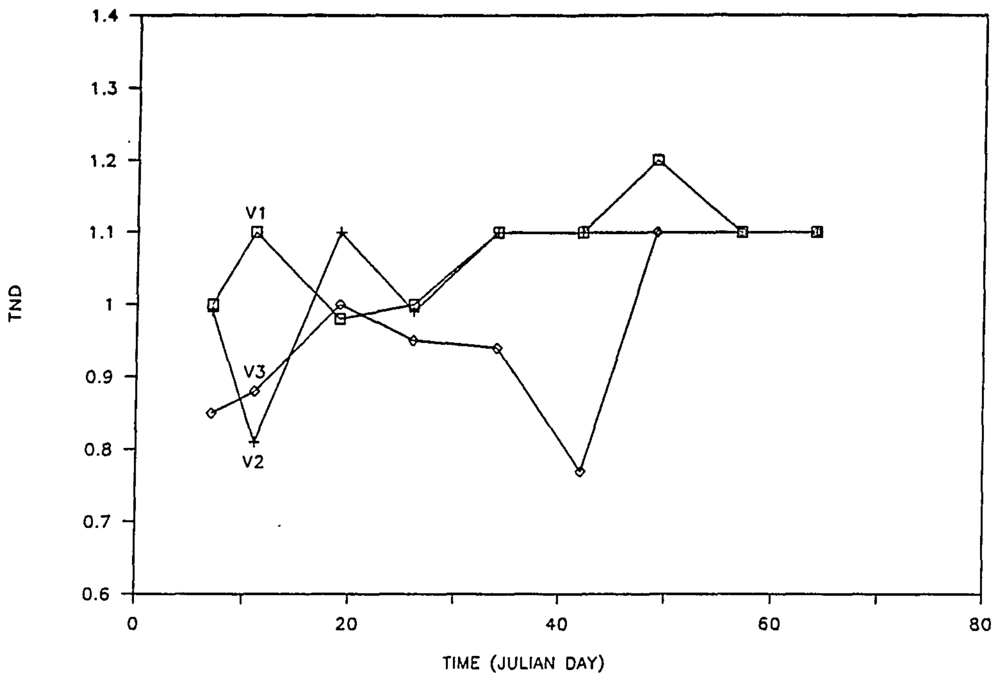

Figure 37. The transformed normalized difference as a function of time for the three varieties of corn under N1.

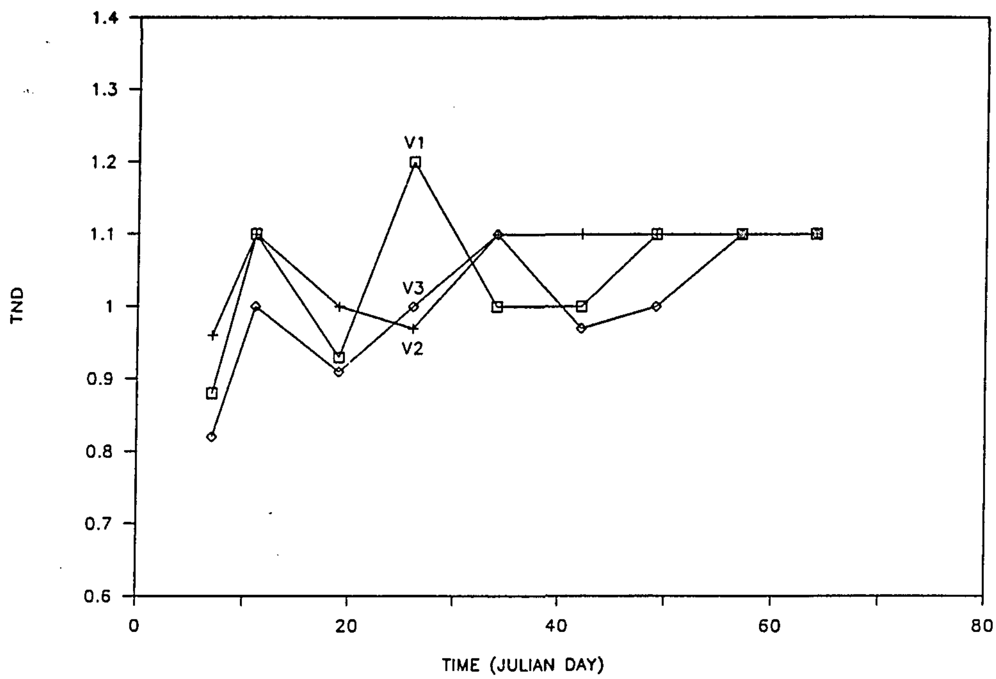

Figure 38. The transformed normalized difference as a function of time for the three varieties of corn under N2

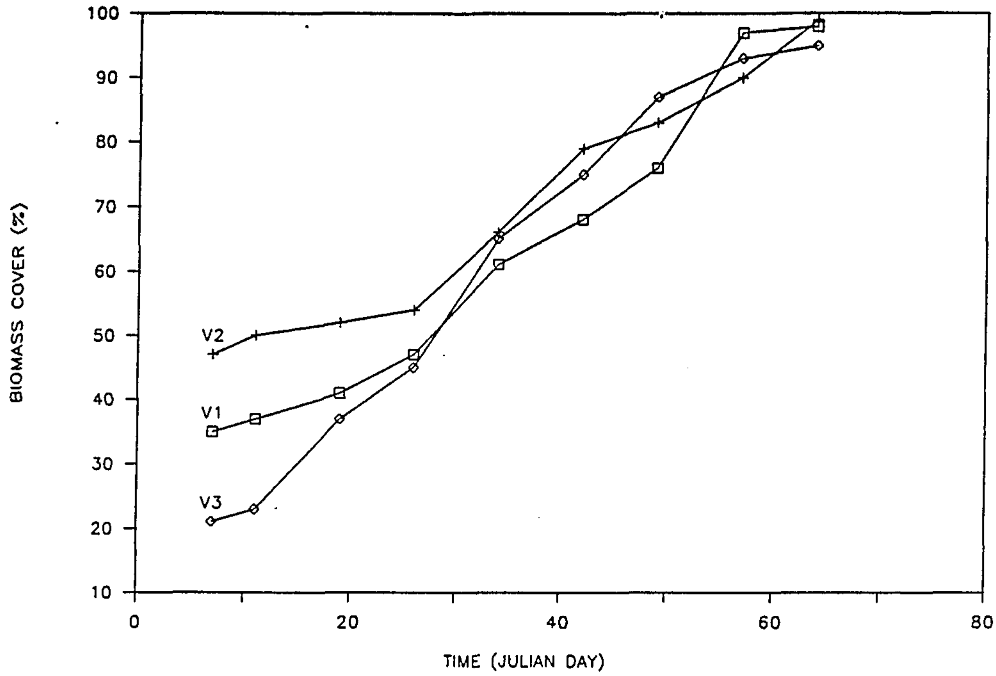

Figure 39. Percentage of biomass cover as a function of time for the three varieties of corn under N0.

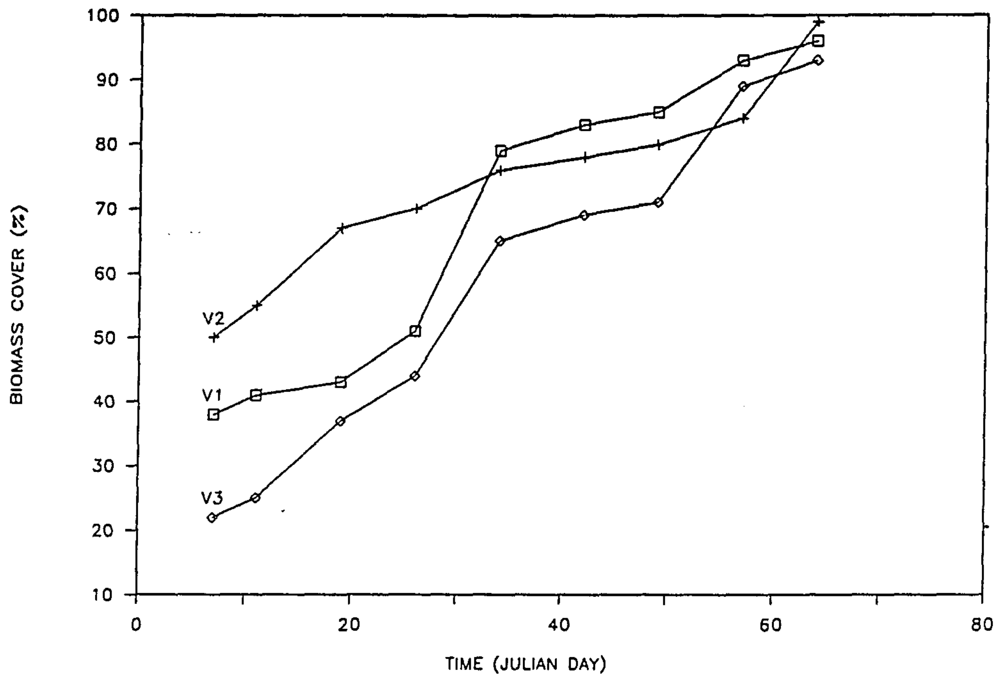

Figure 40. Percentage of biomass cover as a function of time for the three varieties of corn under N1.

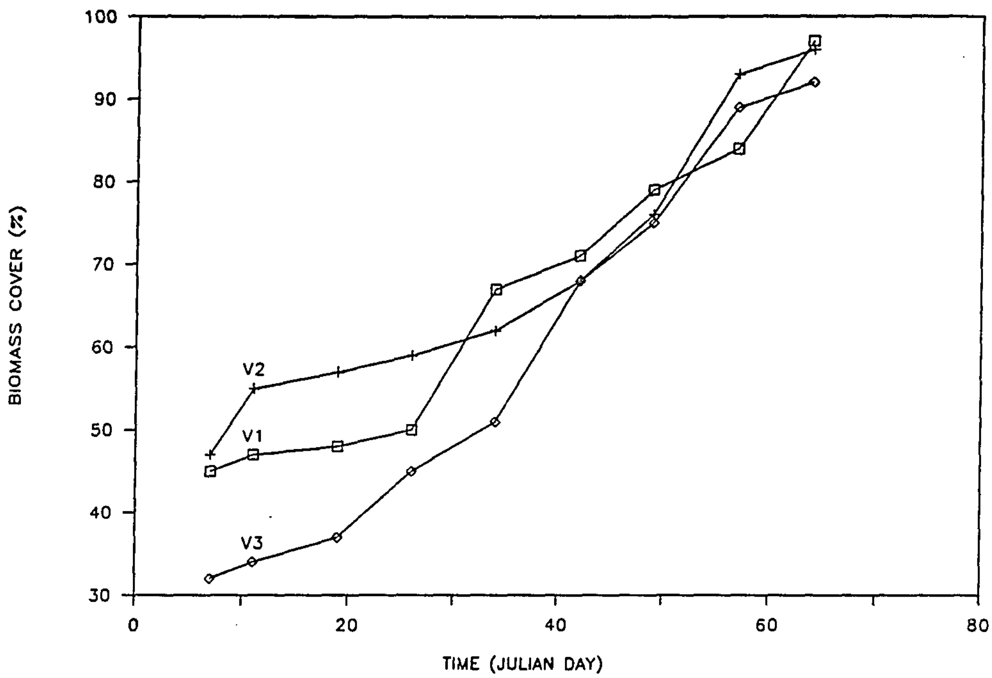

Figure 41. Percentage of biomass cover as a function of time for the three varieties of corn under N2.

N level). However, the three varieties are distinguishable within each of the three levels of N.

Figures 42 through 44 show the positive relationship between the integrated TNDVI data for the three varieties of corn and the end-of-season above-ground dry matter production at each of the three N levels. A t-test applied to that effect showed no significant difference between the means of varieties one and two, but they are significantly higher from the mean of variety three at the 0.05 level. However, the integrated TNDVI values for N1V2 and N1V1 (Figures 42 and 43), respectively) are rather high for their dry matter production compared with the other values. This may be due, at least in part, to the setup of the experiment as mentioned in earlier discussions.

The Statistical Analysis

Table 3a shows the analysis of variance with dry matter production as a dependent variable. The data show that N applications did not significantly affect dry matter production at the 0.05 level. Significant differences among varieties with respect to dry matter production were detected at the 0.05 level. A t-test applied to that effect showed no significant differences between the means of varieties one and two but both significantly higher than the mean of variety three at the 0.05 level.

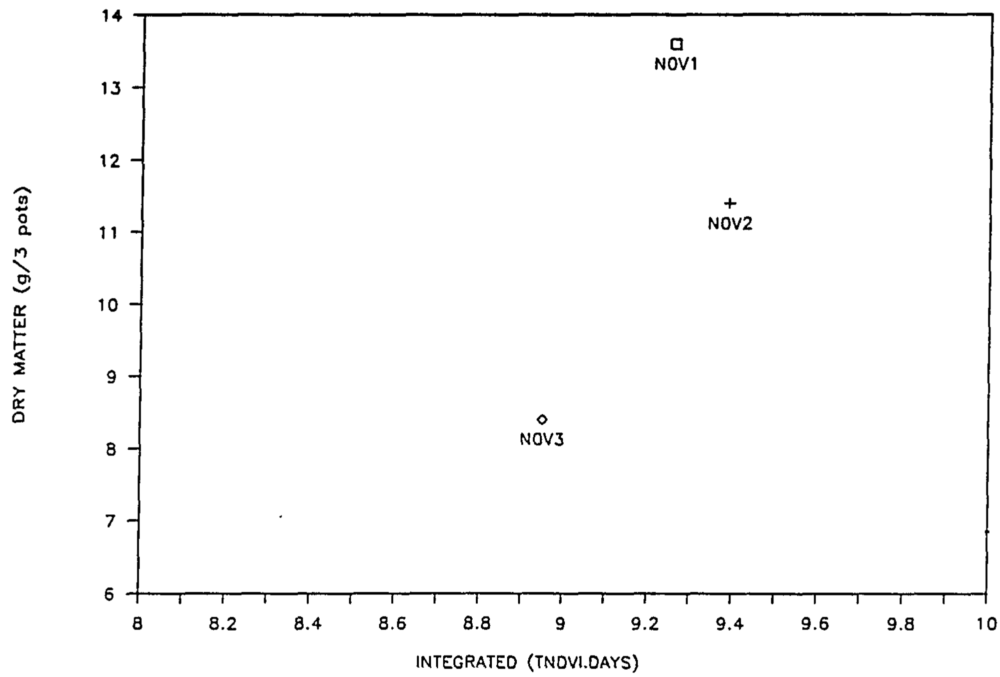

Figure 42. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for the three varieties of corn under N0.

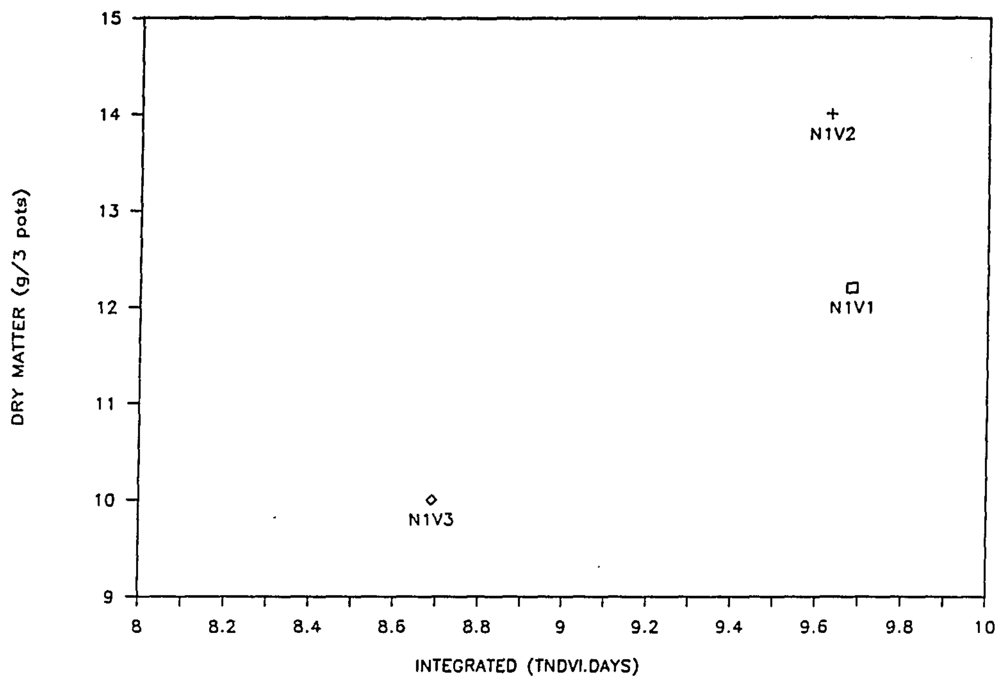

Figure 43. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for the three varieties of corn under N1.

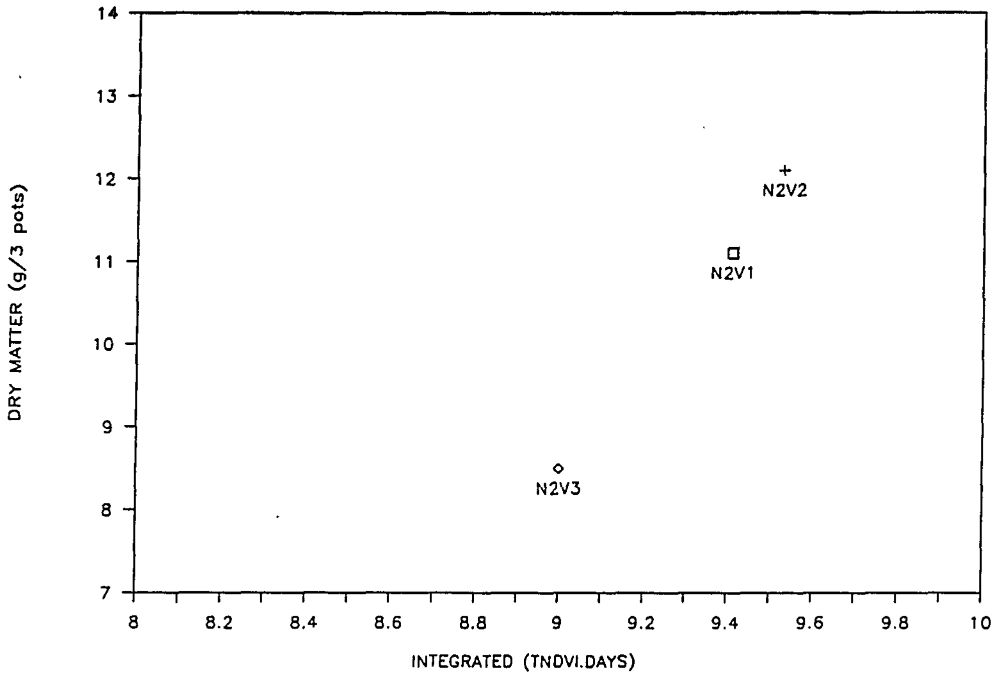

Figure 44. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for the three varieties of corn under N2.

Table 3a. Analysis of variance with dry matter production as a dependent variable.

Source	DS	SS	MS	P Value
Block	2	0.35185	0.17593	0.728
Variety	2	7.8785	3.9393	0.008**
Block x Variety	4	1.3484	0.33704	0.654
Nitrogen	2	1.1474	0.57370	0.376
Nitrogen x Variety	4	1.6415	0.41037	0.571

** Significant difference at the 0.05 level.

Table 3b shows the analysis of variance with chlorophyll being the dependent variable. The analysis indicated that significant differences among varieties with respect to chlorophyll concentration were detected. A t-test applied showed chlorophyll concentration in V3 is significantly higher than in V1, whereas, no significant differences between the mean of V1 and V2 were detected at the 0.05 level. Chlorophyll concentration was significantly affected by N applications. Chlorophyll concentration in leaves increased with increasing N levels (from N0 to N2). The N-variety interaction was significantly different (N and variety are dependent of one another) at the 0.05 level. The analysis of variance of NO_3 being the dependent variable is shown in Table 3c. Significant differences among varieties with respect to NO_3-N concentration were detected at the 0.05 level. A t-test applied to that effect showed no significant difference between the means of V1 and

Table 3b. Analysis of variance with chlorophyll as a dependent variable.

Source	DS	SS	MS	P Value
Block	2	1.7963	0.89815	0.057
Variety	2	14.556	7.2781	0.0001**
Block x Variety	4	1.6659	0.41648	0.215
Nitrogen	2	130.43	65.216	0.0001**
Nitrogen x Variety	4	3.8059	0.95148	0.030**

** Significantly different at the 0.05 level.

Table 3c. Analysis of variance with NO_3 as a dependent variable.

Source	DS	SS	MS	P Value
Block	2	84.327	42.163	0.419
Variety	2	476.16	238.08	0.023**
Block x Variety	4	75.533	18.883	0.792
Nitrogen	2	37574	18786	0.001**
Nitrogen x Variety	4	355.41	88.853	0.1628

** Significant difference at the 0.05 level.

V2, but both significantly higher than the mean concentration of V3 at the 0.05 level. The data also indicated that N applications significantly affected NO_3 concentration at the 0.05 level. A t-test applied showed significant differences among the means of NO_3-N concentration depending on N levels at the 0.05 level. The concentration at N2 (highest) is significantly higher than that at N1 (medium) level, and the latter one is significantly higher than the concentration at N0 level. The N-variety interaction, however, was not significant at the 0.05 level.

Corn and Water Experiment

Analysis of Spectral Data

The spectral response in four thematic mapper bands (TM1 to TM4) of the three varieties of corn under W2 (W2, medium water treatment) on day 34 (69 days after planting) is presented in Figure 45. The three varieties responded virtually the same in the visible region (TM1 to TM3), but differently in the NIR region (TM4) of the spectrum. The three varieties are distinguishable in the NIR band, which resulted from variation in establishing a well developed vegetative cover in response to water application. However, the spectral response pattern during the measurement period is not consistent. The same relationship held for other treatments (for a complete set of data see Appendix A). Figure 46 depicts the spectral response of V2 in the TM1 to TM4 under three water levels, 69 days after planting. The influence of variable water treatments was more visible in the TM4 (NIR) region. The spectral curves indicate, as can be seen in Figures 45 and 46, that

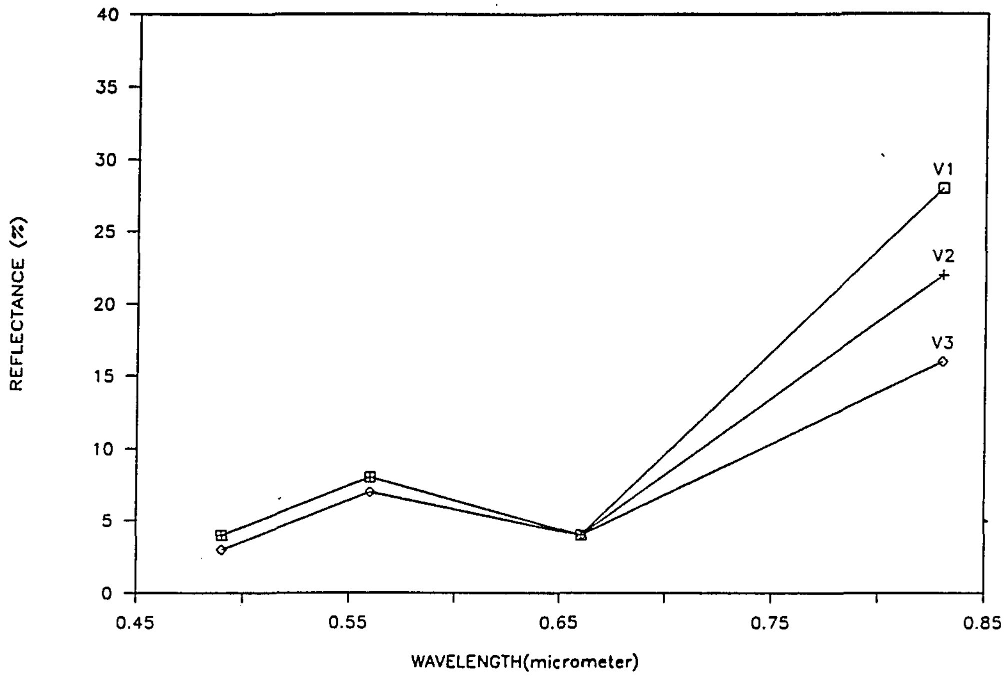

Figure 45. Spectral curve for the three varieties of corn under W2 at day 34 (69 days after planting).

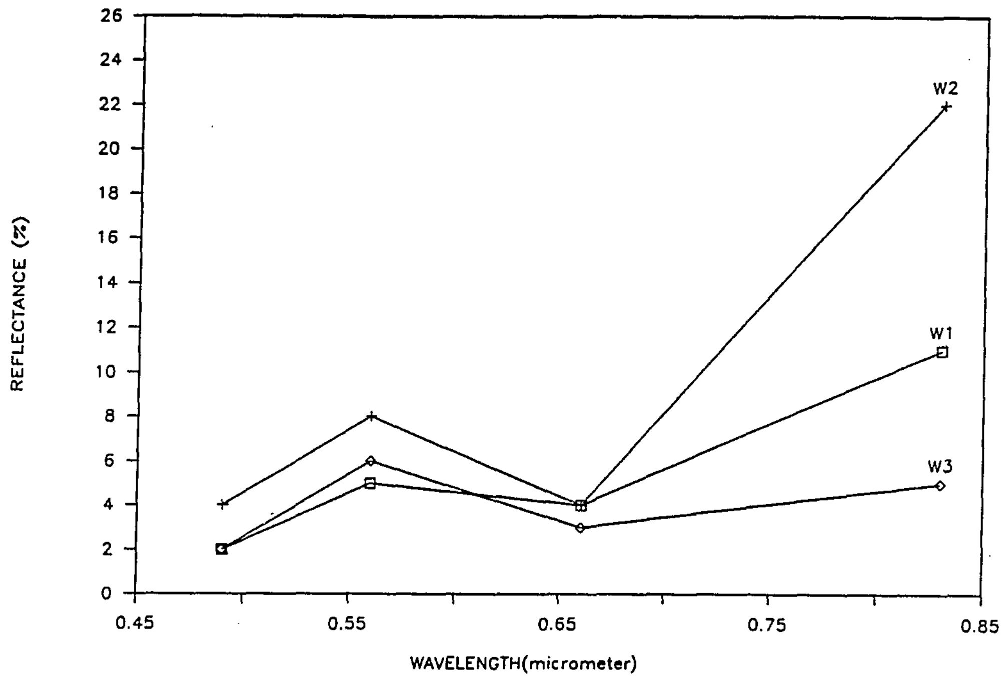

Figure 46. Spectral curve for variety two under three levels of water at day 34 (69 days after planting).

it is difficult to quantify the effect of variable water treatments on the spectral response of corn canopies. However, the spectral data, on the other hand, show its sensitivity to both water treatment and variety but it will not differentiate between the two.

Figure 47 shows the TNDVI calculations over the period of measurement for the three varieties under W1. The results indicated that V1 and V2 responded similarly and exhibited higher TND values than V3. Variety three responded very poorly as it developed the least vegetative cover compared to the other two varieties to all three water levels. The slight increase in TND value on day 11 may be due, at least in part, to the set up of the experiment as explained in earlier sections. However, V3 showed a slight gradual increase in vegetative cover over time. The behavior of V3 is suspected to be due, at least in part, to the greenhouse conditions. The temperature was lower than that required for normal growth. Similar relationships were observed for other treatments (see Appendix A). The results also indicated that the analysis of the time change of this index will help in understanding both the characteristic interaction of a developing plant canopy with solar radiation and the differing response to water treatment on the canopy appearance. A reduced plant cover (poorly developing plant canopy) allows more soil to be "seen" (lower reflectance in NIR and higher in red bands) by the radiometer and reduced chlorophyll formation causes less reflectance in the TM4 (NIR) band.

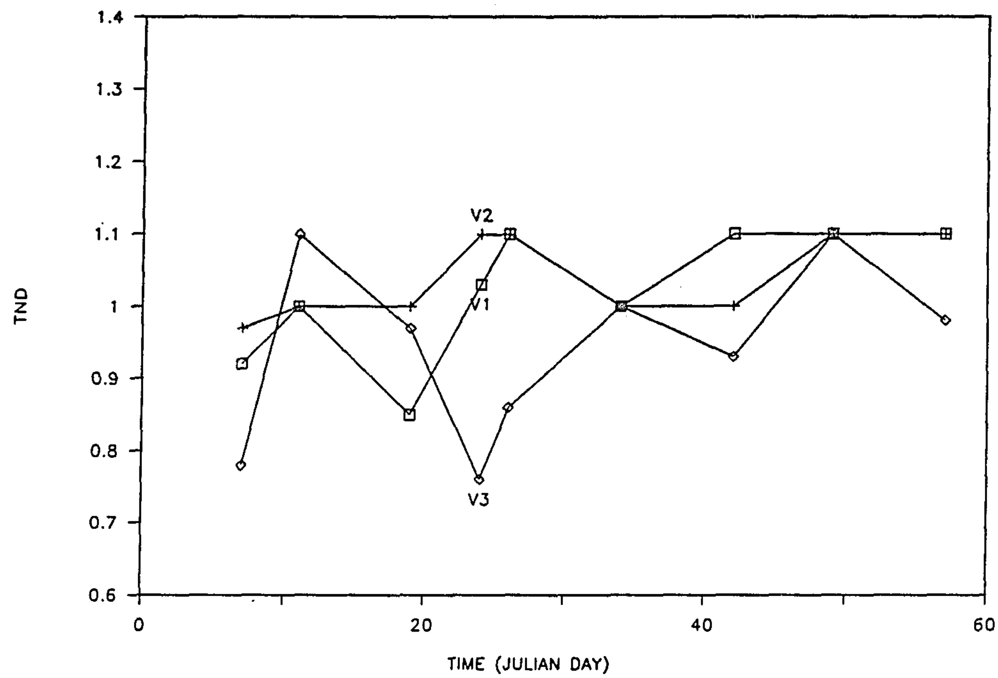

Figure 47. The transformed normalized difference as a function of time for the three varieties of corn under W1.

Figures 48 through 50 show the percent plant cover for the three varieties of corn under each of the three levels of water treatment as a function of time. The results shown in Figure 48 for W1 agree with those found in Figure 47. A close examination of these figures show a gradual increase in the percent plant cover for all three varieties in response to increased water application. Variety two maintained the highest vegetative cover while V3 had the lowest vegetative cover under all three levels of water.

The relationship between the integrated TNDVI values over the growing period and the end-of-season above-ground dry matter production for the three varieties of corn at each of thethree water levels is presented in Figures 51 to 53. The integrated TNDVI value for W3V1 (Fig. 53) is rather high for its dry matter production compared with the other two varieties. This may be due, at least in part, to the set up of the experiment. The relationship presented in the three figures, however, is positively related. A t-test applied to that effect showed no significant difference between the means of V1 and V2 and the means of V1 and V3, but V2 is significantly higher than V3 at the 0.05 level, with respect to dry matter production.

The Statistical Analysis

Table 4a shows the analysis of variance with dry matter production as a dependent variable. Significant difference among varieties with respect to dry matter production were detected at the 0.05 level. A t-test which was applied to that effect

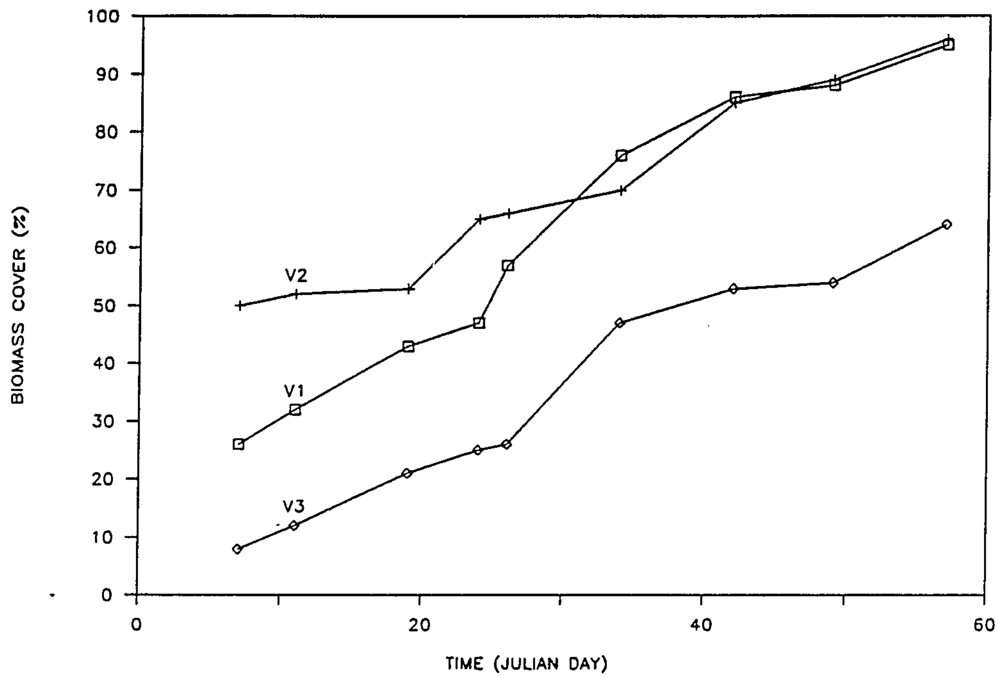

Figure 48. Percentage of biomass cover as a function of time for the three varieties of corn under W1.

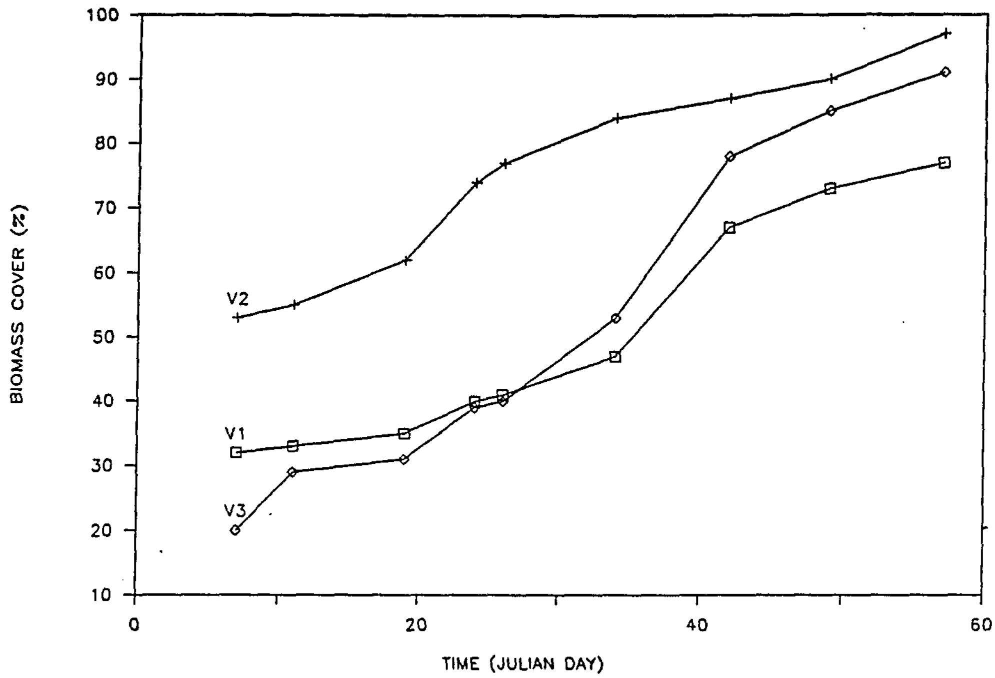

Figure 49. Percentage of biomass cover as a function of time for the three varieties of corn under W2.

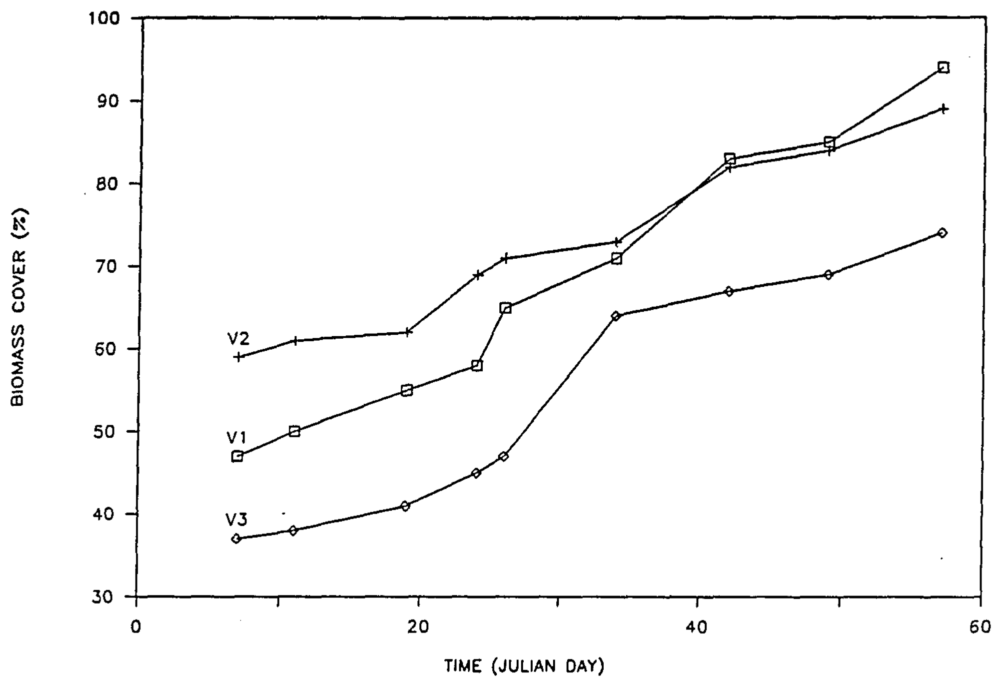

Figure 50. Percentage of biomass cover as a function of time for the three varieties of corn under W3.

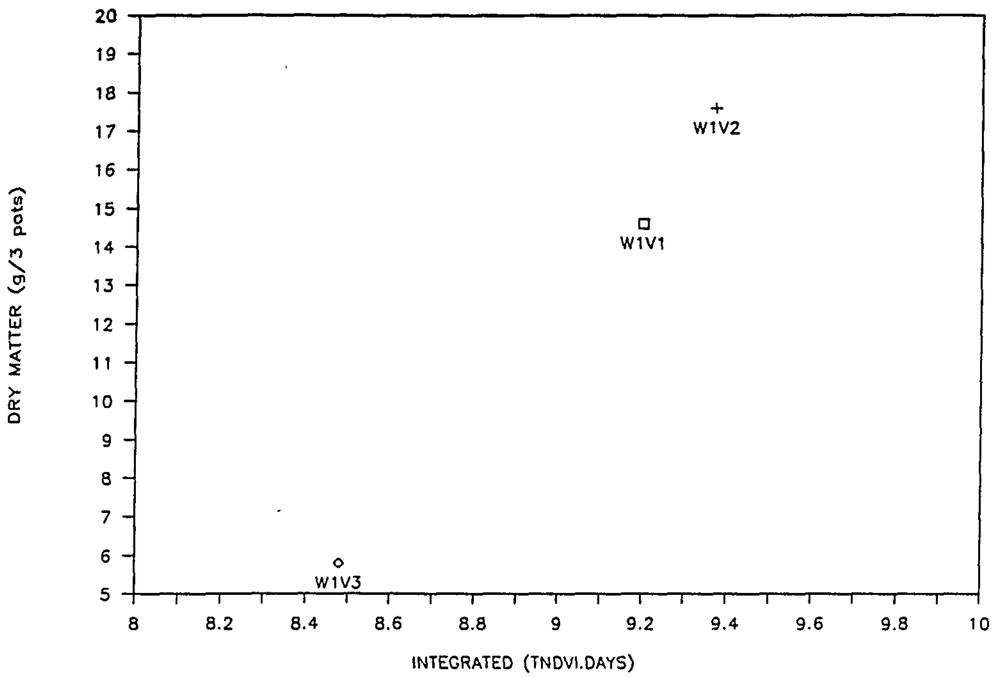

Figure 51. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for the three varieties of corn under W1.

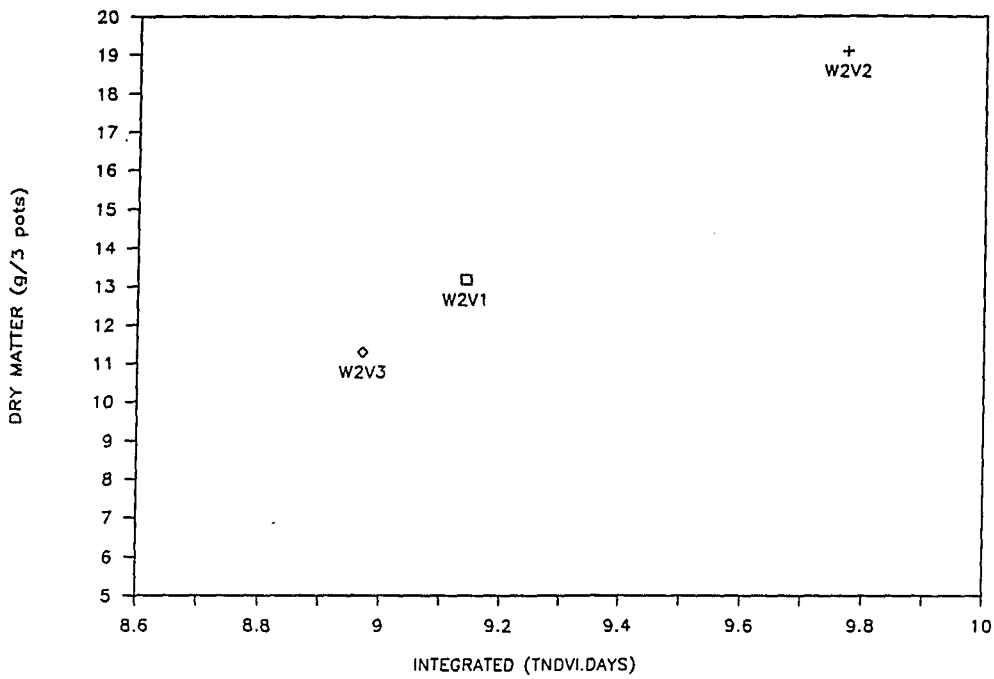

Figure 52. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for the three varieties of corn under W2.

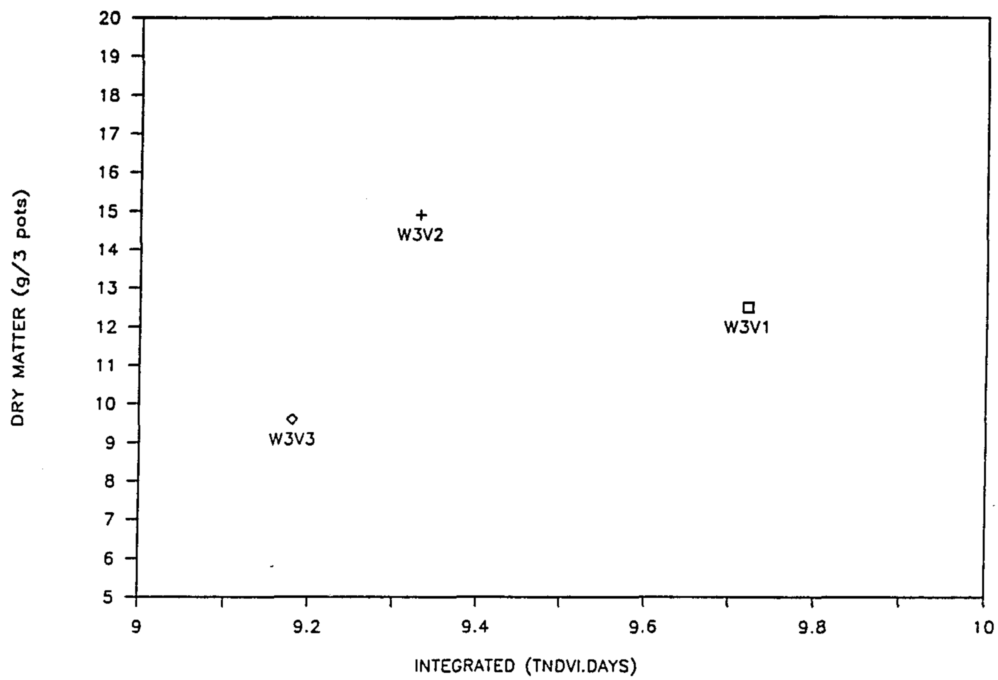

Figure 53. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for the three varieties of corn under W3.

showed that V2 is significantly higher than V3 at the 0.05 level. The test also showed no significant difference between V1 and V2 and V1 and V3 at the 0.05 level. Water levels treatment did not significantly affect dry matter production at the 0.05 level. The data also indicated that water-variety interaction was not significant. Table 4b shows the analysis of variance with chlorophyll as a dependent variable. The analysis shows that chlorophyll concentration were detected. A t-test applied showed that variety three is significantly higher than V1 and V2, whereas, the means of V1 and V2 were not significantly different at the 0.05 level. Chlorophyll concentration was not significantly affected by water applications at the 0.05 level.

Table 4a. Analysis of variance with dry matter production.

Source	DS	SS	MS	P Value
Block	2	1.0941	0.54704	0.624
Variety	2	34.890	17.445	0.0005
Block x Variety	4	12.579	3.1448	0.073
Water	2	0.51852	0.25926	0.796
Water x Variety	4	11.990	2.9976	0.082

Table 4b. Analysis of variance with chlorophyll as a dependent variable.

Source	DS	SS	MS	P Value
Block	2	0.52667	0.26333	0.552
Variety	2	24.007	12.003	0.0001
Block x Variety	4	0.87778	0.21944	0.722
Water	2	1.5622	0.78111	0.199
Water x Variety	4	12.1178	0.52944	0.340

Field Experiment

Analysis of Spectral Data

As mentioned in the preceding sections, the most common method of displaying the spectral response of biomass is simply a plot of percent reflectance vs. wavelength, or a spectral curve. Figure 54 depicts the spectral response of corn canopy to the three N levels (N1, N2 and N3) at water level one (W1) in four thematic mapper bands (TM1 to TM4) on day 109 (56 days after planting). The corn canopy responded virtually the same to all three levels of N. The influence of different concentrations of N is more visible in the NIR region. The variation in response in the NIR portion of the spectrum resulted from establishing a well-developed vegetative cover in response to variable N treatments. A close examination of the spectral data for other treatments during the growing period shows no consistent differences in the curves and no uniform pattern in response to the three levels of applied N. The four thematic mapper-waveband spectral data for all treatments are given in Appendix A. These variations could be attributed to changes in plant appearance and/or to irradiance changes from one day to another. The same results were observed from the spectral response of corn canopy to the three levels of water under nitrogen level one at day 109 (56 days after planting), Figure 55. Examining single band reflectance in more detail, Figures 56 and 57 show, respectively, red and NIR spectral responses of corn canopy at three levels of N under water level two (W2), as a function of time. The change in reflectance in these two bands (red and NIR) illustrated both the characteristic interaction of a developing plant canopy with solar radiation and the differing effect of N treatments at a certain water level on the canopy appearance. The red reflectance decreased with time because of increased chlorophyll absorption by increased green-leaf biomass, until the growing season waned and senescence began (Fig. 56). At that time, the red reflectance began to increase as the chlorophyll level in the corn canopy declined and/or leaf loss. The curves in Figure 57 show a general increasing trend with increased green-leaf biomass. This increase was gradual and leveled off as the growing season progressed, except for N level three (N3). The continuous increase in NIR percent reflectance of N3 treatment may be attributed to some water leakage due to a broken pipe. This leakage resulted in higher green-leaf biomass. However, the curves for N1 and N3 treatment are not smooth, but fluctuate up and down. This fluctuation could be attributed to the changing moisture condition of the underlying soil, to changes in plant appearance and/or to irradiance

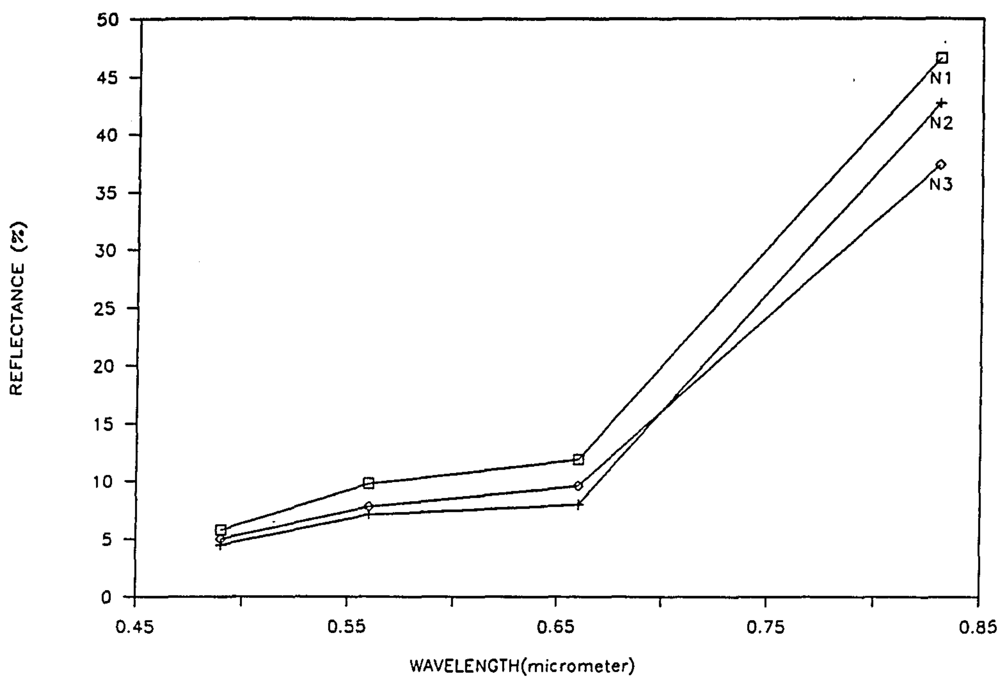

Figure 54. Spectral curve for corn canopy under three levels of N at W1 on day 109 (56 days after planting).

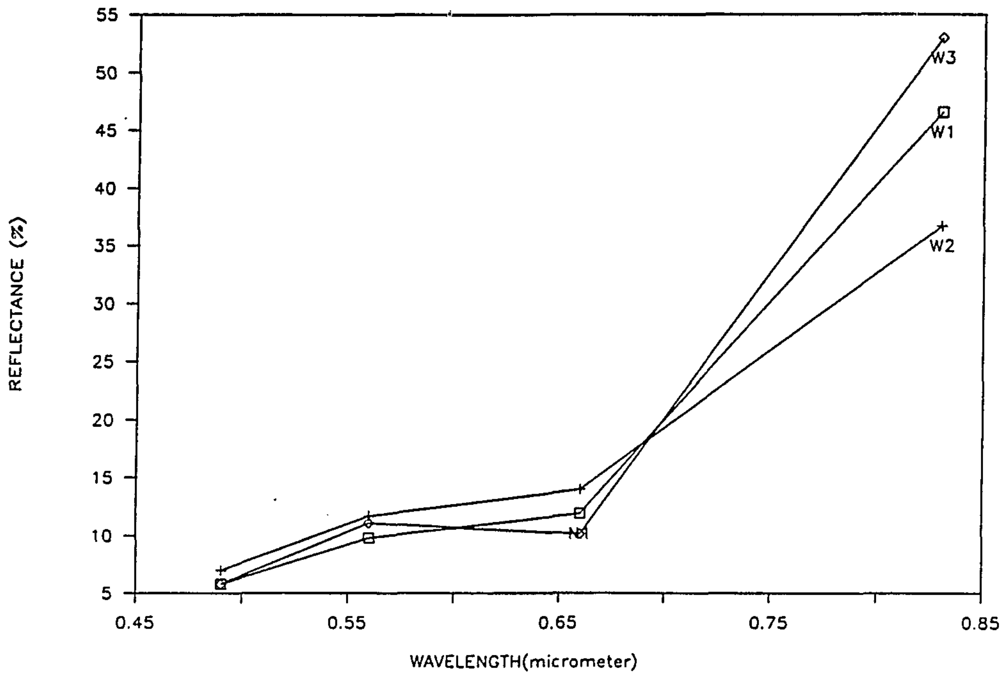

Figure 55. Spectral curve for corn canopy under three levels of water and N1 on day 109 (56 days after planting).

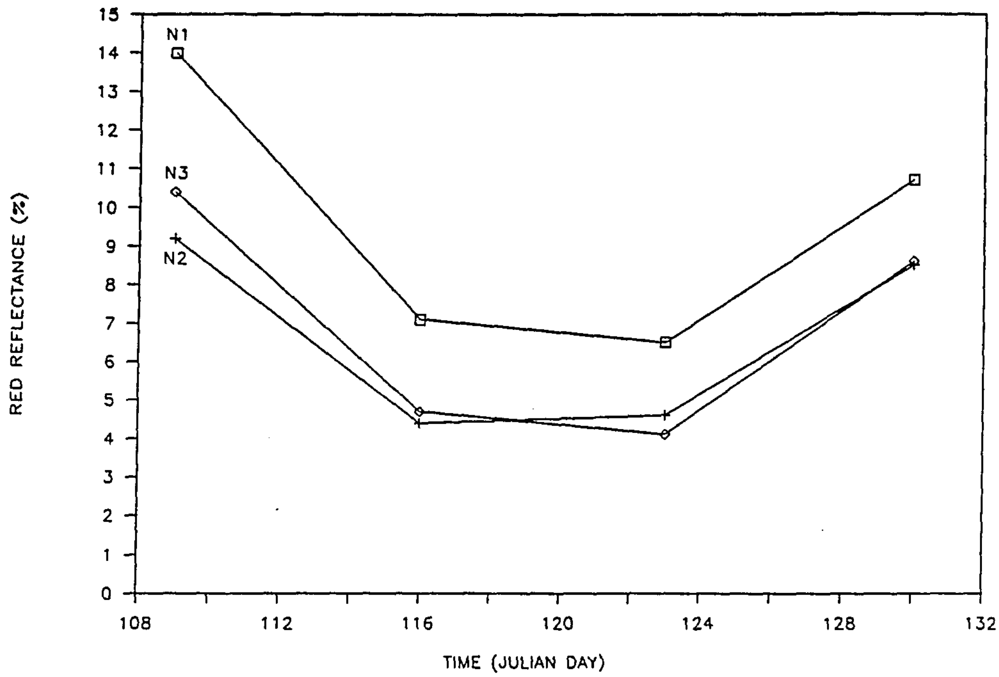

Figure 56. Temporal change in red band (0.63 - 0.69 μm) reflectance factor of a developing corn canopy under three levels of N at W2.

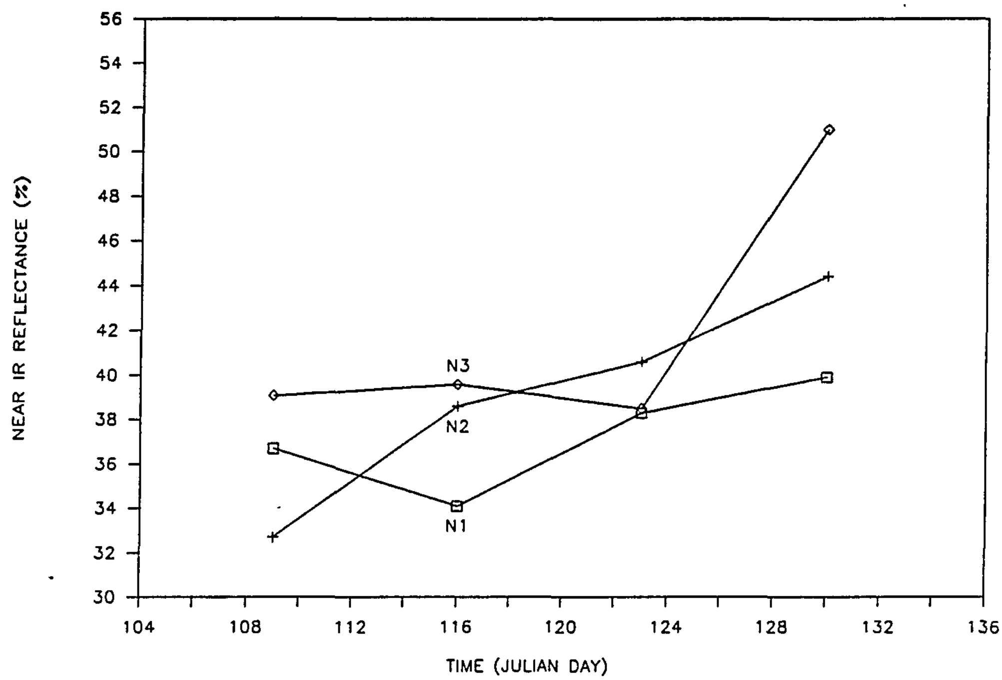

Figure 57. Temporal change in near infrared (0.76 - 0.90 μm) reflectance factor of a developing corn canopy under three levels of N at W2.

changes from one day to another. The presence of these fluctuations may illustrate the inability of a single band to normalize these effects. If only spectral curves or single band are considered during this period, without knowledge of N and/or water application, it could be concluded that more than one variety was grown in the area. Therefore, a logical step seems to be the investigation of vegetation indices that may improve our ability to interpret field conditions.

Figure 58 shows the TNDVI (transformed normalized difference vegetation index) calculations over the period of measurement for the corn canopy under three N levels at W2. The results indicated that corn canopy under N levels two and three responded similarly and exhibited higher TND values than N level one treatment. This could be attributed, as expected, to the presence of higher photosynthetically active biomass or green-leaf biomass in corn canopy under N levels two and three than under N level one. However, the data also indicated that the TND values increased gradually with time because of increased green-leaf biomass, until the growing season waned and senescence began. At that time, the TND values began to decrease as the lower leaves began to turn brown, lose chlorophyll, and mature, resulting in a decrease in the number of actively reflecting leaf layers. The TND calculations for corn canopy under three water levels (W1, W2 and W3) is presented in Figure 59. The TND values were essentially the same for the three water treatments. However, the TND values had the same general trend as those in Figure 58. A comparison between Figures 58 and 59 may suggest, to some degree, that N stress influenced the development of vegetative cover (the number of actively

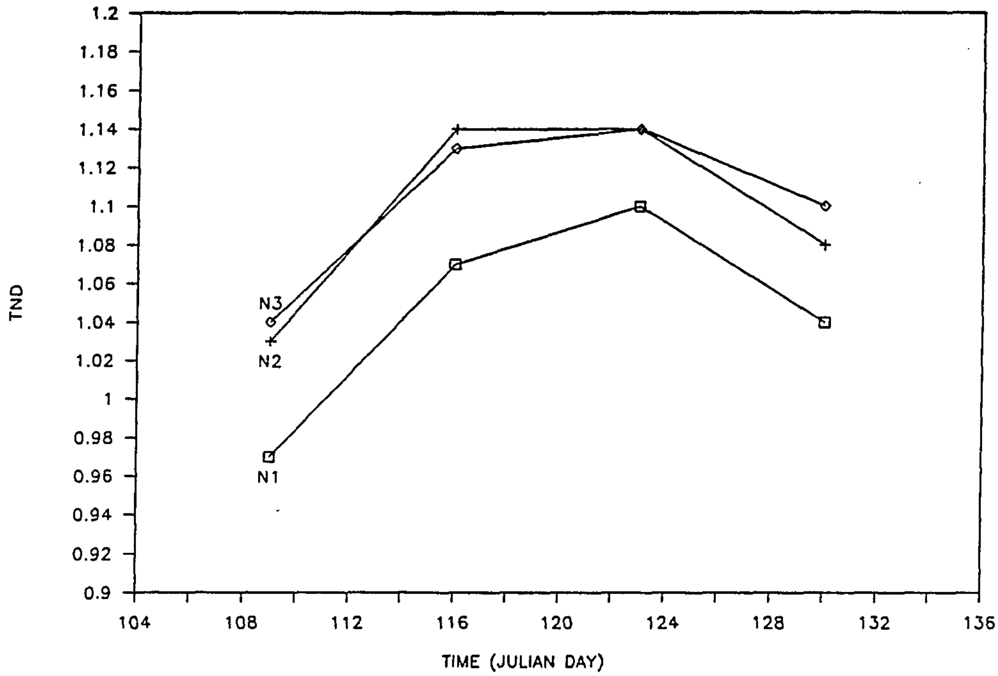

Figure 58. Temporal change in the transformed normalized difference of a developing corn canopy under three levels of N at W2.

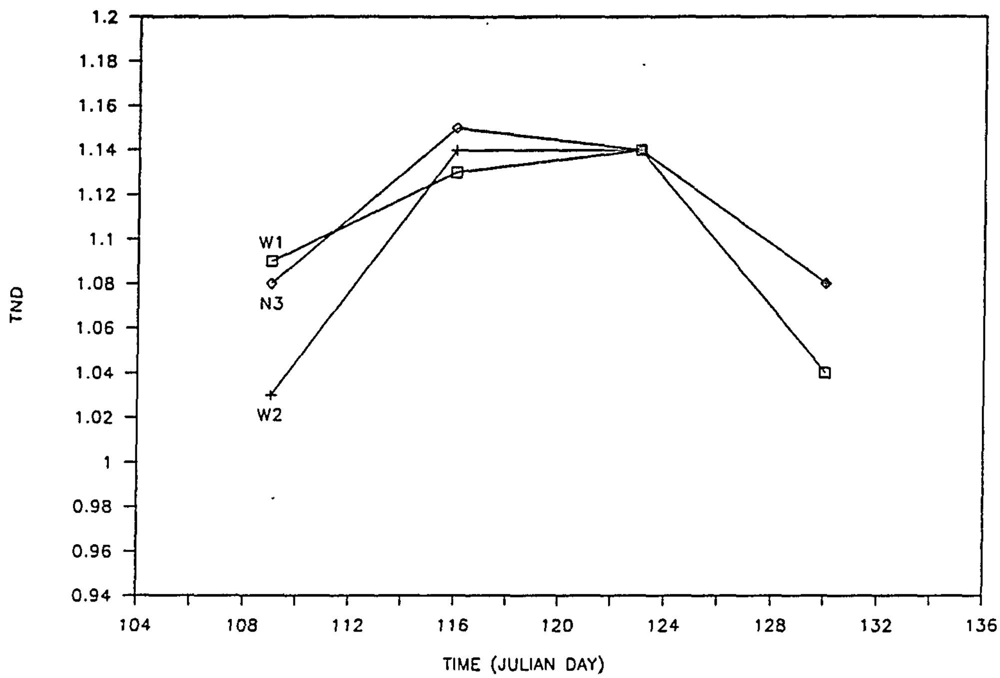

Figure 59. Temporal change in the transformed normalized difference of a developing corn canopy under three levels of water at N2.

reflecting leaf layers) more than water stress. Figure 60 depicts the TND calculations as a function of percent cover (during the period of measurement) for corn canopy under W1N1 (water level one and N level one) treatment. The TND values increased gradually (as the growing season progressed) with increasing percent cover and peaked to decrease rapidly as the growing season waned and senescence began. Figure 61 depicts the percent cover as a function of time for corn plants under three water levels at N1. The percent cover increased gradually with time until plant maturity and senescence began. At that time, the percent cover began to decrease slightly. Similar results were obtained from the spectral data presented in Figure 62 which depicts the TND calculations plotted as a function of time for corn canopy under three water levels at N1. The curves in both plots show the same general trend of increasing (as the growing season progressed) or decreasing (as the season waned). These results presented in Figures 58 to 62 confirm the sensitivity of TNDVI to green-leaf biomass or photosynthetically active biomass present by the plant canopy.

A plot of NDVI, TNDVI and SAVI as a function of time for water level two and N level one (W2N1) treatment is presented in Figure 63. There is a similarity among ND, TND and SAVI values. The TNDVI is similar to NDVI, in that a constant 0.5 was added to the normalized difference vegetation index I(NDVI) and a square-root function was applied. ($\mathrm{TNDVI} = \sqrt{\mathrm{NDVI} + 0.5}$) to avoid negative values which result from very low vegetation densities. Thus, the TNDVI exhibited all the characteristics of the NDVI curve. SAVI, on the other hand, is similar to

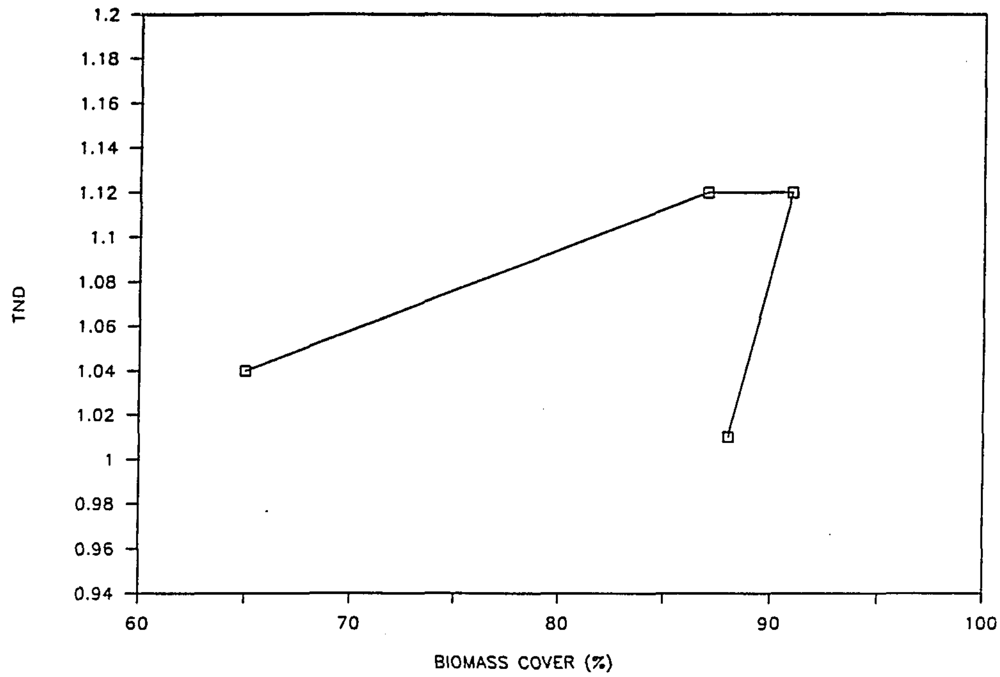

Figure 60. The transformed normalized difference as a function of biomass cover for W1N1 treatment.

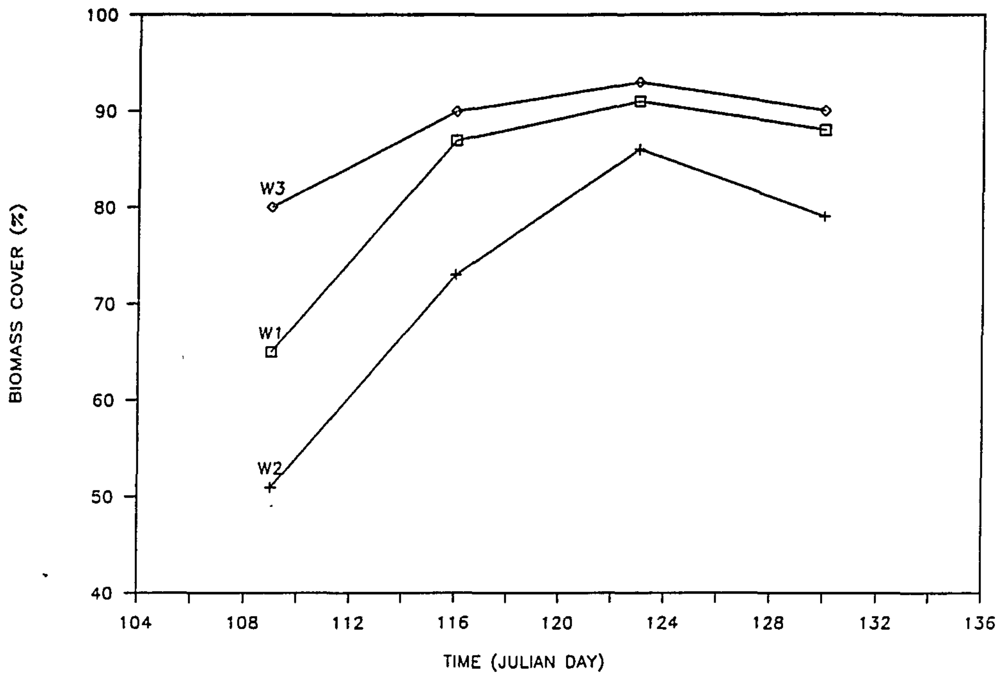

Figure 61. Temporal change in biomass cover of a developing corn canopy under three levels of water at N1.

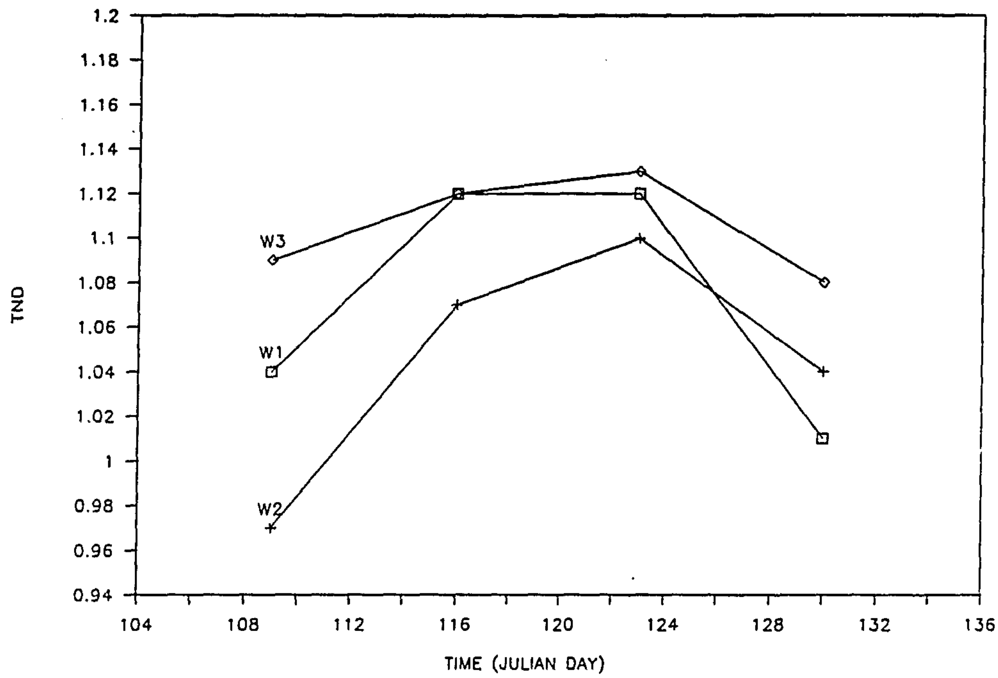

Figure 62. Temporal change in transformed normalized difference of a developing corn canopy under three levels of water at N1.

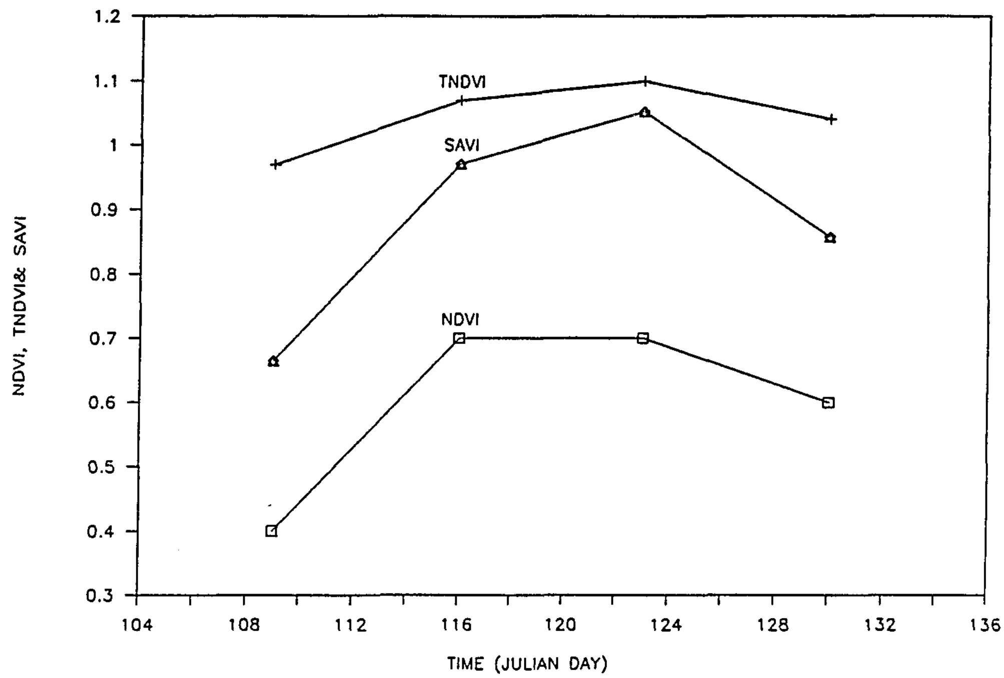

Figure 63. Temporal change in normalized difference, transformed normalized difference and soil-adjusted vegetation index of a developing corn canopy under W2N1 treatment.

NDVI, in that the first is derived by adding an adjustment factor (L = constant) to the NDVI denominator and multiplying the new expression by a factor equal to (1 + L) to maintain the bounded condition of normalized difference index. In this study, L = 0.5 and SAVI was derived as [(NIR - R)/(NIR + R) + 0.5] x 1.5. The SAVI mimics the NDVI when there are no soil influences (a single soil type). Thus, it is easy to understand the fact that SAVI exhibited all the characteristics of the NDVI curve described above.

The relationship between the integrated TND values over the period of measurement and the end-of-season above-ground dry matter production of corn under three water levels at N1 is presented in Figure 64. The values for the three treatments are positively related. A t-test applied to that effect showed that at N1, the mean of W3 treatment is significantly higher than the mean of W1 and the later is significantly higher than the mean of W2 treatment at the 0.05 level. The same relationship held for the other treatments (see data in Appendix A).

The Statistical Analysis

Table 5 shows the analysis of variance with dry matter production as a dependent variable. Significant differences among the three water levels with respect to dry matter production were detected at the 0.05 level. A t-test applied to that effect showed significant difference among the means of the three water levels at the 0.05 level. The test indicated that at N1 treatment, the mean of W3 is significantly higher than the mean of W2 and the later is significantly higher than the mean of

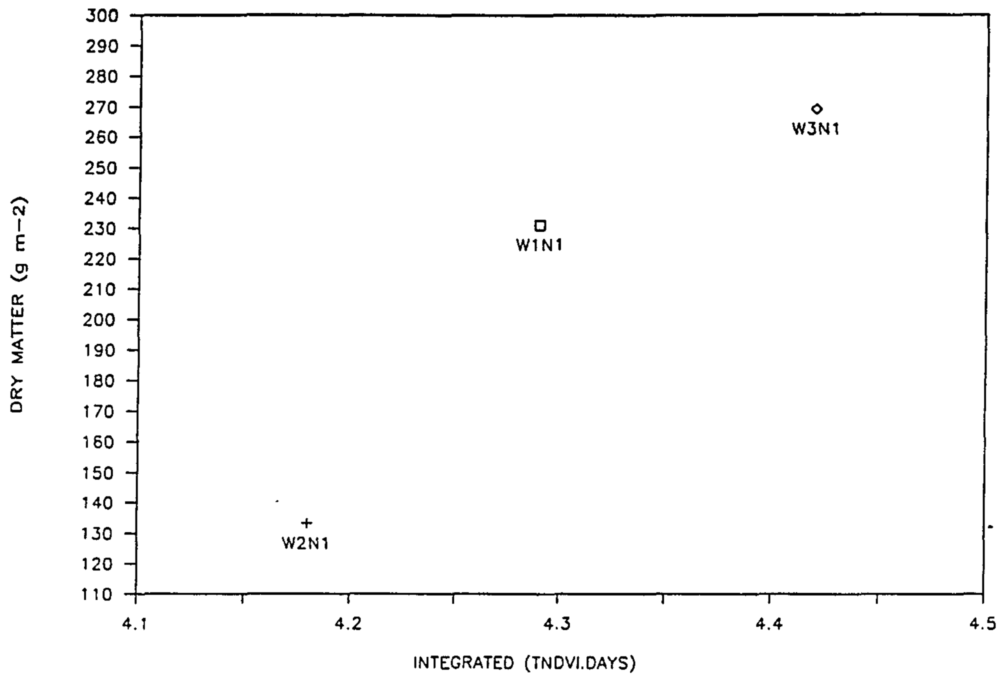

Figure 64. The relationship between integrated TNDVI and end-of-season above-ground dry matter production for corn under three levels of water at N1.

Table 5. Analysis of variance with dry matter production as a dependent variable.

Source	DF	SS	MS	P Value
Block	2	10635	5317	0.4361
Water	2	285742	142871	0.0001
Block x Nitrogen	4	15406	3874	0.6351
Nitrogen	2	390688	195344	0.0001
Water x Nitrogen	4	71439	17859	0.0705

W1; and at N2 and N3 treatments, the mean of W3 is significantly higher than the mean of W1 and the later is significantly higher than the mean of W2 at the 0.05 level. The results also indicated that significant differences among the three levels of N with respect to dry matter production were detected at the 0.05 level. A t-test applied to that effect showed significant difference among the means of the three N levels at the 0.05 level. The test showed that at W1 and W3 treatments, the mean of dry matter production of N3 is significantly higher than that of N2 and the later is significantly higher than the mean of N1; and at W2 treatment, the mean of dry matter production of N2 is significantly higher than the means of N1 and N3 and the later (N3) is significantly higher than the mean dry matter production of N1 at the 0.05 level.

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

Summary

Ground-based, remotely sensed reflectance data were collected over differentially stressed (zinc, water and nitrogen stress), developing corn, bean and squash canopies using a four-band hand-held radiometer. The extent to which ground-based remotely sensed data are suitable in detecting crop stress and distinguishing among varieties, is the objective of this study.

Six experiments were conducted. Five of these experiments were conducted in the greenhouse at the University of Arizona campus during 1988 and 1989. The sixth experiment was conducted in the field during the summer of 1989 at the Maricopa Agricultural Center (MAC). Red and NIR energy along with the indices derived from them (NDVI, TNDVI, SAVI and integrated TNDVI) were examined. Nitrate, Zn and chlorophyll contents were estimated in plant tissues. Statistical analysis was performed to illustrate the influence of different Zn, N and water treatments on dry matter production, Zn, NO_3-N and chlorophyll contents in plant tissues for all varieties grown. Specific results of the study may be summarized as follows:

1. Spectral reflectance and derived vegetation indices showed their sensitivity to different varieties and/or treatments (Zn, N and water). However, the data did not differentiate between the two (variety and treatment). Spectral curves

showed the typical trends in reflectance, throughout the growing period for vegetated surfaces.

2. Rate of crop development (percentages of crop cover and chlorosis) were closely associated with TNDVI. As crop cover increased, a corresponding change was measured by the TNDVI. An increase in plant chlorosis of leaf loss due to maturation or stress resulted in a decrease in the TND values. These results were noticed over the entire study.

3. The study

also showed the positive relationship between the integrated TNDVI and end-of-season above-ground biomass, which suggests that the integrated TNDVI can be interpreted as a general indication of the total above-ground production.

4. Vegetative cover values (biomass cover percent showed their ability to discriminate among varieties, and water and N treatments.

5. Red and NIR reflectance factors showed their ability to follow crop growth and development during the growing period.

6. The study also proved that NDVI, TNDVI and SAVI exhibited virtually the same results when there were no soil influences (single soil type).

Generally, one can conclude that keeping frequent records on the temporal variability of canopy spectral reflectance and derived vegetation indices could facilitate monitoring plant growth and development, discriminating among varieties, and differentiating among variable treatments.

Recommendation

1. Since the amount of water stored in plant leaves has a clear influence on canopy appearance and reflectance characteristics, similar studies should be carried out using extended wavelength field spectroradiometry. This spectral instrument should include the water absorption bands at 1.45, 1.95 and 2.2 μm.

2. Further greenhouse and field studies should be carried out simultaneously to assess the suitability of greenhouse research for conducting remote sensing studies, and relate their reflectance characteristics to the data obtained in this research.

3. Further greenhouse studies should be carried out with a fixed set up (plants are not moved during radiometric measurements) and data compared to the results of this research. Such comparisons may help further and advance application of reflectance characteristics of plant canopy under variable treatments.,

4. Since the amounts of chlorophyll, Zn and water present in plant leaves have direct influences on spectral responses of developing plant canopies, frequent sampling during growing season should be considered in further studies. Such studies may help in a better understanding of the characteristic interaction of developing plant canopies under variable treatments with solar radiation.

However, even though there are still questions to be answered, this study showed that the remote sensing technique can be used as a tool in detecting variable treatments and distinguishing among varieties, provided sufficient ground truth and related data are available.

APPENDIX A

SPECTRAL REFLECTANCE AND SELECTED VEGETATION INDICES

Table A1. Spectral reflectance and selected vegetation indices for corn and zinc experiment.

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
259	Zn0V1	6.3	10.1	7.9	32.2	4.1	1.05
262	Zn0V1	3	6.8	3.1	22.1	7.2	1.12
267	Zn0V1	4.3	9.3	4	29.8	7.4	1.12
268	Zn0V1	3.5	6.9	3.4	25	7.3	1.12
269	Zn0V1	4.2	8	3.6	25.8	7.2	1.12
270	Zn0V1	4.1	8	3.7	24	6.5	1.11
272	Zn0V1	3.7	8.7	3.6	34.8	9.6	1.14
274	Zn0V1	3.2	7.9	3.5	35.2	10.1	1.15
275	Zn0V1	3.4	8.7	3.6	46.2	12.8	1.16
276	Zn0V1	4.3	12.9	4.9	51.7	10.5	1.15
277	Zn0V1	3.4	8.7	3.6	34.9	9.7	1.15
279	Zn0V1	4.3	11	5.4	41.1	7.6	1.13
280	Zn0V1	4.4	9.7	4.8	40	8.4	1.13
259	Zn1V1	5.6	9.7	8.3	28.8	3.5	1.03
262	Zn1V1	3.3	7.9	4.2	28.1	6.7	1.11
267	Zn1V1	7.4	10.9	3.9	31.7	8.2	1.13
268	Zn1V1	6	7.8	3.8	29.4	7.7	1.13
269	Zn1V1	4.6	7.6	4.4	32.4	7.4	1.12
270	Zn1V1	3.8	7.5	3.8	30.8	8.2	1.13
272	Zn1V1	3.8	9.2	4.1	43.4	10.6	1.15
274	Zn1V1	11.1	10.8	6.8	41.3	6.1	1.1
275	Zn1V1	3.9	9.5	3.4	35.9	10.6	1.15
276	Zn1V1	3.4	8.8	4.6	42.3	9.2	1.14
277	Zn1V1	4.5	11.9	5.9	46.7	7.9	1.13
279	Zn1V1	4.7	10	5.9	46.7	7.9	1.13
280	Zn1V1	6.1	10	5.2	46.1	8.9	1.14

Table A1. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
259	Zn2V1	5.7	13.5	8.6	26.4	3.1	1
262	Zn2V1	5.3	7.7	4.8	23.8	5	1.08
267	Zn2V1	3.7	6.1	3.9	22.1	5.7	1.1
268	Zn2V1	3.3	5	3.2	23.1	7.3	1.12
269	Zn2V1	3.5	6.9	3.1	25.3	8.1	1.13
270	Zn2V1	3.6	6.8	3.1	21	6.8	1.12
272	Zn2V1	3.4	6.6	4.1	26.3	6.4	1.11
274	Zn2V1	3.5	8.9	3.7	42	11.5	1.16
275	Zn2V1	3.3	7.6	3.1	36.7	11.7	1.16
276	Zn2V1	3.4	9.1	3.2	32.8	10.3	1.15
277	Zn2V1	4.6	11.1	4.8	40.9	8.5	1.14
279	Zn2V1	4.7	10.9	5.1	33.4	6.6	1.11
280	Zn2V1	4.5	11.7	3.9	35	9	1.14
259	Zn3V1	4.9	10.8	9.3	31.5	3.4	1.02
262	Zn3V1	3.4	6.9	3.4	22.3	6.6	1.11
267	Zn3V1	4.8	8	3.3	17	5.1	1.08
268	Zn3V1	4.2	8	3.6	30.7	8.4	1.13
269	Zn3V1	4.2	7.6	3.2	20.2	6.4	1.11
270	Zn3V1	6.6	8	5.1	28.3	5.6	1.09
272	Zn3V1	4.4	8.9	4	35.2	8.8	1.14
274	Zn3V1	2.7	8.4	4.1	43.7	10.8	1.15
275	Zn3V1	3.8	8.6	4	41.1	10.2	1.15
276	Zn3V1	4	9.2	3.5	44.1	12.6	1.16
277	Zn3V1	4.5	10.6	4.6	45.9	10	1.15
279	Zn3V1	5.5	9.2	5	45.9	9.3	1.14
280	Zn3V1	3.9	10.9	3.8	37.2	9.7	1.15

Table A1. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
259	Zn0V2	4.9	11.1	7	31.8	4.5	1.07
262	Zn0V2	2.7	6.3	3.1	22.8	7.4	1.12
267	Zn0V2	4.1	8.6	3.6	29.4	8.2	1.13
268	Zn0V2	3.3	7.4	3.1	28.2	9	1.14
269	Zn0V2	3.4	8.1	3.9	30.7	7.9	1.13
270	Zn0V2	3.5	6.1	3.2	18.4	5.8	1.1
272	Zn0V2	5.1	8.1	4.5	28.1	6.2	1.11
274	Zn0V2	4.6	9	5.2	37.7	7.3	1.12
275	Zn0V2	3	8.4	3.4	36.1	10.7	1.15
276	Zn0V2	2.7	8.1	3.3	34.3	10.4	1.15
277	Zn0V2	4.8	10.3	4.7	36.9	7.9	1.13
279	Zn0V2	3.9	7.9	4.3	33.7	7.9	1.13
280	Zn0V2	4.2	10.5	4	47.2	11.9	1.16
259	Zn1V2	6.3	11.5	8.2	29	3.6	1.03
262	Zn1V2	3.7	8.5	2.9	24.9	8.4	1.13
267	Zn1V2	4.7	10.8	5.1	36	7.1	1.12
268	Zn1V2	4.6	8.8	3.5	29.6	8.4	1.14
269	Zn1V2	3.4	8.9	4.1	34.2	8.4	1.13
270	Zn1V2	3.5	7.8	4.1	27.5	6.7	1.11
272	Zn1V2	6	9.7	4.1	32.2	7.8	1.13
274	Zn1V2	3.1	7.2	3.2	38	12	1.16
275	Zn1V2	3.2	9.3	4	45.8	11.5	1.16
276	Zn1V2	3.6	9.8	3.8	42.8	11.3	1.16
277	Zn1V2	5.5	12.1	5.1	52.2	10.3	1.15
279	Zn1V2	7.9	12.3	6.4	37.7	5.9	1.1
280	Zn1V2	4.3	11.3	4.8	49.1	10.2	1.15

Table A1. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
259	Zn2V2	5.1	10.1	7.5	24.5	3.2	1.01
262	Zn2V2	5.7	10.7	9.9	32.3	3.3	1.01
267	Zn2V2	4	7	3.3	23.2	7.1	1.12
268	Zn2V2	3.5	6.3	3.5	25.5	7.3	1.12
269	Zn2V2	3.3	7.3	3.6	28.3	7.8	1.13
270	Zn2V2	3.6	6.4	3	25.9	8.7	1.14
272	Zn2V2	3.6	6.7	3.7	29.7	8.1	1.13
274	Zn2V2	3.2	6.7	3	34.7	11.6	1.16
275	Zn2V2	2.9	8.1	3.3	37.7	11.5	1.16
276	Zn2V2	3	8.3	3.3	39.6	12.1	1.16
277	Zn2V2	4.3	8.1	3.5	34.1	9.9	1.15
279	Zn2V2	4.1	9.9	3.8	37.8	10	1.15
280	Zn2V2	3.8	9.9	3.7	38.7	10.5	1.15
259	Zn3V2	5.4	11.1	12.6	33.7	2.7	0.98
262	Zn3V2	3.4	6.7	4.3	20.7	4.9	1.08
267	Zn3V2	4.5	9	3.6	28.6	7.9	1.13
268	Zn3V2	4	7.9	3.4	29	8.7	1.14
269	Zn3V2	3	7.2	3.8	35.9	9.4	1.14
270	Zn3V2	3.5	6.7	2.8	21.4	7.6	1.13
272	Zn3V2	3.6	8.3	3.9	38.2	9.8	1.15
274	Zn3V2	3.4	7.9	2.7	29.8	11	1.15
275	Zn3V2	3.3	8.1	3.1	35.8	11.6	1.16
276	Zn3V2	2.9	8	2.7	37.5	14.1	1.17
277	Zn3V2	3.6	7.9	3.5	31.6	9.1	1.14
279	Zn3V2	3.8	8.7	3.8	50.2	13.2	1.17
280	Zn3V2	3.5	7.8	3.6	40.8	11.3	1.16

Table A1. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
259	Zn0V3	5.5	10.7	7.4	26.7	3.6	1.03
262	Zn0V3	2.9	6.3	3.4	24.9	7.4	1.12
267	Zn0V3	4	7.6	3.4	29	8.7	1.14
268	Zn0V3	3	6.5	3.1	24.3	7.7	1.13
269	Zn0V3	3.1	6.1	3.2	26.8	8.4	1.13
270	Zn0V3	3.8	6.9	3.7	23.5	6.3	1.11
272	Zn0V3	4	7.6	3.9	29.6	7.7	1.13
274	Zn0V3	3.1	8	3.9	39.2	10.2	1.15
275	Zn0V3	3.7	9.2	2.8	39.2	14.1	1.17
276	Zn0V3	3	9.6	3	36.1	12	1.16
277	Zn0V3	3.7	9.3	3.8	38.9	10.2	1.15
279	Zn0V3	4.4	9.5	3.9	44	11.2	1.16
280	Zn0V3	3.8	8.8	3.7	34.8	9.5	1.14
259	Zn1V3	6.6	13.1	7.3	31	4.2	1.06
262	Zn1V3	4	8.2	3.2	27.1	8.5	1.14
267	Zn1V3	4.3	8.5	3.8	35	9.3	1.14
268	Zn1V3	4	8.4	3.6	38	10.6	1.15
269	Zn1V3	4.1	9	3.5	33.3	9.5	1.14
270	Zn1V3	5.7	8.8	3.9	30.9	8	1.13
272	Zn1V3	4.8	10.1	4.1	45	11	1.15
274	Zn1V3	3.3	8.7	3.4	33.7	10	1.15
275	Zn1V3	3.7	10	3.7	37.3	10.1	1.15
276	Zn1V3	3.6	11.1	3.6	39.2	10.8	1.15
277	Zn1V3	4.3	9.7	4	32	8	1.13
279	Zn1V3	4.4	9.6	4.8	40.4	8.4	1.14
280	Zn1V3	4.1	12.7	4.3	44.9	10.4	1.15

Table A1. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
259	Zn2V3	6	12.3	8.7	25.1	2.9	0.99
262	Zn2V3	3.8	6.7	3.3	21.5	6.6	1.11
267	Zn2V3	4.1	7.1	3.1	22.6	7.4	1.12
268	Zn2V3	4	6.2	4.3	27.1	6.4	1.11
269	Zn2V3	3.3	6.8	3.1	28	9.1	1.14
270	Zn2V3	3.1	4.9	3.3	21.9	6.6	1.11
272	Zn2V3	3.1	6.9	3.2	20.1	6.4	1.11
274	Zn2V3	4.1	9.3	3.3	34.6	10.4	1.15
275	Zn2V3	5.5	9.8	3.2	36.1	11.2	1.16
276	Zn2V3	3.2	9.1	3.3	46.4	14.3	1.17
277	Zn2V3	5.7	11.3	4.8	47.4	9.9	1.15
279	Zn2V3	4	8.5	3.8	42.1	11.1	1.16
280	Zn2V3	5	10.3	4.1	47.5	11.5	1.16
259	Zn3V3	4.6	10.4	6.8	34.1	5	1.08
262	Zn3V3	4.7	9.7	4.9	28.4	5.8	1.1
267	Zn3V3	3.5	7.7	4.2	30.2	7.2	1.12
268	Zn3V3	3.4	6.5	3.2	27.6	8.7	1.14
269	Zn3V3	3.4	6.4	2.7	19.9	7.4	1.12
270	Zn3V3	3.8	6	3.5	23.9	6.9	1.12
272	Zn3V3	3.2	7	3.1	30.9	10.1	1.15
274	Zn3V3	2.8	7.7	2.5	34.7	14.1	1.17
275	Zn3V3	2.9	7.3	3	31.8	10.7	1.15
276	Zn3V3	2.8	8	3.1	36.6	11.8	1.16
277	Zn3V3	3.4	8.9	3.5	33.3	9.5	1.14
279	Zn3V3	4.5	9.1	3.6	33.5	9.4	1.14
280	Zn3V3	4	8.6	3.5	36.7	10.6	1.15

Table A2. Spectral reflectance and selected vegetation indices for bean and zinc experiment.

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
315	Zn0V1	3.6	6.2	3.7	24.5	6.58	1.11
316	Zn0V1	5.2	8.8	6.2	27	4.4	1.1
318	Zn0V1	3	5.6	3.7	24.3	6.65	1.11
320	Zn0V1	6.6	9.3	7.2	39.5	5.52	1.09
324	Zn0V1	4.5	9	8.8	56	6.38	1.11
315	Zn1V1	4.2	7.8	5.9	32.7	5.55	1.09
316	Zn1V1	4.6	6.6	5.9	13.6	2.3	0.9
318	Zn1V1	3.1	5.5	3.5	19.4	5.59	1.09
320	Zn1V1	5.8	14.3	7.8	49.9	6.37	1.11
324	Zn1V1	6.6	12.4	8.4	52.4	6.23	1.11
315	Zn2V1	5.6	11.3	6.4	40.3	6.32	1.11
316	Zn2V1	6.7	11.2	8.9	33.6	3.8	1
318	Zn2V1	5.2	11.6	5.7	44.5	7.87	1.13
320	Zn2V1	4.7	8.2	5.6	24.8	4.46	1.06
324	Zn2V1	4	8.7	5.2	25.1	4.83	1.08
315	Zn3V1	6.7	3.6	2.4	10.3	4.31	1.06
316	Zn3V1	5.1	8.6	6.1	29.6	4.8	1.1
318	Zn3V1	2.9	4	3.9	20.4	5.27	1.09
320	Zn3V1	8.3	15.5	7.4	46.9	6.35	1.11
324	Zn3V1	9.1	14.5	10.7	56.5	5.28	1.09

Table A2. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
315	Zn0V2	3.8	6.3	3.9	32.5	8.32	1.13
316	Zn0V2	4.6	7.4	4.5	18.3	4	1.1
318	Zn0V2	3	4.5	3	27.6	9.07	1.14
320	Zn0V2	6	9.3	8.5	62.4	7.31	1.12
324	Zn0V2	4.8	8.9	5.1	47	9.23	1.14
315	Zn1V2	6.8	10.2	6	51.4	8.59	1.14
316	Zn1V2	5.2	10.4	7	56.6	8.1	1.1
318	Zn1V2	5.2	8.7	5.4	42.9	7.91	1.13
320	Zn1V2	3.8	9.8	4.9	45.8	9.35	1.14
324	Zn1V2	4.1	8.6	5.4	54.4	10.15	1.15
315	Zn2V2	6.3	13.3	6.4	59.6	9.31	1.14
316	Zn2V2	5.8	7	6.2	20.7	3.3	1
318	Zn2V2	4.9	10.2	4.8	53.8	11.29	1.16
320	Zn2V2	3.4	7.1	3.7	30.4	8.25	1.13
324	Zn2V2	3.6	7.6	3.4	37.9	11.24	1.16
315	Zn3V2	6.2	3.1	1.4	15.3	10.72	1.15
316	Zn3V2	3.9	6.2	4.7	30.9	6.6	1.1
318	Zn3V2	2.8	4.3	3.3	26.4	7.96	1.13
320	Zn3V2	4.1	6.7	3.5	27.3	7.73	1.13
324	Zn3V2	4.6	8	5.5	54.8	10.04	1.15

Table A2. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
315	Zn0V3	3.5	6.6	3.1	32	10.34	1.15
316	Zn0V3	6.4	10.1	5.1	22.5	4.4	1.1
318	Zn0V3	3.1	4.5	3.2	30	9.41	1.14
320	Zn0V3	5.3	10.7	6.2	59.7	9.62	1.15
324	Zn0V3	5.1	7.2	5.5	42.5	7.73	1.13
315	Zn1V3	4.4	10.8	4.3	50.8	11.82	1.16
316	Zn1V3	5.9	12.5	4.5	61.5	13.8	1.2
318	Zn1V3	4.4	7.8	3.8	53.9	14.22	1.17
320	Zn1V3	3.3	7.6	2.6	45.3	17.76	1.18
324	Zn1V3	5.3	8.1	4.5	55	12.3	1.16
315	Zn2V3	7.7	3.3	1.7	15.7	9.18	1.14
316	Zn2V3	3.4	6.4	3	44.8	14.9	1.2
318	Zn2V3	2.9	4.6	2.2	32	14.67	1.17
320	Zn2V3	4.1	9.9	5.4	64.6	12	1.16
324	Zn2V3	3.6	8.5	4	62.6	15.84	1.18
315	Zn3V3	5.2	4.6	1.6	20.9	12.96	1.16
316	Zn3V3	5.3	8.8	6.6	43.2	6.6	1.1
318	Zn3V3	3.4	6.6	3.2	28.9	9.03	1.14
320	Zn3V3	3.5	7	2.9	48.2	16.71	1.18
324	Zn3V3	4.4	8.4	3.2	45	14.05	1.17

Table A3. Spectral reflectance and selected vegetation indices for squash and zinc experiment.

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
315	Zn0V1	6.3	4.4	2.5	22.7	9.1	1.14
316	Zn0V1	5.1	8.8	5	46.6	9.4	1.1
318	Zn0V1	4.4	4.6	2.9	23.8	8.29	1.13
320	Zn0V1	4.7	8.1	3.9	47.1	11.95	1.16
324	Zn0V1	3.8	6.7	4.3	41.4	9.59	1.15
315	Zn1V1	5.6	4	2.9	21.5	7.29	1.12
316	Zn1V1	6.1	10.5	7.2	49.8	6.9	1.1
318	Zn1V1	4.2	4.3	3.6	20.7	5.8	1.1
320	Zn1V1	4	10	6.2	72.8	11.83	1.16
324	Zn1V1	4.9	9.7	3.3	52	15.56	1.17
315	Zn2V1	4.3	7.1	4.5	38.9	8.66	1.14
316	Zn2V1	4.7	7.9	5.2	50.5	9.7	1.1
318	Zn2V1	3.9	8.1	4.6	48.7	10.55	1.15
320	Zn2V1	4.4	8.8	5.1	60.9	12.06	1.16
324	Zn2V1	3.1	7.2	3.3	65.8	19.97	1.19
315	Zn3V1	4.6	4.3	2.3	18.7	8.18	1.13
316	Zn3V1	5.7	11.3	5.9	50.4	8.6	1.1
318	Zn3V1	2.9	4	3.9	20.4	5.27	1.09
320	Zn3V1	4.1	10.1	5.8	90.6	15.7	1.17
324	Zn3V1	4.2	14	4.8	73.6	15.32	1.17

Table A3. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
315	Zn0V2	5.5	5.9	4.3	28	6.48	1.11
316	Zn0V2	7.9	14.8	11.	60.1	5.3	1.1
318	Zn0V2	4	4.5	3	30.8	10.23	1.15
320	Zn0V2	6.6	11.2	8.3	76.3	9.16	1.14
324	Zn0V2	5.1	12.5	6.3	80.8	12.82	1.16
315	Zn1V2	4.6	9.2	5.8	39.1	6.79	1.11
316	Zn1V2	6.5	12.6	7.9	63.4	8.1	1.1
318	Zn1V2	5	9.3	6.3	29.2	4.62	1.07
320	Zn1V2	4.6	11.8	4.8	77.1	16.16	1.18
324	Zn1V2	4.5	12.2	4.4	70.5	15.93	1.18
315	Zn2V2	4.5	8.4	6.8	29.4	4.32	1.06
316	Zn2V2	4.2	10.3	5	52.1	10.4	1.2
318	Zn2V2	4.3	9.6	4.6	45.1	9.8	1.15
320	Zn2V2	6.3	11.3	7.9	74.7	9.41	1.14
324	Zn2V2	6.3	9.9	7.5	68.9	9.22	1.14
315	Zn3V2	4.5	4.1	2.7	14.9	5.43	1.09
316	Zn3V2	7.2	13.3	9	45.5	5.1	1.1
318	Zn3V2	3.5	5.2	3.5	29	8.3	1.13
320	Zn3V2	5.6	14.1	7.7	50.4	6.56	1.11
324	Zn3V2	4.4	10.3	3.7	70.4	18.99	1.18

Table A3. (Continued)

DAY	TRT	%B	%G	%R	%NIR	NIR/R	TND
315	Zn0V3	4.7	6.9	3.5	24.9	7.14	1.12
316	Zn0V3	7.5	15.1	9.5	72.2	7.6	1.1
318	Zn0V3	3.8	6.2	3.4	29.3	8.68	1.14
320	Zn0V3	6.5	11.9	8.4	74.3	8.84	1.14
324	Zn0V3	5.7	10.9	5.8	68.3	11.73	1.16
315	Zn1V3	4.7	10	5.2	33.7	6.5	1.11
316	Zn1V3	6.2	10.8	7.5	49.4	6.6	1.1
318	Zn1V3	4.1	7.5	5	28.7	5.78	1.1
320	Zn1V3	3.3	9	3.3	49.3	15.01	1.17
324	Zn1V3	4.2	9.6	3.2	56.8	17.66	1.18
315	Zn2V3	4.2	5.5	3.2	22.1	7	1.12
316	Zn2V3	4.6	6.6	5.6	32.9	5.9	1.1
318	Zn2V3	3.7	5.1	2.9	28.9	9.89	1.15
320	Zn2V3	7	16.4	7.1	71.9	10.07	1.15
324	Zn2V3	4.9	15.9	4.9	68.6	14.06	1.17
315	Zn3V3	3.7	5.9	3.6	21.9	6.17	1.1
316	Zn3V3	5.2	11.6	4.6	40.8	8.9	1.1
318	Zn3V3	3.4	6.2	3	31	10.35	1.15
320	Zn3V3	4.8	11.2	3.9	46.2	11.78	1.16
324	Zn3V3	3	8.6	3	47.8	16.19	1.18

Table A4. Spectral reflectance, transformed normalized difference and percentage of biomass cover for corn and nitrogen experiment.

DAY	TRT	%B	%G	%R	%NIR	TND	%COVER
7	N0V1	4	6	8	13	0.88	35
11	N0V1	4	7	4	24	1.1	37
19	N0V1	3	5	4	14	1	41
26	N0V1	3	4	7	18	0.98	47
34	N0V1	3	6	2	18	1.1	61
42	N0V1	2	5	2	9	1	68
49	N0V1	3	5	5	32	1.1	76
57	N0V1	3	7	4	25	1.1	97
64	N0V1	4	6	5	17	1	98
7	N1V1	5	6	6	18	1	38
11	N1V1	3	3	2	13	1.1	41
19	N1V1	2	3	5	13	0.98	43
26	N1V1	4	8	6	24	1	51
34	N1V1	3	9	3	24	1.1	79
42	N1V1	3	7	4	29	1.1	83
49	N1V1	4	12	4	41	1.2	85
57	N1V1	5	9	5	35	1.1	93
64	N1V1	5	12	5	44	1.1	96
7	N2V1	5	6	6	10	0.88	45
11	N2V1	5	12	5	21	1.1	47
19	N2V1	4	9	7	16	0.93	48
26	N2V1	4	10	2	36	1.2	50
34	N2V1	2	4	5	16	1	67
42	N2V1	2	2	5	17	1	71
49	N2V1	3	8	5	25	1.1	79
57	N2V1	3	7	4	20	1.1	84
64	N2V1	3	6	3	25	1.1	97

Table A4. (Continued)

DAY	TRT	%B	%G	%R	%NIR	TND	%COVER	TRT	%B	%G	%R	%NIR	TND	%COVE
7	N0V2	5	8	7	19	0.98	47	N0V3	5	7	9	12	0.79	21
11	N0V2	3	8	5	11	0.95	50	N0V3	4	6	7	19	0.98	23
19	N0V2	3	6	3	16	1.1	52	N0V3	3	5	5	11	0.91	37
26	N0V2	3	6	4	19	1.1	54	N0V3	3	6	4	13	1	45
34	N0V2	2	6	3	16	1.1	66	N0V3	3	3	4	11	0.98	65
42	N0V2	2	6	6	27	1.1	79	N0V3	2	5	3	9	0.99	75
49	N0V2	3	6	4	20	1.1	83	N0V3	3	6	3	23	1.1	87
57	N0V2	4	8	5	20	1.1	90	N0V3	3	7	3	27	1.1	93
64	N0V2	4	10	4	26	1.1	99	N0V3	4	8	4	21	1.1	95
7	N1V2	4	6	6	17	0.99	50	N1V3	4	5	7	12	0.85	22
11	N1V2	6	12	6	8	0.81	55	N1V3	4	7	4	8	0.88	25
19	N1V2	4	9	8	38	1.1	67	N1V3	4	7	7	24	1	37
26	N1V2	4	8	10	29	0.99	70	N1V3	3	7	7	16	0.95	44
34	N1V2	3	6	7	29	1.1	76	N1V3	4	6	5	11	0.94	65
42	N1V2	4	9	7	46	1.1	78	N1V3	4	11	7	8	0.77	69
49	N1V2	5	13	8	49	1.1	80	N1V3	6	8	7	56	1.1	71
57	N1V2	4	10	5	33	1.1	84	N1V3	5	12	5	44	1.1	89
64	N1V2	4	11	5	36	1.1	99	N1V3	4	10	5	34	1.1	93
7	N2V2	4	6	6	16	0.96	47	N2V3	4	6	8	11	0.82	32
11	N2V2	5	14	6	29	1.1	55	N2V3	4	6	5	14	1	34
19	N2V2	4	9	9	29	1	57	N2V3	3	5	6	11	0.91	37
26	N2V2	3	6	7	18	0.97	59	N2V3	3	6	5	19	1	45
34	N2V2	2	4	3	15	1.1	62	N2V3	3	5	4	17	1.1	51
42	N2V2	2	6	3	17	1.1	68	N2V3	3	5	3	9	0.97	68
49	N2V2	4	7	3	18	1.1	76	N2V3	4	5	4	13	1	75
57	N2V2	3	7	4	24	1.1	93	N2V3	4	6	4	24	1.1	89
64	N2V2	3	7	4	26	1.1	96	N2V3	3	6	3	26	1.1	92

Table A5. Spectral reflectance, transformed normalized difference and percentage of biomass cover for corn and water experiment.

DAY	TRT	%B	%G	%R	%NIR	TND	%COVER
7	W1V1	4	5	4	9	0.92	26
11	W1V1	4	7	7	21	1	32
19	W1V1	3	4	5	9	0.85	43
24	W1V1	3	6	5	18	1.03	47
26	W1V1	3	5	4	30	1.1	57
34	W1V1	2	3	3	8	1	76
42	W1V1	2	6	3	22	1.1	86
49	W1V1	3	8	4	19	1.1	88
57	W1V1	3	6	4	20	1.1	95
7	W1V2	4	7	6	16	0.97	50
11	W1V2	4	8	8	27	1	52
19	W1V2	3	6	5	16	1	53
24	W1V2	3	7	3	16	1.1	65
26	W1V2	3	5	4	17	1.1	66
34	W1V2	2	5	4	11	1	70
42	W1V2	3	8	5	15	1	85
49	W1V2	3	7	4	28	1.1	89
57	W1V2	4	9	4	27	1.1	96
7	W1V3	5	6	8	10	0.78	8
11	W1V3	4	8	3	15	1.1	12
19	W1V3	3	5	4	11	0.97	21
24	W1V3	3	4	5	6	0.76	25
26	W1V3	3	5	3	5	0.86	26
34	W1V3	2	2	3	9	1	47
42	W1V3	3	5	3	6	0.93	53
49	W1V3	3	5	3	17	1.1	54
57	W1V3	4	6	5	13	0.98	64

Table A5. (Continued)

DAY	TRT	%B	%G	%R	%NIR	TND	%COVE	TRT	%B	%G	%R	%NIR	TND	%COVE
7	W2V1	5	8	11	15	0.81	32	W3V1	4	6	6	12	0.92	47
11	W2V1	4	5	2	16	1.13	33	W3V1	5	11	3	29	1.1	50
19	W2V1	3	4	6	9	0.84	35	W3V1	4	8	4	30	1.1	55
24	W2V1	3	5	4	17	1.1	40	W3V1	4	8	6	30	1.1	58
26	W2V1	3	3	4	16	1.1	41	W3V1	4	8	4	26	1.1	65
34	W2V1	4	8	4	28	1.1	47	W3V1	2	5	3	16	1.1	71
42	W2V1	4	12	6	22	1	67	W3V1	2	6	4	25	1.1	83
49	W2V1	5	6	7	17	0.96	73	W3V1	3	5	4	19	1.1	85
57	W2V1	4	11	5	28	1.1	77	W3V1	3	5	4	19	1.1	94
7	W2V2	4	7	5	12	0.97	53	W3V2	4	6	5	18	1.04	59
11	W2V2	7	12	7	21	1	55	W3V2	6	13	6	36	1.09	61
19	W2V2	4	9	4	32	1.1	62	W3V2	5	12	3	18	1.1	62
24	W2V2	4	9	6	47	1.1	74	W3V2	3	5	7	26	1	69
26	W2V2	4	10	5	27	1.1	77	W3V2	3	6	5	27	1.1	71
34	W2V2	4	8	4	22	1.1	84	W3V2	2	6	3	5	0.91	73
42	W2V2	4	8	4	28	1.1	87	W3V2	3	6	6	22	1.05	82
49	W2V2	5	13	5	53	1.2	90	W3V2	3	8	5	18	1.04	84
57	W2V2	4	11	4	36	1.1	97	W3V2	4	6	5	17	1	89
7	W2V3	4	6	6	10	0.86	20	W3V3	4	8	7	19	0.97	37
11	W2V3	5	8	11	17	0.84	29	W3V3	4	6	6	19	1	38
19	W2V3	4	7	2	17	1.1	31	W3V3	3	4	3	5	0.91	41
24	W2V3	4	7	8	11	0.81	39	W3V3	3	6	3	14	1.1	45
26	W2V3	4	6	4	21	1.1	40	W3V3	4	7	3	15	1.1	47
34	W2V3	3	7	4	16	1	53	W3V3	3	5	3	11	1	64
42	W2V3	4	5	4	10	0.96	78	W3V3	3	5	6	18	1	67
49	W2V3	4	12	3	37	1.2	85	W3V3	4	7	4	15	1	69
57	W2V3	5	9	6	30	1.1	91	W3V3	4	7	5	23	1.1	74

Table A6. Spectral reflectance, selected vegetation indices and percentage of biomass cover for field experiment.

DAY	TRT	%B	%G	%R	%NIR	NIR/R	ND	TND	SAVI	%COVER
109	W1N1	5.8	9.8	11.9	46.6	3.9	0.6	1.04	0.88	65
116	W1N1	3.4	9	5.4	39.9	7.3	0.8	1.12	1.13	87
123	W1N1	3.6	10.1	5.6	39.6	7.0	0.8	1.12	1.12	91
130	W1N1	8.4	16.7	14.6	45.1	3.2	0.5	1.01	0.76	88
109	W1N2	4.5	7.1	8	42.7	5.3	0.7	1.09	1.02	69
116	W1N2	3.3	5.9	4.4	37.7	9	0.8	1.13	1.17	72
123	W1N2	3.7	8.5	4	38	9.4	0.8	1.14	1.20	87
130	W1N2	6.9	16.5	11.2	41.8	3.8	0.6	1.04	0.86	85
109	W1N3	5	7.8	9.6	37.4	3.9	0.6	1.04	0.88	65
116	W1N3	2.8	7.5	4.4	42.5	9.9	0.8	1.15	1.21	81
123	W1N3	4.4	8.9	5.2	41.4	7.9	0.8	1.13	1.15	87
130	W1N3	7.8	18	8.3	52.1	6.4	0.7	1.11	1.08	86
109	W2N1	7	11.7	14	36.7	2.6	0.4	0.97	0.67	51
116	W2N1	4	8.8	7.1	34.1	4.8	0.7	1.07	0.97	73
123	W2N1	3.6	11.4	6.5	38.3	5.9	0.7	1.1	1.05	86
130	W2N1	6.5	16.2	10.7	39.9	3.8	0.6	1.04	0.86	79
109	W2N2	4.5	8.2	9.2	32.7	3.6	0.6	1.03	0.83	73
116	W2N2	3.3	6.6	4.4	38.6	8.7	0.8	1.14	1.18	74
123	W2N2	3.6	7.5	4.6	40.6	8.9	0.8	1.14	1.18	88
130	W2N2	6.3	14.3	8.5	44.4	5.2	0.7	1.08	1.01	86
109	W2N3	5.3	9.3	10.4	39.1	3.8	0.6	1.04	0.86	69
116	W2N3	3	6	4.7	39.6	8.7	0.8	1.13	1.17	83
123	W2N3	3	7	4.1	38.5	9.4	0.8	1.14	1.20	93
130	W2N3	5.8	14	8.6	51	6.1	0.7	1.1	1.06	90
109	W3N1	5.8	11.1	10.1	53	5.2	0.7	1.09	1.01	80
116	W3N1	3.7	9.7	5.6	41.1	7.4	0.8	1.12	1.13	90
123	W3N1	3.6	12.8	5	41.3	8.2	0.8	1.13	1.16	93
130	W3N1	5.6	15.5	8.1	41	5.2	0.7	1.08	0.99	90
109	W3N2	5.2	8.4	8.2	40	4.9	0.7	1.08	0.98	86
116	W3N2	3.1	7.4	4.4	43.8	10.1	0.8	1.15	1.21	89
123	W3N2	4.1	10.6	5	42.9	8.6	0.8	1.14	1.17	94
130	W3N2	6.9	14.8	9.1	45.8	5.1	0.7	1.08	0.99	91
109	W3N3	5	10.3	9.8	41.2	4.2	0.6	1.06	0.91	83
116	W3N3	4	7.5	4.3	45.1	10.4	0.8	1.15	1.23	93
123	W3N3	2.8	7.1	3.5	43.4	12.6	0.9	1.16	1.26	99
130	W3N3	6.8	15.2	7.2	46.5	6.7	0.7	1.11	1.09	95

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